OBSERVATION OF A CHARGE ASYMMETRY IN $e^+e^- \to \mu^+\mu^-$

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The angular distribution and the s dependence of the total cross section for the process $e^+e^- \to \mu^+\mu^-$ have been measured using the JADE detector at PETRA. After radiative corrections, a forward–backward asymmetry of $-(11.8 \pm 3.8)\%$ was observed at an average centre of mass energy of 33.5 GeV. For comparison, an asymmetry of -7.8% is expected on the basis of the standard Glashow–Salam–Weinberg model.

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We report on the measurement of the process $e^+e^- \to \mu^+\mu^-$ at centre of mass (cms) energies in the range $12.0 \leqslant \sqrt{s} \leqslant 36.8$ GeV. At low energies, this process is well described by QED if contributions up to order α^3 are included [1]. At the highest PETRA energies the standard electro-weak theory [2] predicts sizeable interference effects between electromagnetic and weak neutral currents which should manifest themselves in an angular asymmetry. The angular distribution contains in first order, in addition to the familiar $1 + \cos^2\theta$, a term linear in $\cos\theta$ [3]. In the present letter, evidence for the existence of such a linear term is presented which is the first observation of electro-weak interference at time-like momentum transfers and for processes involving leptons only. Preliminary results from this and other experiments at PETRA and PEP have been presented in refs. [4,5] [‡1]. We note that electro-weak interference has been observed previously in the interaction of leptons and hadrons at space-like momentum transfers, in the experiment on inelastic scattering of polarized electrons from deuterium [6].

The measurement was made using the JADE detector, a solenoidal spectrometer at PETRA. The apparatus has been described elsewhere [7]; here we shall mention only those features used for the present analysis.

The cylindrical jetchamber, which is situated in a magnetic field of 4.8 kG along the direction of the e^+e^- beams, was used to measure directions, momenta and charges of the outgoing particles. Separation of muon pair candidates from background processes was achieved with the help of time-of-flight (TOF) counters, lead glass shower counters, and a muon filter.

The 42 TOF counters surrounding the jetchamber measured the flight time with a resolution of $\sigma = 0.4$ ns. They were also used for triggering, in conjunction with a track requirement in the jetchamber, demanding 2 tracks coplanar within ± 56 rad.

Electrons were recognized in a cylindrical array of 2520 lead glass blocks of 12.5 radiation lengths each, which surrounded the jetchamber. Finally, muons were identified in the segmented muon filter, consisting of 4 layers of absorber, interspersed with drift chambers.

A particle originating from the interaction point and traversing the whole filter had to penetrate a minimum of 6 absorption lengths, resulting in a probability of 0.2% for a hadron to pass through without interacting. For the momenta considered here, less than 0.1% of pions decay in flight, before reaching the first absorber.

Data were accumulated between autumn 1979 and spring 1981, corresponding to a total integrated luminosity of 19.02 pb^{-1} above a cms energy of 25 GeV. The $\mu^+\mu^-$ candidates were selected according to the following criteria:

(1) Events with two tracks which emerged back to back from the interaction region with an acollinearity of less than 0.2 rad were selected. The acceptance in the azimuthal angle was 2π. The polar angle θ of both tracks, measured with respect to the positron flight direction, was limited to $36.9 \leqslant \theta \leqslant 143.1°$.

(2) In order to reject events from Bhabha scattering, tracks which deposited more than 1/3 of the beam energy in the lead glass counters were rejected. The remaining background is less than 0.4% of the final muon pair sample, and no correction was applied for this. Any resulting asymmetry is positive and less than 1%.

(3) Cosmic rays were rejected by TOF measurements. Both tracks were required to have equal times of flight within 2.9 ns, whereas cosmic ray events have a time difference of at least 6.1 ns. In addition the time of flight of each particle had to agree within 4 ns with the flight time calculated from the path length, assuming the velocity of light. The contamination from cosmic rays in the final sample is negligble (<0.2%), and is not corrected for.

(4) Two-track events coming from two-photon scattering were rejected by demanding that both tracks have a momentum of at least 1/3 of the beam energy. The contamination from two-photon processes was computed to contribute less than 0.5% to the final muon pair sample.

The candidate events obtained after these cuts were visually scanned. At this stage the information from the muon filter was used in addition. The pattern of hits in the chambers of the muon filter had to be compatible with that produced by two penetrating tracks.

Most background eliminated by the scan came from τ pairs. Events where one τ decayed into 1 charged particle and the other into 3 charged particles, such that 2 of the tracks satisfied all selection criteria, were easily recognized. Events where both τ decays yielded only

[‡1] In ref. [4] the preliminary results from the PETRA experiments JADE, MARK J, PLUTO and TASSO were combined yielding $A = (-7.7 \pm 2.4)\%$. The PLUTO result is published in ref. [5].

one charged particle (namely π, e, μ) were eliminated with the help of the lead glass and the muon filter, except for the case where both charged particles were muons. These events could not be distinguished from genuine muon pairs, and their contribution was calculated to be 1.3% and subtracted statistically. The final event sample consisted of 778 muon pairs. The charge assignment was done using separate fits to the two tracks as well as a combined charge determination. The two methods gave compatible results and opposite charges were assigned to all pairs. The probability to assign the wrong charge combination is estimated to be less than 0.5%.

Radiative corrections, calculated using the programs of Berends and Kleiss [8], were applied to the data. They include graphs up to order α^3 and vacuum polarisation by leptons as well as hadrons. The correction varies with polar angle (θ) and the asymmetry produced by radiative effects is +1.3% in the angular range of this experiment.

In order to determine the absolute cross section, two overall corrections were applied. The cuts described above were estimated to reject 3.6% of genuine muon pairs, and the loss due to trigger inefficiency was measured to be 9.2%. The resulting total cross section is

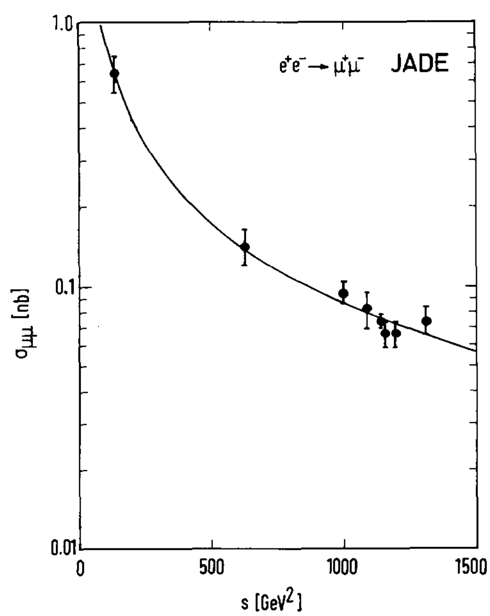

Fig. 1. Total cross section for $e^+e^- \to \mu^+\mu^-$ as a function of s. The curve shows the QED prediction ($\equiv 86.9/s$ nb).

$s\sigma_{\mu\mu} = 85.7 \pm 3.1$ nb GeV^2 with a normalisation error estimated to be 6%. The s-dependence of $\sigma_{\mu\mu}$ is shown in fig. 1. It agrees well with the $1/s$ behaviour predicted by QED.

The corrected angular distribution of the positive muon for the data above a cms energy of 25 GeV is shown in fig. 2. An asymmetry can be seen immediately. The forward–backward asymmetry is defined to be

$$A = [I(\theta) - I(\pi - \theta)]/[I(\theta) + I(\pi - \theta)] ,$$

where $I(\theta) = \int_0^{\cos\theta} \mathrm{d}\sigma/\mathrm{d}\Omega \; \mathrm{d}\cos\theta$. From the corrected number of events in the forward and backward hemisphere, an asymmetry $A = -(11.8 \pm 3.8)\%$ was calculated. This value extends to $\cos\theta = \pm 0.8$, the acceptance limit of this experiment. In order to extrapolate to $\cos\theta = \pm 1$ a fit to the function $y = p(1 + \cos^2\theta) + q\cos\theta$ was performed, where p and q were free parameters. The values came out to be $p = 5.06 \pm 0.19$, $q = 1.72 \pm 0.51$. From this fit an overall asymmetry of $A = -(12.8 \pm 3.8)\%$ was obtained. (In the acceptance region the fit gave $-(11.0 \pm 3.3)\%$, in agreement with the value computed from the data.)

The errors quoted are statistical only. The following sources of systematic error were studied. The radiative corrections, being angle dependent, could introduce such an error. This is believed to be small since the corrections and their asymmetry are small. The overall efficiency corrections are independent of angle and cancel when computing the asymmetry. The θ dependence of the efficiency was estimated to be small by examining the angular distribution of cosmic ray

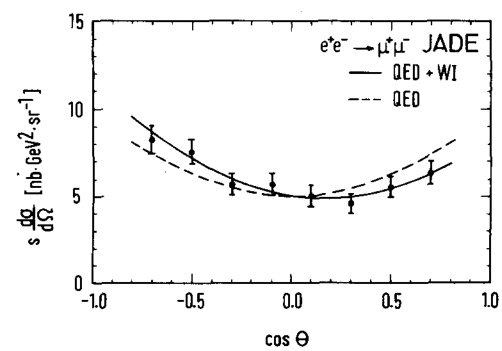

Fig. 2. Angular distribution for $e^+e^- \to \mu^+\mu^-$ for $\sqrt{s} > 25$ GeV. θ is the angle between the outgoing μ^+ and the incoming e^+. The curves show fits to the data: $p(1 + \cos^2\theta) + q\cos\theta$ (full curve), $p(1 + \cos^2\theta)$ (dashed curve).

tracks which penetrated the detector while beam–beam data were being taken. The trigger and event selection were the same as for genuine muon pairs, except, of course, for a modified TOF cut. A possible source of systematic error in the momentum determination and hence charge assignment, is a twist of the jetchamber. By studying the momentum distributions for opposite sides of the apparatus a limit of $|\Delta A| < 0.2\%$ was derived.

As a consequence of these considerations we estimate the total systematic error on the asymmetry to be less than 1%. Additional confirmation was obtained by determining the forward–backward asymmetry of high momentum cosmic rays from the sample mentioned above. For momenta above 10 GeV/c, an asymmetry of $+(0.8 \pm 1.7)\%$ was observed, which is in agreement with expectations from cosmic ray experiments [9].

Recently data were taken at cms energies of 14 and 22 GeV. The measured asymmetry of $(+0.7 \pm 4.6)\%$ compared to a value of -2.6% expected from the standard model [2] also indicates that the asymmetry measured at high energies is not caused by instrumental effects.

The final experimental result is

$$A = -(11.8 \pm 3.8 \pm 1)\% ,$$

where the first error is statistical and the second one systematic. It agrees well with the standard model SU(2) × U(1) of Glashow, Salam and Weinberg [8], which predicts an asymmetry of $A = -7.8\%$ for $|\cos\theta| \leqslant 0.8$. It agrees also with the expectation from a point-like four-fermion coupling, as at our energies the propagator effect of the Z_0 is only 20%.

If the measured asymmetry is attributed to the presence of a weak neutral current, information about the axial vector coupling constant, a, can be obtained in a model independent way. For the exchange of one neutral vector boson Z_0, assuming μ–e universality an expression for the differential cross section $e^+e^- \to \mu^+\mu^-$ is derived in ref. [10]. Retaining only contributions from the interference of the electromagnetic and weak amplitudes a simplified expression for the asymmetry is obtained:

$$A = \tfrac{3}{2} a^2 R ,$$

with

$$R = \frac{G_F}{8\sqrt{2}\pi\alpha} \frac{M_Z^2 s}{s - M_Z^2} .$$

G_F is the Fermi coupling constant and M_Z the mass of Z_0. Using the measured overall asymmetry and $M_Z = 88.8$ GeV (which corresponds to $\sin^2\theta_W = 0.23$) a value of $a^2 = 1.45 \pm 0.43$ was obtained.

Information about the vector coupling constant can in principle be obtained from the total cross section:

$$\sigma_{\mu\mu} = \sigma_{QED}[1 + 2v^2R + (v^2 + a^2)^2R^2] ,$$

where R is defined as in the asymmetry. A value of $v^2 = 0.20 \pm 0.33$ was obtained using the measured axial coupling constant. Due to the limited number of muon pairs this result is much less significant than the one obtained from Bhabha scattering [10]. These results are in accordance with the "standard model", which predicts $a^2 = 1$ and $v^2 = 0.01$ for $\sin^2\theta_W = 0.23$.

In conclusion we have observed a charge asymmetry in $e^+e^- \to \mu^+\mu^-$ which excludes pure QED by three standard deviations. It agrees within one standard deviation with the prediction of the Salam–Weinberg model. A model independent determination of the axial vector coupling gives the value $a^2 = 1.45 \pm 0.43$, of the vector coupling constant $v^2 = 0.20 \pm 0.33$.

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