# Test of Quantum Electrodynamics at $s^{1/2} = 13$ and 17 GeV

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We report on the measurement of the reaction $e^+e^- \rightarrow e^+e^-$ with a large-solid-angle electromagnetic shower detector at center-of-mass energies $\sqrt{s} = 13$ and 17 GeV. Comparison of our results with predictions of quantum electrodynamics shows excellent agreement in both the angular distribution and energy dependence. Values of cutoff parameters are also given.

In the last decade there have been many experiments designed to test the validity of quantum electrodynamics. In earlier days one performed experiments of the type $\gamma + A \rightarrow A + e^+ + e^-$,[1] whereby one checked the electron propagators at small distances. These types of experiments are limited to an accuracy of $\simeq 5\%$ by the lack of precise knowledge of nuclear form factors and by the difficulty in monitoring the incident photon flux. With the construction of $e^+e^-$ and $e^-e^-$ colliding beams, we by-pass most of these difficulties, as we have a purely electrodynamic system (to order $\alpha^4$) and can use the low-momentum-transfer part of the interaction (as in the small-angle $e^+e^- \rightarrow e^+e^-$ process) to monitor the interaction rate and compare the large-angle (with large momentum transfer) part of the interaction with the prediction of QED, such as angular distributions, energy dependence, etc. Before the construction of PETRA the most notable experiments were done by Alles-Borelli *et al.*,[2] Newman *et al.*,[3] Augustin *et al.*,[4] and O'Neill *et al.*[5] For a good review of QED work see Brodsky and Drell.[6]

The detector we used, known as MARK-J,[7] is shown in Fig. 1. It is a detector designed to measure and distinguish charged and neutral hadrons, electrons, photons, and muons. It covers a solid angle of $\varphi = 2\pi$ and $\theta = 9°$ to $171°$ ($\theta$ is polar angle and $\varphi$ is azimuthal angle). The detector is symmetrical in both $\varphi$ and $\theta$ directions.

As shown in Fig. 1, the particles leaving the intersection region pass through a ring of thirty-two Lucite Cherenkov counters, L, sixteen on each side of the intersection point. Each counter extends through 0.13 radiation lengths. These counters are used to distinguish charged particles from neutrals and are insensitive to synchrotron radiation. They cover an angle region of $\theta = 9°$ to $171°$. The twenty A counters have one tube at each end, are made out of 3 radiation

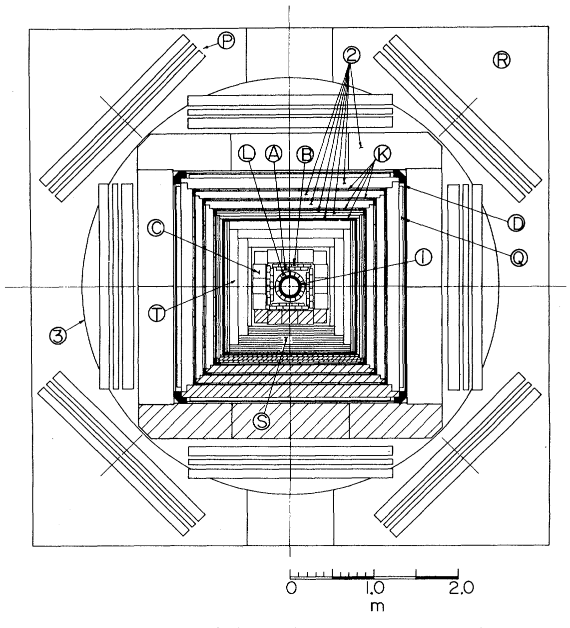

FIG. 1. End view of the MARK-J detector. A, B, and C are the shower counters; L is the Lucite counters; S, T, Q, R, and P are drift chambers; 1 is the beam pipe; 2 is the magnet iron; and 3 is the aluminum rotation ring.

lengths of lead sandwiched with three 5-mm layers of scintillators, and cover angular ranges of $\theta = 12°$ to $168°$. The 24 B counters are constructed identically to the A counters and cover an angular range of $\theta = 16°$ to $164°$. The counters A and B enable us to locate electromagnetic shower maxima in various $\theta$ and $\varphi$ directions. The sixteen C shower counters consist of twelve layers (twelve radiation lengths) of lead scintillator sandwich also with one tube at each end. The drift chambers S, T, Q, R, and P are used to measure tracks from hadron showers and measure the muon angles and momenta. The hadron calorimeter, K, consists of an iron scintillator sandwich. The D and E counters are used to trigger on single- and multiple-muon events and to reject cosmic rays and beam sprays.

The luminosity monitor consists of two arrays of 28 lead-glass counters each with dimensions of 8 cm × 8 cm × 70 cm located 5.8 m from the intersection point. They are designed to measure the reaction $e^+e^- \rightarrow e^+e^-$ at small angles. Scintillators in front of the lead glass define the acceptance and the lead-glass counters measure the angle and energy of the electron pairs. In addition, for this experiment the luminosity was monitored with the L, A, B, and C hodoscopes which measure the forward-angle Bhabha scattering (11.5° to 26°).

The total energy of each interaction and directions of particles or groups of particles were computed from the time and pulse-height information of the shower counters and calorimeter counters. From the difference in time between the two phototubes of each shower counter and from the ratio of their pulse height we obtained two measurements of the position along the beam direction at which the particles struck the counter. The algorithms used were developed from analysis of test-beam data which were accumulated for incident electrons and pions between 0.5 and 10 GeV. The azimuthal position was determined by the finely segmented shower counters. This method enables us to determine the angles $\theta$ and $\varphi$ to $<5°$ for $e$ or $\gamma$ and $<15°$ for $\mu$ or hadrons.

In Fig. 2 we show the measurement of the acoplanarity angle $\Delta\varphi$ in the detector with large-angle Bhabha scattering.

For each particle, or group of particles emitted within a cone of 20° which were not separable in the counters, the vector momentum was computed from pulse-height and counter-position information using the position of the interaction region (which is checked to ± 2 cm by fitting tracks in the chambers for $e^+e^- \rightarrow \mu^+\mu^-$ events). Photons emitted close to either electron are included in the fitted electron momentum.

The Bhabha events are identified by requiring two back-to-back showers which are collinear to within 20° in $\varphi$ and $\theta$ and with a measured total shower energy greater than 8 GeV. Because there are few events near the 20° cut in the $\varphi$ acoplanarity spectrum shown in Fig. 2 and a very similar acolinearity spectrum in $\theta$, we conclude that the background to elastic scattering events

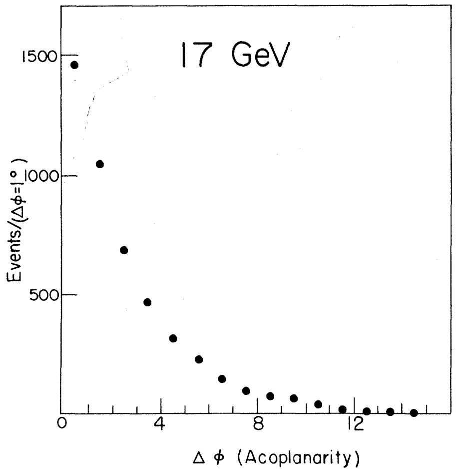

FIG. 2. The measured acoplanarity angle $\Delta\varphi$.

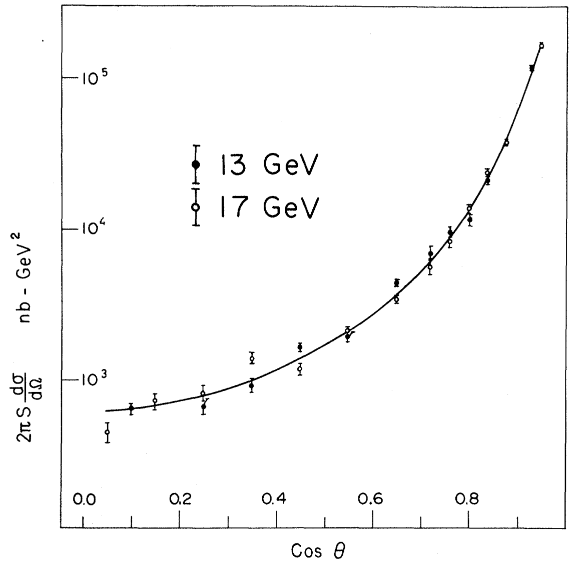

FIG. 3. The data for $\sqrt{s} = 17$ GeV and $\sqrt{s} = 13$ GeV compared with the predictions from QED.

is negligible. The test-beam data mentioned above yield a resolution on the energy sum of

$$\Delta E/E = 12\%/\sqrt{E}.$$

To eliminate most background from hadron jets, the energy in the K counters was required to be less than 7% of the total energy. Because the QED test is most sensitive to background in the large-angle region, all events having $\theta$ larger than 60° were scanned on graphic displays which showed the distribution of counter hits. On the basis of a Monte Carlo study of hadron events, we conclude that the background from this source is less than 1% of these events. The total numbers of $e^+e^-$ events are 4660 at center-of-mass energy of 17 GeV and 7193 at 13 GeV.

The acceptance for $e^+e^- \to e^+e^-$ was computed using a Monte Carlo technique and is defined by the geometry of the first shower counter A. Both energy and acceptance losses in the corners were found to be small.

The results for $\sqrt{s} = 13$ GeV and $\sqrt{s} = 17$ GeV are shown in Fig. 3. Since the first-order QED photon propagator produces an $s^{-1}$ dependence in the $e^+e^- \to e^-e^+$ cross section, the quantity $s\, d\sigma/d\Omega$ vs $\theta$ is independent of $s$. This distribution is plotted for our data in Fig. 3 and shows excellent agreement with the QED predictions. To express this agreement analytically we compare our data with the QED cross section in the following form[8] (since charge is not distinguished here):

$$\frac{d\sigma}{d\Omega} = \frac{\alpha^2}{2s}\left\{\frac{q'^4+s^2}{q^4}|F_s|^2 + \frac{2q'^4}{q^2 s}\operatorname{Re}(F_s F_T{}^*) + \frac{q'^4+q^4}{s^2}|F_T|^2 + \frac{q^4+s^2}{q'^4}|F_s'|^2 + \frac{2q^4}{q'^2 s}\operatorname{Re}(F_s' F_T{}^*) + \frac{q'^4+q^4}{s^2}|F_T|^2\right\}\{1+C(\theta)\}, \tag{1}$$

where

$$F_s = 1 \mp q^2/(q^2 - \Lambda_s{}^2)$$

is the form factor of the spacelike photon,

$$F_s' = 1 \mp q'^2/(q'^2 - \Lambda_s{}^2),$$

$$F_T = 1 \mp s/(s - \Lambda_T{}^2)$$

is the form factor of the timelike photon $q^2 = -s \cos^2(\theta/2)$, $q'^2 = -s \sin^2(\theta/2)$, and $\Lambda$ is the cutoff parameter in the modified photon-propagator model and $C(\theta)$ is the radiative correction term as a function of $\theta$.

The radiative correction to the $e^+e^-$ elastic-scattering process was calculated using a modified program from Berends[9] which includes the contribution of the heavy-lepton ($\tau$) loop and the hadronic vacuum polarization. The inclusion of these two effects changes the radiative correction from minus a few percent, as was commonly used previously, to +4.6% at $\theta = 14°$ and +1.3% at $\theta = 90°$ for $\sqrt{s} = 17$ GeV[4]. It is slightly smaller at $\sqrt{s} = 13$ GeV.

Electron-positron pairs are generated according to Eq. (1) in a Monte Carlo program. Each electron is then traced through the detector. The effect of measured $\theta, \varphi$ resolutions are included. A $\chi^2$ fit was made, using this Monte Carlo-generated angular distribution, to both 13- and 17-GeV data. The normalization was treated in two ways: (1) The total number of Monte Carlo events in the region $0.9 < \cos\theta < 0.98$ was set equal to the total number of measured events in the same region. (2) The minimum-$\chi^2$ fit to the entire data sample determines the normalization. The two methods agree with each other to within 3% and give essentially the same result in the cutoff parameter $\Lambda$. The curve in Fig. 3 is the result of our fit to the data at both energies. The lower limits of $\Lambda$ at 95% confidence level under various assumptions are shown in Table I.

In this model, and without assuming $\mu$-$e$ universality, our present limits on $\Lambda$'s are considerably larger than the previously published limits with $e^+e^- \to e^+e^-$ data of Augustin *et al.*[4] Our limits are compatible with the excellent work of O'Neill *et al.*[5] at SPEAR energies ($\sqrt{s} = 7.0$ and 7.4 GeV), where they measured the ratio of $\theta \approx 4°$ yield with much higher statistics.

We wish to thank Professor H. Schopper and Professor G. Voss who made the experiment pos-

TABLE I. Limits on $\Lambda$ (GeV) (95% confidence level).

| Form factor | $1 - \frac{q^2}{q^2 - \Lambda^2}$ | $1 + \frac{q^2}{q^2 - \Lambda^2}$ |
|---|---|---|
| $\Lambda_s$ | 37 | 21 |
| $\Lambda_T$ | 22 | 21 |
| $\Lambda$ (if $\Lambda_s = \Lambda_T$) | 38 | 26 |
| $\Lambda$ (Ref. 4) | 19 | 15 |
| $\Lambda$ (Ref. 5) | 33.8 | 38.06 |

sible. We also thank T. D. Lee for his helpful discussions. We are grateful for the cooperation of the Minister für Forschung und Technologie, the Joint Research Program of FOM and ZWO of the Netherlands, the U. S. Department of Energy, and the Institute of High Energy Physics of the Chinese Academy of Science in this endeavor. We especially thank Dr. F. J. Eppling, Dr. M. Deutsch, Dr. H. Feshbach, Dr. G. Soehngen, and Dr. G. Weber for their valuable advice and support. We thank Miss I. Schulz, Miss S. Marks, Mr. P. Berges, and Mr. D. Osborne for technical and administrative help. We also thank D. Hubert, G. Kessler, J. Kouptsidis, and F. Schwickert as well as our technicians from Rheinisch-Westfälische Technische Hochschule, Massachusetts Institute of Technology, and DESY for their dedicated services which contributed to the efficient installation of this experiment.

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[9] S. A. Berends *et al.*, Phys. Lett. 63B, 432 (1976), and private communication. We wish to thank Dr. Berends for providing us with his up-to-date computer program for our experiment.

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# Measurement of the Relative Total Hadronic Cross Section $R$ at PETRA

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We report the first measurement of the ratio $R = (\sigma_{e^+e^- \to \text{hadrons}})/(\sigma_{e^+e^- \to \mu^+\mu^-})$ (with negligible $\tau$-lepton contribution) at a center-of-mass energy $\sqrt{s} = 13$ GeV and $\sqrt{s} = 17$ GeV, from the just finished electron-positron colliding-beam facility PETRA. The detector, MARK-J, has an approximately $4\pi$ solid angle and measures $\gamma$, $e$, $\mu$, and charged and neutral hadrons simultaneously. Our results yield $R(\sqrt{s} = 17\text{ GeV}) = 4.9 \pm 0.6$ (statistical) $\pm 0.7$ (systematic error), and $R(\sqrt{s} = 13\text{ GeV}) = 4.6 \pm 0.5$ (statistical) $\pm 0.7$ (systematic error). The ratio $R(\sqrt{s} = 17\text{ GeV})/R(\sqrt{s} = 13\text{ GeV})$ is $1.08 \pm 0.18$.

The high-energy electron-positron colliding-beam accelerator PETRA was finished ahead of its schedule. In the last two months we have been able to use the facility in a stable condition with a luminosity between $10^{29}$ and $10^{30}$ cm$^{-2}$/sec to perform our experiment. The machine operates in two-bunch mode. The lifetime is typically three hours and the filling time has been kept to a maximum of thirty minutes. Thus we are able to perform our physics experiments without much difficulty.

The detector we used, known as MARK-J, is shown in Fig. 1. It is a detector designed to measure and distinguish hadrons, electrons, neutral particles, and muons. It covers a solid angle of $\varphi = 2\pi$ and $\theta = 9°$ to $171°$ ($\theta$ is polar angle and $\varphi$ is azimuthal). The detector is symmetrical in both $\varphi$ and $\theta$ directions.