Measurements of the Reaction $e^+e^- \to e^+e^-$ at Center-of-Mass Energies of 7.0 and 7.4 GeV*

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Measurements of the cross section for the reaction $e^+e^- \to e^+e^-$ (Bhabha scattering) at angles close to 90°, relative to Bhabha scattering at 4°, are reported at center-of-mass energies of 7.0 and 7.4 GeV. The results are in agreement with quantum electrodynamics, and new limits on cutoff parameters for the photon propagator are given.

A fundamental test of quantum electrodynamics (QED) is provided by a measurement of the cross section for the reaction $e^+e^- \to e^+e^-$ (Bhabha scattering) at the highest available center-of-mass energy and at large scattering angle. At angles close to 90° large spacelike values of the invariant four-momentum transfer q^2 dominate the scattering process and QED may not be valid. This Letter reports the results of such a test of QED in which the cross section at large angles is measured in one apparatus relative to that for the same reaction at very small angles (~ 4°) in an independent apparatus, or luminosity monitor. At very small angles only relatively small values of q^2 are involved and the validity of QED may be assumed. This experiment was carried out recently at the electron-positron storage ring SPEAR-II at the Stanford Linear Accelerator Center. Measurements of the cross-section ratio, relative to that predicted by QED, were made at center-of-mass energies of 7.0 and 7.4 GeV, which are close to the maximum possible energy (7.6 GeV) available at SPEAR-II. For the events detected at large angles the spacelike q^2 values involved are in the range -13.2 to -40.0 (GeV/$c)^2$.

The apparatus in the 90° region is identical to that already described by Simpson *et al.*[1] and very similar to that used earlier by Beron *et al.*[2] in a test of QED at SPEAR-I. This apparatus consists of two identical spectrometers mounted in a collinear configuration about the beam interaction region. The essential elements in each spectrometer for the present study are three multiwire proportional chambers (MWPC's) close to the beam interaction region and a 20-radiation-length–thick NaI(Tl) total-absorption crystal 30 in. in diameter. Throughout the experiment these spectrometers were oriented at an azimuthal angle of 45° relative to the plane of the circulating beams in order to eliminate any influence on the measured cross sections of the transverse beam polarization at SPEAR-II.[3]

The electron trigger used to detect $e^+e^- \to e^+e^-$ events required only the observation of greater than 0.2 GeV in each crystal in fast coincidence (~ 30 nsec) with the crossing of the beams. This trigger is extremely efficient since it requires only the observation of a very small fraction (~ 5%) of the electron or positron energy in a total-absorption detector with excellent energy resolution. Upon receipt of this trigger the track information in the MWPC's and the pulse heights in the NaI(Tl) crystals were recorded. In addition, the time of occurrence of each NaI(Tl) pulse, relative to the beam cross, was recorded.

The absolute luminosity of the storage ring was monitored through the measurement of Bhabha scattering at a mean angle of 4° with an apparatus very similar to the precision luminosity monitor described in detail by Crawford *et al.*[4] Although the operating principle is unchanged, the design of the new monitor is optimized for SPEAR-II and includes diagnostic features not available to Crawford *et al.*[4] A sketch of this new monitor is shown in Fig. 1. It consists of four quadruplets of counters symmetrically located with respect to the beam interaction region. Bhabha events are recognized by a coincidence between all four counters in any quadruplet and the opposite C, S pair. The geometrical acceptance for such events is determined by the small counters P. The sum of the four possible signatures of this type, which is very insensitive to the size and to all possible movements of the luminous region, is used as the measure of luminosity.

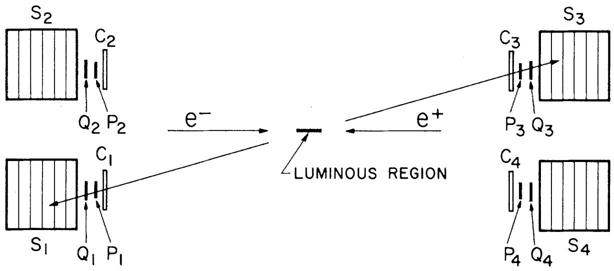

FIG. 1. A schematic diagram illustrating the operating principle of the luminosity monitor. The lead-scintillator shower counters S have an energy resolution of 25% full width at half-maximum and a trigger threshold of 0.7 GeV.

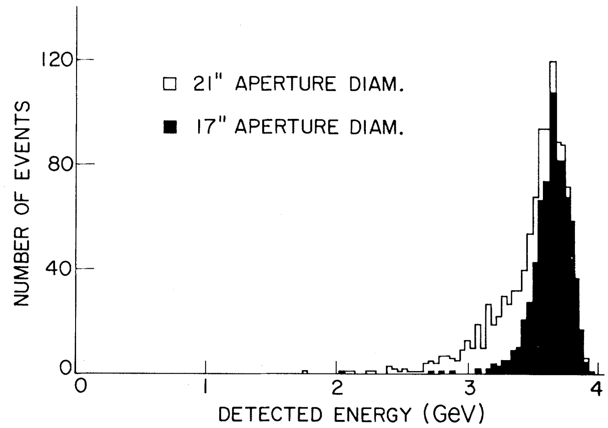

FIG. 2. The energy distribution observed in one of the NaI(Tl) crystals for 1147 $e^+e^- \to e^+e^-$ candidate events at a center-of-mass energy of 7.4 GeV. Also shown is the distribution observed for 742 of these events which satisfy an aperture requirement of 17 in. in both crystals. The peak is broadened at the larger aperture diameter because of the inclusion of particles which enter the crystal obliquely and close to its edge and for which energy leakage occurs. 21 in. is judged to be the maximum aperture diameter for which Bhabha events can be unambiguously distinguished from background events depositing less energy in the crystal.

The luminosity event trigger required only a signal from a P counter in coincidence with signals from both the adjacent and the opposite S counters.[5] For each event the pulse heights in all sixteen counters were recorded. This makes it possible to impose the C and Q counter requirements off-line but, more importantly, allows the identification of nonaccidental background events. The only significant source of events is due to Bhabha particles striking a C, S pair but not the associated P counter. Soft γ rays can subsequently emerge from the face of the S counter and fire the adjacent P counter, but they are extremely unlikely also to fire the associated Q counter.[6] All other nonaccidental backgrounds are extremely small. Accidental event triggers were also measured but amounted to only 0.1% of the real event rate. Considerable care was taken to define the dimensions and relative locations of the P counters and to operate all sixteen counters with very high efficiency.[7] In consequence, the systematic uncertainty on the number of Bhabha events detected by the monitor is estimated to be no more than $\pm 0.5\%$. In comparison, the statistical error is negligible.

Candidate events for the reaction $e^+e^- \to e^+e^-$ were selected by requiring the deposition of a minimum of 0.75 GeV in each NaI(Tl) crystal and the occurrence of fired wires in at least four of the six MWPC coordinate planes in each spectrometer. The efficiencies of all of these planes were continuously monitored throughout the experiment by the observation of cosmic-ray muons and shown to be very high ($\sim 99.8\%$). Those events for which it was possible to reconstruct only two tracks, one in each spectrometer, and for which the event reconstruction was excellent were automatically accepted into the event sample. All other events were displayed for inspection on a graphic terminal and, as necessary, edited with the help of an interactive software system to complete the track reconstruction. Events were not accepted at this stage if two or more charged particles were found in either spectrometer. Subsequently, events were also rejected if the two reconstructed tracks displayed a collinearity angle larger than 15°.

The event sample was further restricted by the requirement that both reconstructed tracks intersect the respective entrance planes of the NaI(Tl) crystals within circular apertures 21 in. in diameter and that a minimum energy of 2.0 GeV be deposited in each crystal. Figure 2 shows, at a center-of-mass energy of 7.4 GeV, the energy distribution observed in one of the NaI(Tl) crystals for $e^+e^- \to e^+e^-$ candidate events which satisfy all of the above criteria, with the exception of the energy requirement in this one crystal. A clear peak is observed as a result of the detection of 3.7-GeV electrons or positrons. The number of background events depositing energies less than 2 GeV is insignificant and the choice of the threshold energy is quite uncritical. At a center-of-mass energy of 7.0 GeV the qualitative appearance of the data is identical to that shown in Fig. 2.

TABLE I. A summary of the observed and expected number of events. The observed, unweighted numbers of events are 1040 and 1146, respectively, at center-of-mass energies of 7.4 and 7.0 GeV.

Center-of-mass energy (GeV)	7.0	7.4
Integrated luminosity (10^{35} cm^{-2})	7.6	10.2
Radiative correction (to lowest-order rate in spectrometers)	0.911	0.911
Number of events expected (point source)	1067 ± 16	1300 ± 20
Number of events observed (weighted sum)	1118	1241
Ratio of observed to expected events	1.05 ± 0.04	0.96 ± 0.03

In order to compare the results of this experiment with QED it is necessary to take into account the longitudinal profile of the luminous region.[8] This is done by computing the expected number of events for a point luminous region and comparing this to a weighted sum of the observed number of events. The weight factor for each event depends only on the displacement of the event vertex from the center of the luminous region, which is measured to an accuracy of ~ 1 mm for each event, and corrects for the geometrical bias against the acceptance of events for which this displacement is nonzero. The weighted sums of the observed numbers of events are shown in Table I, together with the numbers expected from QED. The radiative corrections, including a correction of 4.0% to the observed luminosities, are computed according to Berends *et al.*,[9] who have provided the differential cross section for Bhabha scattering valid to order α^3, where α is the fine structure constant. The weight factor for each event is also computed according to Berends *et al.* The total systematic error assigned to the expected event numbers is 1.5%.[10] The estimated backgrounds due to collinear hadron pair production and to the reaction $e^+e^- \rightarrow e^+e^-e^+e^-$ are negligible (≤ 0.2 events).

The conclusion to be drawn from Table I is that the rates we observe are consistent with the predictions of QED. If, as usual, we anticipate that a possible breakdown of QED can be described by a propagator modification in the lowest-order Feynman diagram of the form $1/q^2 \rightarrow (1/q^2)[1 \pm q^2/(q^2 - \Lambda_\pm^{\,2})]$,[11,12] then our results can be used to place new lower limits (95% confidence level) on the cutoff parameters Λ which, in this experiment, primarily relate to the spacelike photon propagator. These values, together with the limits set by earlier experiments, are given in Table II.

As a further test of the ability of QED to reproduce our observations we compare, in Table III, the observed and expected numbers of events with relatively large acollinearities or acoplanarities. Within the range of the observations, up to 15°, there is excellent agreement between theory and experiment. This result demonstrates explicitly that the observed rate of inelastic Bhabha events can be accounted for by the α^3 approximation to QED in which the emission of one hard photon is allowed.

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TABLE II. The lower limits (95% confidence level) on the cutoff parameters Λ_+ and Λ_- set by this and earlier experiments.

	Λ_+ (GeV)	Λ_- (GeV)
This experiment	38.0	33.8
Ref. 2	22.8	14.4
Ref. 13	15	19

TABLE III. A comparison between the observed and expected number of events with large acollinearities or acoplanarities.

	Fraction of events (%)	
	Observed	Expected
Acollinearity > 5°	8.0 ± 0.5	8.3 ± 0.3
Acollinearity > 10°	2.9 ± 0.3	2.5 ± 0.2
Acoplanarity > 3°	3.2 ± 0.3	2.8 ± 0.1
Acoplanarity > 6°	1.0 ± 0.2	1.0 ± 0.05

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[4]J. F. Crawford *et al*., Nucl. Instrum. Methods 127, 173 (1975).

[5]For diagnostic purposes luminosity event triggers were also generated by a Q counter in coincidence with the adjacent and opposite S counter.

[6]Luminosity event triggers of this type accounted for 4% of the total rate. After the experiment the association of these events with the backscattered γ rays from the S counters was directly and quantitatively verified in an electron test beam.

[7]The dimensions of the P counters were 2 in.$\times 1\frac{3}{8}$ in. $\times\frac{1}{8}$ in. and their heights and widths were measured to $\pm 10^{-3}$ in. Their vertical edges were tapered to be parallel to the incident particles and pulse heights smaller than the Landau edge were observed with a probability of $\sim 0.1\%$ for otherwise acceptable events.

[8]The length of the luminous region at SPEAR-II is small. By fitting to the observed distribution of vertex coordinates we find the luminous region to be 5.2 and 4.7 cm (full width at half-maximum) at center-of-mass energies of 7.4 and 7.0 GeV, respectively.

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[10]The principal sources of systematic error are uncertainties of $\pm 1.0\%$ and $\pm 0.5\%$ assigned to the radiative corrections at 90° and 4°, respectively. These conservative errors are intended to reflect the fact that the radiative corrections were evaluated only to order α^3 in the fine structure constant.

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Is Charm Found?*

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A new neutral narrow meson decaying into $K\pi$ and $K\pi\pi\pi$ was recently discovered in e^+e^- annihilation at SPEAR. Unexpected structure was observed in the recoil-mass spectrum associated with the new particle. We demonstrate that what has been seen coincides with what was expected by advocates of charm. We explain the observed suppression of $D\bar{D}$ production and the scarcity of charged D's. Predictions about the production of charmed hadrons not yet seen are given.

New hadrons are made copiously and in association by e^+e^- annihilation if ideas about charm are true.[1,2] Evidence for this has been reported.[3] We demonstrate that what has been seen conforms to theoretical expectations.

Weakly decaying pseudoscalar D mesons ($c\bar{u}$ and $c\bar{d}$) were predicted at 1.83 ± 0.03 GeV.[4] Their vector counterparts D^* are split from D by the color analog to electromagnetic spin-spin coupling. This mass splitting [or hyperfine splitting (hfs)] must be positive, like other "hyperfine splittings" (K^*-K, $\rho-\pi$, $\Delta-N$, etc.), but smaller because the charmed quark is heavy. We estimated[4] $M(D^*)-M(D)\sim M(\pi)$. Whether $D^*\to D\pi$ strongly or $D^*\to D\gamma$ electromagnetically depends on the precise hfs value.

Reported $K\pi$ and $K\pi\pi\pi$ enhancements at 1.865 ± 0.015 GeV are identified with D^0. No evidence for $D^\pm$ in $K\pi\pi$ is reported.[3] When D^0 is observed, the recoil mass is $\geqslant 1.86$ GeV as needs be if charmed mesons are produced in association. At e^+e^- energy $s^{1/2}\sim 4.1$ GeV, an enhancement in this recoil-mass distribution is seen at 2–2.2 GeV, possibly with unresolved structure. *What is the nature of the recoil spectrum and how will it change with energy? Why no recoil peak at 1.86 GeV? Where is $D^\pm$?*

Answers to these questions require analysis of quasi-two-body production of charmed mesons (including threshold, form factor, and spin effects), the possibility of kinematical reflections in recoil-mass plots, and surprisingly, electromagnetic mass splittings (ems) D^+-D^0 and $D^{*+}-D^{*0}$.

First, we discuss the relative production of D and D^* neglecting their mass differences. Then, we estimate ems, and discuss its impact on D^* decay and on the data analysis. Finally, we take into account the mass differences, obtaining agreement with data, and making predictions