Direct Photon Production in e^+e^- Annihilation

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Direct photon production in hadronic events from e^+e^- annihilation has been studied at $\sqrt{s} = 29$ GeV with use of the MAC detector at the PEP storage ring. A charge asymmetry $A = (-12.3 \pm 3.5)\%$ is observed in the final-state jets. The cross section and the charge asymmetry are in good agreement with the predictions of the fractionally charged quark-parton model. Both the charge asymmetry and total yield have been used to determine values of quark charges. Limits have been established for anomalous sources of direct photons.

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The production of direct photons in e^+e^- annihilation into hadrons has been recognized as a powerful tool to explore the properties and interactions of quarks at short distances.[1] Quarks and gluons fragment into hadrons once they leave the short-distance regime, whereas photons can leave without further interactions. If a photon radiated from a quark is detected with a large transverse momentum relative to the hadron jets, short distances are probed and it is possible to study properties of the quark-gluon system before the hadron fragmentation takes place. One of the consequences of photon emission is that the interference between photon radiation from initial-state electrons and final-state quarks generates a charge asymmetry proportional to the cube of the quark charge,[2] which will cause a charge asymmetry in the resultant jets. Measurements of both the jet charge asymmetry and the total photon yield can then be used to determine the color-averaged charge squared $\langle e_q^2 \rangle$ of the quark charges. This information may distinguish between fractional- and integer- charge schemes such as the Han-Nambu model,[3] which have different charge assignments for colored quarks but keep the average charge within a color multiplet fixed. This distinction can not be made with experiments such as the measurement of the hadronic total cross section and the measurement of the average charge of leading hadrons in a quark jet.[4] Processes which have two-photon couplings to the quark, such as the present experiment and two-photon-annihilation jet production,[5] can in principle accomplish this distinction since they are sensitive to higher charge moments rather than the average charge. This experiment reports the first results on a high-statistics analysis of multihadron final states containing a hard photon under conditions of maximal interference between initial- and final-state radiation.

The parent data sample consists of approximately 10^5 multihadron events collected with the MAC detector at the Stanford Linear Accelerator Center PEP storage ring. The sample corresponds to an integrated luminosity of 220 pb^{-1} at a center of mass energy of 29 GeV. A detailed description of the MAC detector has been given elsewhere.[6] The hadronic-event selection criteria have also been described previously.[7] For the present analysis the direct photons are selected from the event sample with at least five charged particles. A photon candidate is defined as a shower detected in the central electromagnetic calorimeter with no significant energy deposition in the hadron calorimeter and separated by at least 30° from the nearest charged particle or other electromagnetic shower. The showers must have energy greater than 3 GeV and less than 10 GeV in the angular region $35° \leq \theta \leq 145°$. The lower-energy cut is chosen to reduce the background coming from meson decays (mostly $\pi^0 \rightarrow \gamma\gamma$). The higher-energy cut is applied because above 10 GeV (1) initial-state radiation is the dominant source of direct photons, thus lowering the fraction of events due to final-state photon radiation; and (2) it becomes more difficult to calculate the true jet direction and to assign the jet charges properly.

Assuming that all events are $e^+e^- \rightarrow q\bar{q}\gamma$, two jets are reconstructed as follows. The event is Lorentz transformed into the hadronic center-of-mass system using the measured photon energy and direction. This is done for all calorimeter hits and all charged particles with momentum greater than 250 MeV/c, assigning each the pion mass. Since two jets are back-to-back in the $q\bar{q}$ rest system, the jet axis is obtained by calculating the thrust axis using the transformed calorimeter information. A net charge is then computed for both jets by summing over all the charged particles in the forward and backward hemispheres with respect to the thrust direction. The angle between the photon candidate and either jet axis, as transformed back into the laboratory system, is then required to be greater than 55°.

A Monte Carlo method has been used in order to estimate backgrounds and to study the direct photon signal. The Monte Carlo program of Berends, Kleiss, and Jadach[8] was used to calculate the predictions for $e^+e^- \rightarrow q\bar{q}$ and $e^+e^- \rightarrow q\bar{q}\gamma$ to order α^3. The Lund Monte Carlo program was used to simulate QCD effects and parton fragmentation into hadrons.[9] The events generated by this program were then put through the MAC detector simulation program to trace in detail their interactions and the detector response. After subjecting these events to the same selection criteria used in the data sample, these Monte Carlo events provided the spectra for both signal and background studies. From these results the reconstructed jet axes determine the quark direction with an uncertainty of 4°. About 68% of the jets are predicted to be charged, in excellent agreement with the data, and approxmiately 70% of the charged jets are predicted to have the same sign as the parent quark.[10]

There are 1049 direct photon candidates which pass the selection criteria, or about 1% of the parent sample. The meson-decay background is estimated to be 226 ± 40, where the error includes statistical and systematic contributions, the latter due primarily to the uncertainty in the parameters of the Lund Monte Carlo program. An additional background coming from $e^+e^- \rightarrow \tau^+\tau^-\gamma$ is estimated to be 15 ± 3. Photons from final-state hadron bremsstrahlung in the detector material are totally negligible. Subtracting the above backgrounds, the direct photon signal is measured to be 808 ± 51 events.

Figure 1 shows the energy distribution of the background-subtracted direct photon signal together with the calculated background coming from meson decays. Also shown is the Monte Carlo prediction for the direct photon signal assuming five flavors of fractionally charged quarks. The predicted yield is 762 ± 39 events. The measured yield is thus in good

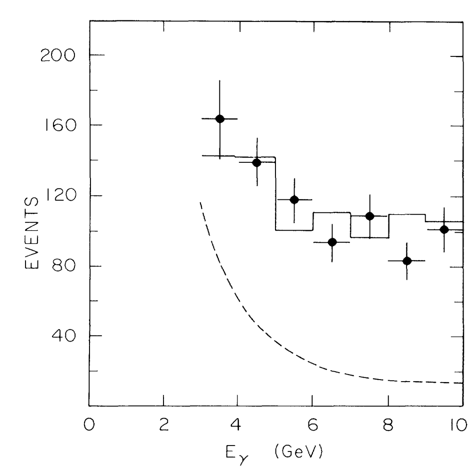

FIG. 1. The energy distribution of the background-subtracted direct photon sample. The histogram is the Monte Carlo prediction for fractional charges. The meson-decay background is indicated as a dashed curve.

agreement with the prediction of the fractionally charged quark model and shows no evidence of anomalous photon production. An upper limit for excess photon production from unknown sources such as $e^+e^- \to H+\gamma$ has been calculated in terms of the ratio $R_H = \sigma_{H\gamma} B(H \to \text{hadrons})/\sigma(e^+e^- \to \mu^+\mu^-)$. The 95%-confidence-level upper limit for R_H varies as a function of the invariant mass M_H of the hadronic system, from 0.2% at $M_H = 16$ GeV/c^2 to 0.9% at $M_H = 26$ GeV/c^2.

Figure 2 shows the polar-angle distribution of the jet axis for the charged-jet subsample. The quantity $N^+(\cos\theta) + N^-(-\cos\theta)$ is plotted versus $\cos\theta$, where θ is measured relative to the e^+ beam direction, and $N^+(N^-)$ is the number of jets with positive (negative) net charge in each angular bin. Jets with zero net charge are not entered. A large asymmetry about $\cos\theta = 0$ is evident. The average charge asymmtery, defined as

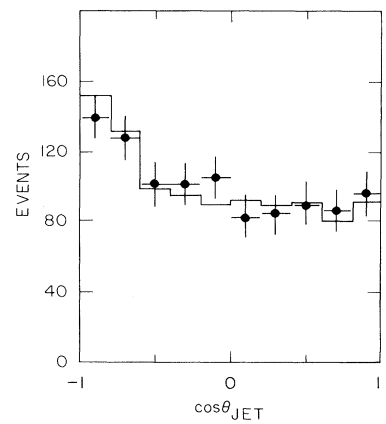

FIG. 2. The polar-angle distribution of the jet axes as described in the text. The histogram is the Monte Carlo prediction for fractional charges.

$$A = \frac{N^+(\theta < \frac{1}{2}\pi) + N^-(\theta > \frac{1}{2}\pi) - N^+(\theta > \frac{1}{2}\pi) - N^-(\theta < \frac{1}{2}\pi)}{N^+ + N^-},$$

is $A = (-12.3 \pm 3.5)\%$. The angular distribution predicted by the Monte Carlo analysis for five fractionally charged flavors of quarks is shown as the histogram in Fig. 2 and yields a charge asymmetry $A = (-11.7 \pm 2.6)\%$. The interference with weak-interaction terms is expected to create an additional contribution to the asymmetry in the direct photon signal. However, because of the cancellations between contributions from charge $\frac{2}{3}$ and $-\frac{1}{3}$ quarks and the reduced center-of-mass energy due to initial-state photon radiation, this weak contribution is small and has been estimated to be $|\delta A| < 1\%$.

As checks for false asymmetries resulting from π^0 decay background or possible detector biases, control samples were made from the parent hadron events by (1) applying the photon candidate requirements to charged particles, and (2) loosening the selection criteria to allow the meson-decay background to dominate. The asymmetry observed in these samples is $A = (+1.8 \pm 3.5)\%$, and $A = (-1.9 + 1.1)\%$, respectively, consistent with zero for the contribution from background. As further checks we have defined the jets with charged tracks instead of calorimeter hits, and varied the charged-particle momentum cut over the range 200–400 MeV/c; in each case the result differs from that quoted above by less than 1%.

The charge asymmetry and total yield may be interpreted in terms of quark charges. The cross section is proportional to the incoherent sum of initial- and final-state photon-radiation terms and depends on the charges as follows:

$$d\sigma \sim B_i \sum (e_q)^2 + B_f \sum \langle e_q^2 \rangle^2.$$

The factors B_i and B_f represent the initial- and final-state radiation contributions respectively. Approximately 15% of the total yield is estimated to result from radiation of the final-state quarks assuming the conventional fractional-charge assignments. The jet charge asymmetry takes a simple form when expressed as a ratio to the corresponding asymmetry for $\mu^+\mu^-\gamma$ final states:

$$\frac{d\sigma(\text{jet}^+) - d\sigma(\text{jet}^-)}{d\sigma(\mu^+) - d\sigma(\mu^-)} = 3C \sum \langle e_q \rangle \langle e_q^2 \rangle.$$

C is a factor which includes all the efficiencies for a quark to be reconstructed as a charged jet of the same sign and has been calculated from the Monte Carlo events, e_q is the quark charge in units of the magnitude of electron charge, and $\langle e_q^n \rangle$ is the average value of e_q^n within a color multiplet. The sum is taken over all five quarks flavors.

Since the charge asymmetry and the final-state radiation contribution to the total yield are sensitive to the quark charge and probe the charge with two photons, it should be possible to test models which have different charge assignments for the quarks. In particular, the predictions of the Han-Nambu model have been calculated using Monte Carlo simulations. Table I shows the Monte Carlo predictions for the total number of events and the average jet-charge asymmetry from the fractional- and integer-charge models, together with the experimental results. The total yield and charge asymmetry may be used to calculate values for $3\sum\langle e_q^2\rangle^2$ and $3\sum\langle e_q\rangle\langle e_q^2\rangle$ of the quark charges respectively.[11] These results are also shown in Table I. The

TABLE I. Results and predictions for direct photon signal.

	Events	Asymmetry (%)	$3\sum\langle e_q^2\rangle^2$	$3\sum\langle e_q\rangle\langle e_q^2\rangle$
Data	808 ± 51	-12.3 ± 3.5	1.75 ± 0.63	1.97 ± 0.61
Fractional charge	762 ± 39	-11.7 ± 2.6	$\frac{35}{27} = 1.30$	$\frac{19}{9} = 2.11$
Integer charge	1006 ± 50	-19.2 ± 2.2	$\frac{11}{3} = 3.67$	$\frac{11}{3} = 3.67$

The $\langle e_q\rangle^2$ contribution to the total yield is assumed to be given by the usual fractional-charge assignments as confirmed by the measurements of the total hadron-production cross section. Both the total-yield and the charge-asymmetry results favor the conventional fractional-charge assignments for five quark flavors and deviate from the integer-charge predictions by about 2.8 and 3.0 standard deviations respectively.

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[10]The charge-determination probability has been studied using both string and incoherent jet-fragmentation models. The results of these studies show less than a 2% variation in this quantity for the different parameters and models.

[11]The quark-mass effects have been studied with the Monte Carlo simulation program using masses $m_u = m_d = 0.3$ GeV/c^2, $m_s = 0.5$ GeV/c^2, $m_c = 1.6$ GeV/c^2 and $m_b = 5.0$ GeV/c^2. The corrections to the values of $3\sum\langle e_q^2\rangle^2$ and $3\sum\langle e_q\rangle\langle e_q^2\rangle$ are negligible.