Measurement of e^+-e^- Asymmetry in Deep-Inelastic Bremsstrahlung*

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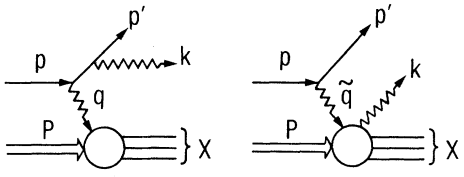
We have measured $(e^+p \to e^+\gamma X)/(e^-p \to e^-\gamma X) = 1.080 \pm 0.036$ in the scaling region, despite our finding e^+ and e^- total inelastic scattering to be the same to the $\frac{1}{3}\%$ level. The magnitude and sign of the difference signal are consistent with the parton model, from which we extract a mean sum of cubes of parton charges in the proton, $\langle\sum_i Q_i^3\rangle = 0.89 \pm 0.34$. Statistics are insufficient to distinguish between fractional ($\langle\sum_i Q_i^3\rangle = 0.56$) and integral charge ($\langle\sum_i Q_i^3\rangle = 1$, or 0.78 for colored quarks).

Despite the great success of the quark-parton model,[1,2] particularly in understanding leptonic processes, there have been experiments[3-5] involving inelastic Compton scattering which appear to disagree with that model. Many more photons are produced than would be expected from Compton scattering off single partons in the proton, whether for quark or integral parton charges. This photon excess could be due to the decay of unknown hadronic states, the domination[5] of photon dissociation into a parton-antiparton pair over the parton Compton scattering process which had been expected[6] to yield the parton charge, the existence of partons of large charge,[7] or the failure of the model. We report here an experiment which helps to resolve this problem by checking the parton model and the parton charge. The experiment is a measurement of the difference between electron-proton and positron-proton inelastic scattering in which an energetic photon is produced. The first two of the explanations for the inelastic Compton results are irrelevant to this difference measurement: *All* hadronic processes must subtract out, and the photon dissociation process cannot contribute to such an interference.[8] Although the results of this short experiment are not precise enough to distinguish fractional from integral charges for the partons, they are consistent with the parton model for reasonable charge values. The problem with the inelastic Compton scattering results is thus most likely not associated with a failure of the quark-parton model, but rather (as suggested by the constituent interchange model[9] and our previous work[5]) is probably due to the photon dissociation process.

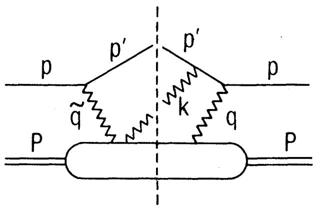
This experiment, which was suggested by Brodsky, Gunion, and Jaffe,[10] is an attempt to measure the interference between the Bethe-Heitler bremsstrahlung amplitude and the virtual Compton amplitude, as shown in Fig. 1. It is seen in these diagrams that one photon interacts with a parton in the Bethe-Heitler case, and two photons interact with a single parton in the Compton case, so that in taking the square, the interference term [Fig. 1(c)] is effectively a three-photon interaction with the parton and depends on the cube of the parton's charge. Only the interference term has odd charge conjugation, and hence it is measurable by taking the e^+-e^- difference. It defines a structure function, V, through the equation,

$$\frac{d\sigma(e^+p \to e^+\gamma X)}{dp_0'd\Omega_e'dk_0d\Omega_k} - \frac{d\sigma(e^-p \to e^-\gamma X)}{dp_0'd\Omega_e'dk_0d\Omega_k} = \frac{\alpha^3 p_0'k_0|T_{\text{int}}|^2V(x')}{2\pi^2M_Pp_0(-q^2)}, \tag{1}$$

where M_P, p_0, p_0', and k_0 are the energy components of the four-vectors shown in Fig. 1, Ω_e,



(a) Bethe-Heitler (b) Compton



(c) Compton-Bethe-Heitler Interference

FIG. 1. Diagrams for the reaction $e^\pm + p \to e^\pm + \gamma$ + anything.

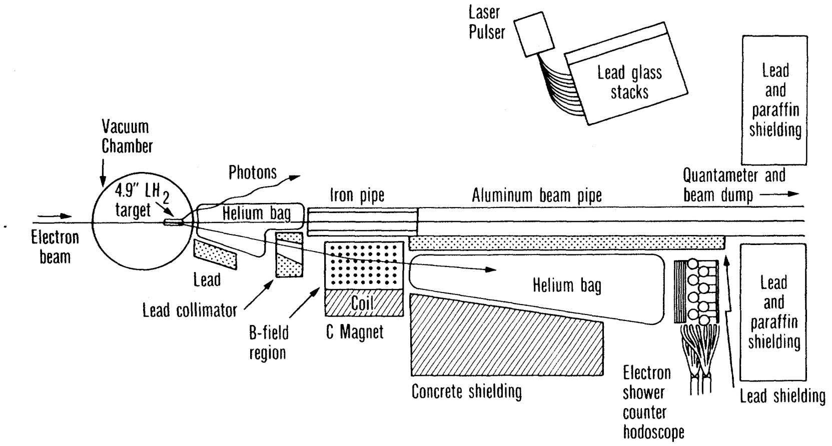


FIG. 2. Schematic experimental layout for the experiment.

and Ω_k are the solid angles for the outgoing $e^\pm$ and photon, $x' = -q^2/(2P\cdot q + M_P^2)$, and T_{int} is a known interference amplitude. In a parton model, V depends on the single kinematic variable, x', and has the form $V(x') = \sum_i Q_i^3 u_i(x')$, where $u_i(x')$ is the probability per unit x' that the proton contains a parton of charge Q_i with fraction x' of the proton's momentum in an infinite-momentum frame. For comparison, the structure function νW_2 determined in inelastic lepton scattering has the form $x'\sum_i Q_i^2 u_i(x')$.

Since the run was limited to only 200 h, we could not determine $V(x')$. However, we did get some measure of $\int_0^1 V(x')dx' = \langle \sum_i Q_i^3\rangle$. This exact sum rule[10] would give $\langle \sum_i Q_i^3\rangle = \frac{5}{9}$ for fractionally charged quarks (independent of the presence of gluons or quark-antiquark pairs), or 1 if all partons have charge 0 or ±1, or $\frac{7}{9}$ for integrally charged colored quarks below the color threshold[11] (because there is a color-octet contribution to intermediate states in the Compton diagram).

The experimental apparatus used to measure the e^+-e^- difference was a two-arm spectrometer, as shown in Fig. 2. The electron arm, made up of a magnet, lead-scintillator hodoscope, and some auxiliary counters, was set at a mean angle of 8° from the beam line. It had an acceptance of 3.1 msr in solid angle and 4 to 11.5 GeV in energy and is described in more detail elsewhere.[12]

The photon arm consisted of two stacks of SF2 lead-glass counters, one made up of forty counters, each $6.4\times6.4\times34.3$ cm^3, and the other consisting of 48 counters, each $6.4\times6.4\times58.4$ cm^3. The two stacks, which were arranged in a fly's-eye configuration, pointed at the 12.5-cm hydrogen target at a mean angle of about 7°, subtended a solid angle of 8.8 msr, and covered an energy range of 2 to 8 GeV. The kinematic region covered in the experiment is shown in Table I.

The nearly identical electron and positron beams were both made one-third of the way down the Stanford Linear Accelerator and then accelerated to 13.5 GeV. The polarity was alternated periodically to minimize systematic errors, and about equal amounts of data were collected at three intensities (3, 5, and $7\times10^7 e^\pm$ per 1.6 μsec pulse) so as to monitor rate effects, which turned out to be unimportant. A total of 3.23×10^{15} incident $e^\pm$ were used. The electron beam is discussed in more detail elsewhere.[12]

Whenever a signal in the $e^\pm$ arm was larger than 3.8 GeV, all lead-glass blocks and hodoscope elements were pulse-height analyzed. When there was also a signal in the photon arm, the relative time between the $e^\pm$ trigger and the photon was also measured and recorded on magnetic tape. In addition to this data information, pulse heights in the lead-glass blocks and hodoscope elements in response to light pulses were also periodically recorded to help maintain the basic calibration,

TABLE I. Kinematic range covered by the experiment for variables defined in Fig. 1, except $x' = -q^2/(2P\cdot q + M_P^2)$.

Variable	Range
$-\tilde{q}^2$	1.5–3.3 (GeV/c)^2
$\tilde{q}_0$	2–9.5 GeV
$-q^2$	0.75–2.0 (GeV/c)^2
k_0	2–8 GeV
x'	0.12–1.0

which was done with e^+ of known energy.

In addition to normal data runs and empty-target runs, some information was obtained with the magnet polarity of the $e^\pm$ arm reversed from that of the incident beam. For example, to measure the effect of π^+ simulating an e^+ in the trigger, we ran with an e^- beam but with the spectrometer magnet set for e^+ and assumed that the e^- produced as many π^+ as the e^+ beam would have.

To get an idea of the sensitivity required in the experiment, the anticipated size of the e^+-e^- difference in Eq. (1) is of the order of 0.2 nb/GeV^2 sr^2, and our acceptance was $\Delta p_0'\Delta\Omega_e'\Delta k_0\Delta\Omega_k \approx 0.0007$ GeV^2 sr^2. Thus the signal was small. We detected 2366 events of the type $e^+p\to e^+\gamma X$ and 2161 events of the type $e^-p\to e^-\gamma X$. After correcting these numbers for π contamination, we found

$$\frac{N(e^+p\to e^+\gamma X)}{N(e^-p\to e^-\gamma X)} = 1.080 \pm 0.036. \tag{2}$$

This ratio would be unity if the photons came from π^0 decays or any other hadronic process. In fact, most of the events were due to electroproduced π^0's, which subtract out in the difference, but which tend to wash out the sought-after asymmetry in the ratio.

This result, (2), applies to those events which are likely to lie in the scaling region, because the following cuts have been applied: $|\tilde{q}^2| \geq 1.5$ (GeV/c)^2, $|q^2| \geq 0.75$ (GeV/c)^2, and $|\tilde{q}^2 - q^2| \geq 0.75$ (GeV/c)^2, where q and $\tilde{q}$ are defined in Fig. 1. These cuts are meant to insure that the three-photon interactions of the interference term are with the same parton, and that the partons can be treated as free during the interaction.[10] The cuts are a little less stringent than advocated in Ref. 10, but we have used the variable x' which gives scaling at smaller $|q^2|$ values than does $x = -q^2/2P\cdot q$, which is used in Ref. 10. Other kinematic constraints of that reference are automatically satisfied by the acceptance of our apparatus.

A systematic error could arise from possible gain changes in the counters in the electron or photon arm when the magnetic fields were reversed. We have several reasons for believing that we have essentially no error from this source: (1) Our light pulser calibration system enabled us to correct for such gain changes (typically $<3\%$). (2) Monte Carlo studies showed that the observed gain changes would have been too small to account for our observed asymmetry, even if we had not corrected for them. (3) In the case of the photon arm, it would take at least an 8% gain difference in order to produce the observed asymmetry. However, such a difference would cause an 8% difference in the measured mass of those π^0's for which both decay photons entered the photon arm. Less than 1% mass difference was observed. (4) In the case of the electron arm, our simultaneous measurement[12] of the ratio

$$\frac{N(e^+p\to e^+X)}{N(e^-p\to e^-X)} = 1.0027 \pm 0.0035. \tag{3}$$

provides evidence that the $e^\pm$ arm was equally sensitive to electrons and positrons.

This comparison of inelastic electron and positron scattering serves two other purposes. First, the e^+ and e^- beams were sufficiently alike so as not to affect the asymmetry of Eq. (2). Second, this lack of two-photon exchange effects in the total cross section makes it unlikely that such effects could contribute to that asymmetry.

Another check on the behavior of the photon side, in addition to the one given by comparing the masses of the π^0's produced by e^+ and e^-, is provided by comparing the number of π^0's detected with each beam polarity. That number was the same within the statistical error for the 400 π^0's for which we could measure both photons.

Since an e^+-e^- difference of the correct sign and a reasonable magnitude was observed, we sought an estimate of $\langle\sum_i Q_i^3\rangle$ from the data. To do this we weighted each event by a function which was largest in kinematic regions where we expected a large interference term and a small π^0 background. The result of such a weighting leads to an unbiased estimate of $\int_0^1 V(x')dx'$, provided that a shape, but not a normalization of $V(x')$, is assumed. The shape assumed was

$$V(x') \propto x'^{-1/2}(1-x')^3(1+2.5x'), \tag{4}$$

which is very close to the $V(x')$ that one would compute from the modified Kuti-Weisskopf quark distribution,[13,14] and which was designed to fit deep-inelastic lepton scattering data.

The result of this procedure was

$$\langle\textstyle\sum_i Q_i^3\rangle = \int_0^1 V(x')\,dx' = 0.89 \pm 0.34. \tag{5}$$

In getting this result we made the small corrections (which were close to the same for both polarities) for $\pi^\pm$ contamination ($\sim 3\%$) and empty-target events ($\sim 10\%$), but neglected the effect of accidentals ($\sim 15\%$), since the beam intensities at the two polarities were well controlled, and examination of out-of-time (o.t.) e-γ coincidences gave

$$\frac{N(e^+p\to e^+\gamma X)_{\text{o.t.}}}{N(e^-p\to e^-\gamma X)_{\text{o.t.}}}=1.00\pm0.08. \qquad (6)$$

Systematic uncertainties occur in the conversion of the observed asymmetry into an estimate of $\langle\sum_i Q_i^3\rangle$. For example, we used $|T_{\text{int}}|^2$ of Ref. 10 as computed for partons of spin $\frac{1}{2}$, but when $|T_{\text{int}}|^2$ for spin-0 partons was used, the result increased $\langle\sum_i Q_i^3\rangle$ by only 5%. More serious was the uncertainty in the assumed shape of $V(x')$. When we used an alternative parton distribution,[15] also like (4) in that it was designed to fit the lepton scattering data, we obtained a result only 7.5% higher than that presented in (5). Both shapes for $V(x')$ become infinite as x' goes to zero. When we tried $V(x')\propto x'(1-x')^3$, which goes to zero when x' becomes zero and which is not designed to fit other experimental data, our result (which went down to $x'=0.12$) decreased by 26%. The spread in these values gives some idea of the systematic error to be expected from the assumption of a shape for $V(x')$.

In conclusion, we have found an asymmetry between $e^+p\to e^+\gamma X$ and $e^-p\to e^-\gamma X$. The resulting estimate, $\langle\sum_i Q_i^3\rangle=0.89\pm0.34$, while not statistically precise enough to distinguish between fractional and integral parton charge, does support models with partons of low charge, since $\int V(x')dx'$ would have had a big value if partons had the large charges needed if this were the explanation of the inelastic Compton results, or it could have any arbitrary positive or negative value if the parton model were wrong.

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