reported by Reines and Gurr. Even using their most conservative estimate of $\sigma_{\nu e} = 100_{V-A}$ we should have observed 11 events in the first bin of Fig. 1.

The author is indebted to Professor Helmut Faissner for suggesting the present analysis and for his continued interest. He wants to thank Dr. Jürgen von Krogh for checking the computations and for numerous discussions. He also wishes to thank Dr. Max Reinharz for helpful comments. Finally, he extends his grateful appreciation to the members of the CERN Neutrino Spark Chamber Group on whose work this analysis is based.

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SEARCH FOR T-INVARIANCE VIOLATION IN THE INELASTIC SCATTERING OF ELECTRONS FROM A POLARIZED PROTON TARGET*

Stephen Rock, Michel Borghini,† Owen Chamberlain, Raymond Z. Fuzesy, Charles C. Morehouse, Thomas Powell, Gilbert Shapiro, and Howard Weisberg‡
Lawrence Radiation Laboratory, University of California, Berkeley, California 94720

and

Roger L. A. Cottrell, John Litt, Luke W. Mo,§ and Richard E. Taylor
Stanford Linear Accelerator Center, Stanford University, Stanford, California 94305
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We have searched for an asymmetry in the inelastic scattering of electrons from a polarized proton target in the region of resonance excitation, at values of four-momentum transfer squared of 0.4, 0.6, and 1.0 $(\mathrm{GeV}/c)^2$. Data were also taken using an incident positron beam in order to distinguish any possible effect of time-reversal invariance violation from that due to higher-order (α^3) contributions to the scattering. No sizable violation of time-reversal invariance was found.

Following the discovery[1] of CP invariance violation in the decay of the $K_L{}^0$ meson, Bernstein, Feinberg, and Lee[2] pointed out that the violation might result from the existence of a part of the hadronic electromagnetic current that violates time-reversal (T) invariance. Christ and Lee[3] proposed a test of this hypothesis involving the inelastic scattering of electrons from a polarized proton target, in which only the scattered electron is detected. Let $\sigma_\uparrow$ ($\sigma_\downarrow$) denote the cross section, summed over all outgoing hadronic states Γ, for the reaction

$$ep \rightarrow e\Gamma, \tag{1}$$

where the target proton spin is along (opposite to) the normal $\hat{n}$ to the electron scattering plane,

$$\hat{n} = \vec{p}_{\text{in}} \times \vec{p}_{\text{out}} / |\vec{p}_{\text{in}} \times \vec{p}_{\text{out}}|, \tag{2}$$

defined by the momentum vectors of the incident ($\vec{p}_{\text{in}}$) and scattered ($\vec{p}_{\text{out}}$) electron. Then, in the single-photon-exchange approximation, the asymmetry

$$A = (\sigma_\uparrow - \sigma_\downarrow)/(\sigma_\uparrow + \sigma_\downarrow) \tag{3}$$

must vanish unless T invariance is violated. (For elastic scattering, A can be shown to vanish independently of T, from current conservation and Hermiticity alone.) A nonzero value of A

can also arise from higher-order (α^3) effects[4] (such as the interference between one-photon-exchange and two-photon-exchange amplitudes) without requiring T-invariance violating amplitudes. This contribution should be small, however, because it involves an additional power of α. Furthermore this contribution will depend on the sign of the lepton charge and, therefore, will change sign when the experiment is repeated with a positron beam. A T-invariance violation effect will have the same sign for electrons or positrons.

Such a test of time-reversal invariance has several advantages. It involves only a single experiment. It probes the hadronic current at large momentum transfer. Since the target spin direction is reversed by making a small change in the frequency of the microwaves irradiating the target, without any other changes in the experimental setup, this experiment is relatively free from systematic error and is potentially sensitive to very small effects.

In the absence of definite models of T-invariance violating currents, it is difficult to calculate a "maximal" asymmetry with which to compare experimental results. Effects of such currents might be observable in the region of resonance excitation, where only a few partial waves contribute to the cross sections. An asymmetry due to T-invariance violation can only be due to an interference between the cross sections for longitudinally (σ_L) and transversely (σ_T) polarized photons. Some data exist on the ratio σ_L/σ_T for the $\Delta(1236)$[5] and $N^*(1512)$[6] resonances near the four-momentum transfer values of this experiment; however, the errors are large.

It has been argued on theoretical grounds[7] that any T-invariance violating hadronic electromagnetic current would have to be isoscalar ($\Delta I = 0$). It is reasonable to assume that the resonant amplitudes in the 1512-MeV mass region involve $\Delta I = 0$ transitions to the $I = \frac{1}{2}$ nucleon isobars which are known[8] to exist near this region. Furthermore, there is experimental evidence of longitudinal excitation in this region[6] near the four-momentum transfers studied in this experiment. Therefore, one might expect, on the hypothesis of maximally T-invariance violating electromagnetic currents, to see a nonzero asymmetry in the 1512-MeV mass region that would be detected in our experiment.

If one abandons the $\Delta I = 0$ rule, it is possible to make a crude estimate of the maximum asymmetry due to T-invariance violation at the $\Delta(1236)$ resonance [which, at the momentum transfers of this experiment, is excited more strongly than the $N^*(1512)$]. Assuming that the entire cross section in this mass region arises from the $(\frac{3}{2}, \frac{3}{2})$ resonance, that its transverse excitation is magnetic dipole,[9] and that there is maximum interference between the measured[10] transverse and longitudinal cross sections, a T-invariance violating asymmetry as large as 35% could occur here at a four-momentum transfer squared (q^2) value of 0.6 $(\mathrm{GeV}/c)^2$.

A similar experiment has been performed recently by Chen et al.,[11] at the Cambridge Electron Accelerator. To an accuracy of 4 to 12%, they found no asymmetry (A) at q^2 values from 0.2 to 0.7 $(\mathrm{GeV}/c)^2$. The measurements which are here reported provide a detailed study of the resonant states at q^2 values of 0.4, 0.6, and 1.0 $(\mathrm{GeV}/c)^2$, and include some data on positron scattering.

Incident electron beams of 15 and 18 GeV (and a positron beam of 12 GeV) from the Stanford Linear Accelerator were momentum analyzed to a total $\Delta p/p$ of 0.2 to 0.3% and focused onto a polarized butanol target.[12] Scattered electrons (typically 3° lab) were momentum analyzed and identified using the 20-GeV/c magnetic spectrometer.[13] The detection apparatus consisted of scintillation counters and a shower counter for discriminating electrons from pions. The target polarization was reversed every 3 min in order to determine the asymmetry in counting rate,

$$\epsilon = (N_\uparrow - N_\downarrow)/(N_\uparrow + N_\downarrow), \tag{4}$$

where $N_\uparrow$ ($N_\downarrow$) is the number of counts per unit incident beam for target polarization along (opposite to) the direction $\hat{n}$. The asymmetry A, defined in Eq. (3) above, is related to the experimentally measured asymmetry ϵ by

$$A = \epsilon/|P_T|H_F, \tag{5}$$

where P_T is the target proton polarization and H_F is the fraction of the counts due to hydrogen in the target. The asymmetry A would be equal to ϵ for a 100% polarized target consisting of pure hydrogen.

The incident beam currents, of typically 2×10^{11} electrons/sec, were monitored by two toroid induction monitors[14] placed upstream of the target, and a secondary emission quantameter.[15] The beam, typically 2 to 3 mm in diameter, was swept once per second over the full area of the polarized target to insure that there was uniform radiation damage of the target.

The polarized target[12] consisted of a mixture of 95% 1-butanol and 5% water, saturated with an additional 2% of porphyrexide (a free radical). About 35% polarization of the free protons (hydrogen nuclei) was obtained. The 4-cm-thick target presented to the beam about 10% (polarizable) hydrogen, 10% plastic, 9% liquid helium, and 10% beam windows and helium gas bag; the rest was mainly carbon and oxygen from the alcohol mixture. The target polarization decreased approximately exponentially with the radiation dose; a flux of about 4×10^{14} electrons/cm^2 reduced the polarization to $1/e$ of its initial value. A phase transition in solid butanol[16] enabled us to anneal out most of the radiation damage by warming the target to about 140°K for 10 min. The performance of the target deteriorated after several annealings and, therefore, a new solution was installed each day. Over the entire experiment, the weighted average of the target polarization was about 20%.

The scattered electrons were detected by a ten-element scintillation-counter hodoscope which was positioned so that each counter detected electrons whose kinematics corresponded to a constant missing mass of the recoiling hadronic state. Electrons were identified from their pulse heights in a total-absorption lead-scintillator shower counter. Pion contamination in the data was found to be less than 0.2% and therefore can have only a negligible effect on the measured asymmetry. An SDS-9300 computer analyzed, checked, and displayed the data online[17] and recorded the data on magnetic tape.

From Eq. (5), with typical values of $P_T = 0.2$ and $H_F = 0.1$, an error of 0.05% in ϵ leads to an error of 2.5% in A. Since 4 million counts per missing-mass bin were collected at $q^2 = 0.6$ $(\mathrm{GeV}/c)^2$, corresponding to a statistical error of 0.05% in ϵ, it was necessary to reduce systematic errors to below this level. Random fluctuations in factors such as the detector or beam-current monitor efficiencies, if uncorrelated with polarization sign reversals, would tend to cancel out over many target polarization reversals.

In the analysis of the data, cuts were made to reject data which had large beam-intensity fluctuations, accidental-rate fluctuations, misread scalers, and monitor inconsistency, usually at the level of 5 standard deviations. About 15% of the data were thus rejected. The results were insensitive to the strictness of these cuts.

As a means of determining whether the accuracy of the data was commensurate with the statistical errors, 27 "test" asymmetries were calculated. These were based on the same data as the real asymmetry, but were calculated by pretending that the sign of the target polarization followed a pattern in time different from the real one. These patterns were chosen so that they should give a zero test asymmetry, even if there were a real effect. One test asymmetry had a reversal frequency which was the same as (but 90° out of phase with) the real polarization, and the other test asymmetries used both higher and lower reversal frequencies and with positive, negative, and zero phase lags. If the random fluctuations had roughly equal Fourier components at all these frequencies the test asymmetries should have given us a measure of the random signal, i.e., the errors to be expected in the real channel, independent of any assumptions about their source. The errors calculated from the root mean square of the test asymmetry values for each missing-mass bin were completely consistent with error bars calculated from counting statistics alone. The test asymmetries and errors followed closely a Gaussian distribution calculated from counting statistics. For example, at $q^2 = 0.6$ $(\mathrm{GeV}/c)^2$, out of 1053 test asymmetry values, the fractions exceeding 1, 2, 3, and 4 standard deviations were 0.322, 0.049, 0.0019, and 0, respectively (0.317, 0.046, 0.0027, and 0.0001 were expected). In one of the test asymmetries we were able to detect a systematic effect[18] (at the 0.06% level in ϵ) which was out of phase with the real asymmetry, and thus did not affect the results. Thus, we believe that our measurement errors can be represented by counting statistics alone.

The fraction of counts due to hydrogen in the target, H_F, was determined to an accuracy of ±20% in supplementary runs with carbon and polyethylene targets. Because of the difference between the missing-mass spectra from hydrogen and other elements, the fraction H_F must be obtained for each missing-mass interval. (For further details, see Powell et al.[19]) For the range of missing mass in this experiment, H_F had values between 0.06 and 0.11. Since it is only a normalization factor, the uncertainty in the determination of H_F cannot introduce or hide an asymmetry.

Figure 1 shows the asymmetry values A as a function of missing mass for our different running conditions. The errors shown are the standard deviations calculated from counting statis-

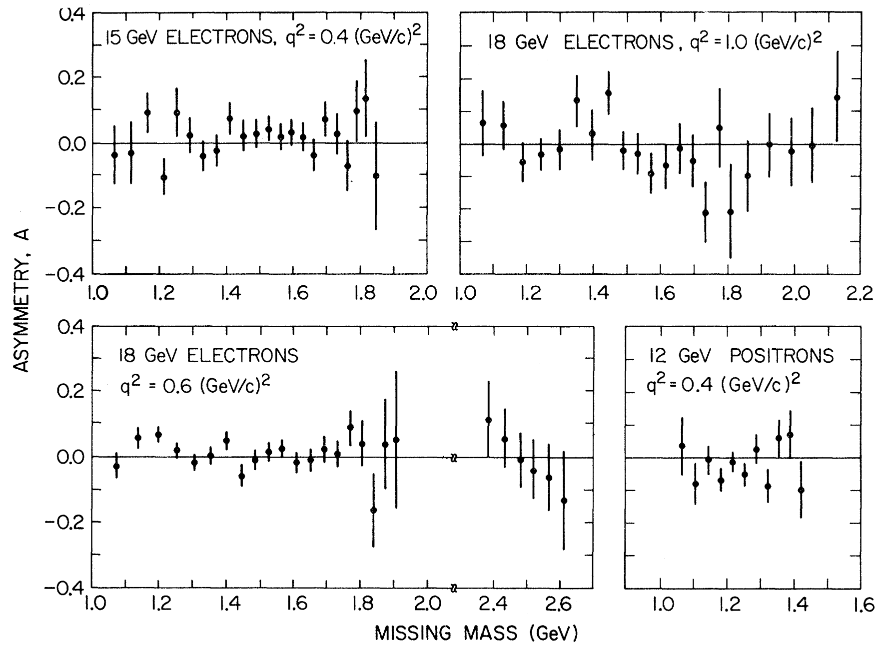

FIG. 1. The asymmetry values A are shown as a function of missing mass, where the errors are standard deviations calculated from counting statistics. On each graph we indicate the incident beam (electrons or positrons), the incident energy, and the four-momentum transfer squared (q^2). Although these data are binned corresponding to the counter size in the detection apparatus, the final missing-mass resolution is equivalent to 1.5 of these bin intervals.

tics. Table I shows the values of A averaged over each of the resonances $\Delta(1236)$, $N^*(1512)$, and $N^*(1688)$ using the resonance widths quoted in the table. The results of Chen et al.[11] are included for comparison.

The data are everywhere consistent with $A=0$. On the basis of T-invariance violating hadronic electromagnetic current with $\Delta I=0$, we would

Table I. The percentage asymmetry values A averaged over missing-mass bins corresponding to the resonances $\Delta(1236)$, $N^*(1512)$, and $N^*(1688)$, using widths of 0.15, 0.12, and 0.11 GeV, respectively. In addition, a measurement in the deep inelastic region (mass 2.37–2.62 GeV), for $E_0=18.0$ GeV and $q^2=0.54$ $(\mathrm{GeV}/c)^2$, found $A=(-1.6\pm3.5)$ %. The data of Chen et al. (Ref. 11) are shown for comparison.

Incident beam	Incident electron energy, E_0 GeV	Four-momentum transfer squared q^2 $(\mathrm{GeV}/c)^2$	Asymmetry value, A(%) Δ(1236)	N*(1512)	N*(1688)	
e^-	18.0	0.58^a	2.8 ± 1.4	-1.3 ± 1.7	0.8 ± 2.1	This experiment
e^+	12.0	0.42^b	-3.0 ± 1.8	---	---	
e^-	15.0	0.37^a	2.3 ± 2.9	3.1 ± 2.2	2.0 ± 3.1	
e^-	18.0	0.96^a	-2.8 ± 3.3	-4.8 ± 3.6	-8.2 ± 4.7	
e^-	3.98	0.23^b	3.8 ± 4.3	---	---	Chen et al.
e^-	5.97	0.72^a	---	3.6 ± 4.7	-0.5 ± 4.4	
e^-	5.98	0.52^a	---	-2.6 ± 8.2	3.6 ± 7.3	

[a]At 1.512-GeV missing mass. [b]At 1.236-GeV missing mass.

have expected to see an effect near the $N^*(1512)$ resonance. Our failure to see an asymmetry in this mass region, to a statistical error in A of $\pm 1.7\%$ at $q^2=0.6$ $(\mathrm{GeV}/c)^2$, is evidence against the hypothesis of Bernstein, Feinberg, and Lee.[2]

The data at $q^2=0.6$ $(\mathrm{GeV}/c)^2$ in Fig. 1 show that there are three adjacent bins centered at 1200 MeV which, when combined, result in an asymmetry of $(4.5\pm1.4)\%$. We estimate (on the basis of counting statistics, from independently generating random data graphs, and from the test asymmetries) that there is about a 10% probability that a random fluctuation of this prominence would occur somewhere in the data of Fig. 1.

It is difficult to find a satisfactory physical explanation for an effect of this magnitude near 1200 MeV; for example:

(a) As noted above, T-invariance violation with $\Delta I=1$ is improbable on theoretical grounds.

(b) On the basis of T-invariance violation with $\Delta I=0$, a 5% asymmetry near the $\Delta(1236)$ (where isovector currents dominate) would correspond to a rather large amount of T-invariance violation. In this case, it is surprising that an even larger effect did not appear near the $N^*(1512)$ resonance.

(c) The positron data in Fig. 1 are consistent with $A=0$. However, when averaged over the $\Delta(1236)$ resonance (see Table I) the positron result suggests an asymmetry with opposite sign as compared with the electron data (at slightly different q^2 values). Thus, one cannot rule out the possibility that this effect may be due to higher-order contributions to e-p scattering. Our experimental results[19] for the elastic scattering of electrons from a polarized proton target do not show any asymmetry (to within an accuracy of about α). Thus, to interpret the bump as being due to two-photon exchange would require a theoretical mechanism for enhancing the magnitude of the two-photon effects in the region just above inelastic threshold.

We conclude that a reasonable interpretation of our data is that they are everywhere consistent with no T-invariance violation.

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†Present address: CERN, Geneva, Switzerland.

‡Present address: Department of Physics, University of Pennsylvania, Philadelphia, Pa.

§Present address: The Enrico Fermi Institute and the Department of Physics, The University of Chicago, Chicago, Ill.

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intensity starting from the time that the beam intensity (which was reduced during polarization reversals) was restored. When coupled with a rate-dependent dead time, this effect introduced a deviation from zero in one of the test asymmetries. However, this produced a negligible correction to the real data.

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MEASUREMENT OF THE POLARIZATION IN ELASTIC ELECTRON-PROTON SCATTERING*

Thomas Powell, Michel Borghini,† Owen Chamberlain, Raymond Z. Fuzesy, Charles G. Morehouse, Stephen Rock, Gilbert Shapiro, and Howard Weisberg‡
Lawrence Radiation Laboratory, University of California, Berkeley, California 94720

and

Roger L. A. Cottrell, John Litt, Luke W. Mo,§ and Richard E. Taylor
Stanford Linear Accelerator Center, Stanford University, Stanford, California 94305
(Received 24 February 1970)

We have measured the asymmetry in the elastic scattering of electrons from a polarized proton target. An interference between the imaginary part of the two-photon-exchange amplitude and the one-photon-exchange amplitude could produce a polarization effect. The results indicate no asymmetry within the experimental accuracy of 1 to 2% at four-momentum-transfer-squared values of 0.38, 0.59, and 0.98 $(\mathrm{GeV}/c)^2$.

The customary reliance on one-photon-exchange calculations in electron-proton scattering makes it important to study those processes which could only arise from higher-order effects. A measurement of nonzero proton polarization in elastic electron-proton scattering would be evidence for a two-photon-exchange amplitude, since the polarization must vanish for pure one-photon exchange. The interference between one-photon-exchange and two-photon-exchange amplitudes is expected to be smaller than the one-photon-exchange contribution by an order of α, but it may be enhanced due to the presence of some resonance process.[1]

In electron-proton elastic scattering, one-photon exchange leads to the Rosenbluth formula[2] for the differential cross section. Higher-order effects, which could show up as deviations from the Rosenbluth form, have not been observed so far.[3]

The interference between the one-photon amplitude and the real part of some two-photon amplitudes can be obtained by comparing electron-proton and positron-proton elastic scattering. These measurements[4] (after allowing for radiative losses[5]) have shown no evidence of two-photon effects, to an accuracy of about the order α, up to four-momentum-transfers squared of 5.0 $(\mathrm{GeV}/c)^2$.

Information relating to the imaginary part of a different combination of two-photon-exchange amplitudes can be measured by performing a polarization experiment. Two kinds of experiments are possible. One can measure the polarization P of the recoiling nucleon in the elastic scattering of unpolarized electrons from an unpolarized proton target. Alternatively (as in the present experiment), one can measure the asymmetry A in the scattering of electrons from a polarized proton target, defined as

$$A=\frac{\sigma_\uparrow-\sigma_\downarrow}{\sigma_\uparrow-\sigma_\downarrow}=\frac{\epsilon}{|P_T|H_F}, \qquad (1)$$

where $\sigma_\uparrow$ and $\sigma_\downarrow$ denote the cross sections on hydrogen polarized parallel and antiparallel to the normal ($\hat{n}$) to the electron scattering plane. The quantity ϵ is the asymmetry in the raw counts from the polarized target, and the factors P_T and H_F allow for the target proton polarization and the fraction of hydrogen counts present in the data, respectively. We define $\hat{n}$ as

$$\hat{n}=\frac{\vec{p}_{\rm in}\times\vec{p}_{\rm out}}{|\vec{p}_{\rm in}\times\vec{p}_{\rm out}|}, \qquad (2)$$

where $\vec{p}_{\rm in}$ and $\vec{p}_{\rm out}$ are the momenta of the initial and final electron, respectively.

The asymmetry A is related to the polarization P. If only one photon is exchanged, then $A=P=0$ because Hermiticity and current conservation combine to prohibit any polarization of the recoil proton or, equivalently, any dependence of the cross section on the initial proton spin direction.[6] If T invariance holds, then $A=P$ to all orders in the electromagnetic interaction. Four