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

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ABSTRACT

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 violation from that due to higher-order (α^3) contributions to the scattering. No sizeable violation of time-reversal invariance was found.

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Following the discovery[1] of CP violation in the decay of the K_L^o 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 invariance (T). 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

$$ep \longrightarrow e\Gamma \tag{1}$$

where the target proton spin is along (opposite to) the normal to the electron scattering plane:

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

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

$$A = \frac{\sigma_\uparrow - \sigma_\downarrow}{\sigma_\uparrow + \sigma_\downarrow} \tag{3}$$

must vanish unless T 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-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-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 set up, this experiment is relatively free from systematic error and is potentially sensitive to very small effects.

In the absence of definite models of T-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-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-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 $I = 1/2$ 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-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-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 (3/2, 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-violating asymmetry as large as 35% could occur here at a four-momentum transfer squared (q^2) value of 0.6 $(\text{GeV}/c)^2$.

A similar experiment has been performed recently by Chen et al.,[11] at CEA. To an accuracy of 4 to 12%, they found no asymmetry (A) at q^2 values from 0.2 to 0.7 $(\text{GeV}/c)^2$. 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 $(\text{GeV}/c)^2$, 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 at 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 periodically in order to determine the asymmetry in counting rate:

$$\epsilon = \frac{N_{\uparrow} - N_{\downarrow}}{N_{\uparrow} + N_{\downarrow}} \qquad (4)$$

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:

$$A = \frac{\epsilon}{|P_T| H_F} \qquad (5)$$

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 beam, typically 2 to 3 mm in diameter, was swept once per second over the full area of the polarized target to insure that the beam uniformly sampled the polarized target. The polarization of the target protons was measured by a nuclear-magnetic-resonance (NMR) apparatus that sampled the target uniformly. Thus, although the radiation damage by the beam caused deterioration of the target polarization, we could be sure that the polarization as sampled by the beam was the same as sampled by the NMR apparatus. To minimize the radiation damage of the target, the beam current was reduced during the time that the spin direction was being reversed.

The incident beam currents were monitored by two toroid induction monitors[14] placed upstream of the target, and a secondary emission quantameter[15] which made up part of a shielded beam dump. The agreement between the monitors was found to be much better than the statistical uncertainty in the measured asymmetries. Absolute calibration of the monitors was unnecessary since only the ratios of cross section were measured. The beam intensity was about 2×10^{11} electrons per second.

A polarized target of the doped hydrocarbon type[12] was used in order to obtain an acceptable resistance to radiation damage and to have a high percentage of free protons (about 10%). A mixture of 95% 1-butanol and 5% water, saturated with an additional 2% of porphyrexide (a free radical) was cooled to 1.0°K in an aluminum cavity filled with liquid helium. About 35% polarization of the free protons (hydrogen nuclei) was obtained when the target was placed in a 25 kG field and appropriately stimulated by 70 GHz microwave energy. To ensure good thermal contact with the liquid helium bath, the target mixture was contained in 2 mm-diameter tubes made from 12μ-thick nonhydrogenous plastic. The tubes were folded to form a target which was 2.5 × 2.5 cm in area and 4 cm thick. The target as seen by the beam was 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 polarized target was online to a PDP5 computer. The direction of polarization was reversed every three minutes to help cancel long-term drifts, the reversal time being about 40 seconds. 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^{0}K for 10 minutes. The performance of the target deteriorated after several anneals and, therefore, a new solution was installed each day. Over the entire experiment, the weighted average of the target polarization was about 20%. It was proved that local heating by the beam did not depolarize the target by measuring the beam-on relaxation time of the target polarization with the microwave power off, and also from irradiation tests of a small-size target.

The scattered electrons were detected by a ten-element scintillation-counter hodoscope placed close to the momentum focus of the spectrometer. The hodoscope was positioned so that each counter detected electrons whose kinematics corresponded to a constant missing mass of the recoiling hadronic state. The momentum resolution of the detection system was about 0.6% in $\Delta p/p$ corresponding to a missing-mass resolution of about 60 MeV FWHM for the measurements at a missing mass of 1512 MeV and $q^2 = 0.6\ (\text{GeV}/c)^2$. 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.

A fast coincidence between the pulses from a trigger counter and the shower counter generated a gate which permitted a set of 100 MHz scalers to accept pulses from the ten hodoscope counters. The scalers, beam-current monitors and target polarization were read by an SDS 9300 computer about three times per second and kinematic corrections were made to allow for the movement of the beam. The 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. The asymmetry in one beam-current monitor relative to another was found to be about one-fifth of the size of the error due to counting statistics. Special attention was given to any effects that might correlate with target polarization. For example, the helium level in the cavity might have depended upon the microwave power level, which could have shifted with microwave frequency.

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 Ref. 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 statistics. 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 <u>et al.</u>,[11] are included for comparison.

The data are everywhere consistent with $A = 0$. On the basis of T-violating hadronic electromagnetic current with $\Delta I = 0$, we would 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 ± 1.7% at $q^2 = 0.6$ $(\text{GeV}/c)^2$, is evidence against the hypothesis of Bernstein, Feinberg and Lee.[2]

The data at $q^2 = 0.6$ $(\text{GeV}/c)^2$ in Fig. 1 show that there are three adjacent bins centered at 1200 MeV which, when combined, result in an asymmetry of $(4.5 \pm 1.4)\%$. 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 <u>somewhere</u> 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-violation with $\Delta I = 1$ is improbable on theoretical grounds.

b) On the basis of T-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-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 <u>elastic</u> 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-violation.

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REFERENCES AND FOOTNOTES

1. J. H. Christenson et al., Phys. Rev. Letters 13, 138 (1964); A. Abashian et al., Phys. Rev. Letters 13, 243 (1964).
2. J. Bernstein, G. Feinberg, and T. D. Lee, Phys. Rev. 139, B1650 (1965).
3. N. Christ and T. D. Lee, Phys. Rev. 143, 1310 (1966).
4. R. Cahn and Y. S. Tsai, Report No. SLAC-PUB-722, Stanford Linear Accelerator Center, (1970), (to be submitted to Phys. Rev.).
5. A. A. Cone et al., Phys. Rev. 156, 1490 (1967); H. L. Lynch, J. V. Allaby, and D. M. Ritson, Phys. Rev. 164, 1635 (1967); F. W. Brasse et al., Nuovo Cimento 55A, 679 (1968); W. Bartel et al., Phys. Letters 27B, 660 (1968).
6. W. Albrecht et al., DESY-69/7 (Deutsches Elektronen-Synchrotron, Hamburg).
7. T. D. Lee, Phys. Rev. 140, B959 (1965); L. B. Okun, Phys. Letters 23, 595 (1966).
8. Particle Data Group, Rev. Mod. Phys. 41, 109 (1969).
9. D. Imrie, C. Mistretta, and R. Wilson, Phys. Rev. Letters 20, 1074 (1968).
10. W. Bartel et al., Phys. Letters 27B, 660 (1968).
11. J. R. Chen et al., Phys. Rev. Letters 21, 1279 (1968).
12. S. Mango, Ö. Runólfsson, and M. Borghini, Nucl. Instr. and Methods 72, 45 (1969). Details of our target are described in M. Borghini et al., "Polarized proton target for use in intense electron and photon beams," (to be submitted to Nucl. Instr. and Methods).
13. SLAC User's Handbook, Section E, Stanford Linear Accelerator Center; and W.K.H. Panofsky, Proceedings of the International Symposium on Electron and Photon Interactions at High Energies, Hamburg, Germany (1965).
14. R. S. Larsen and D. Horelick, Report No. SLAC-PUB-398, Stanford Linear Accelerator Center (1968).

15. G. E. Fischer and Y. Murata, Report No. SLAC-PUB-605, Stanford Linear Accelerator Center (1969), (to be published in Nucl. Instr. and Methods).

16. V. K. Ermolaev, Yu N. Molin and N. Ya Buben, Kinetika i Katiliz 3, 58 (1962), English translation Kinetics and Catalysis 3, 46 (1962).

17. A. Boyarski, "The online control, analysis and display system for the SLAC multi-GeV/c spectrometers," Proceedings of the Conference on Computer Systems in Experimental Physics, Skytop, Penn., (March 1969).

18. The effect was due to a systematic increase in beam intensity starting from the time that the beam intensity was restored following a polarization reversal. When coupled with a rate-dependent deadtime, this effect introduced a deviation from zero in one of the test asymmetries. However, this produced a negligible correction to the real data.

19. T. Powell *et al.*, Report No. SLAC-PUB-721, Stanford Linear Accelerator Center (1970), (to be published in Phys. Rev. Letters).

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 $A = (-1.6 \pm 3.5)\%$. 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(%)			
			$\Delta(1236)$	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.

FIGURE CAPTION

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.

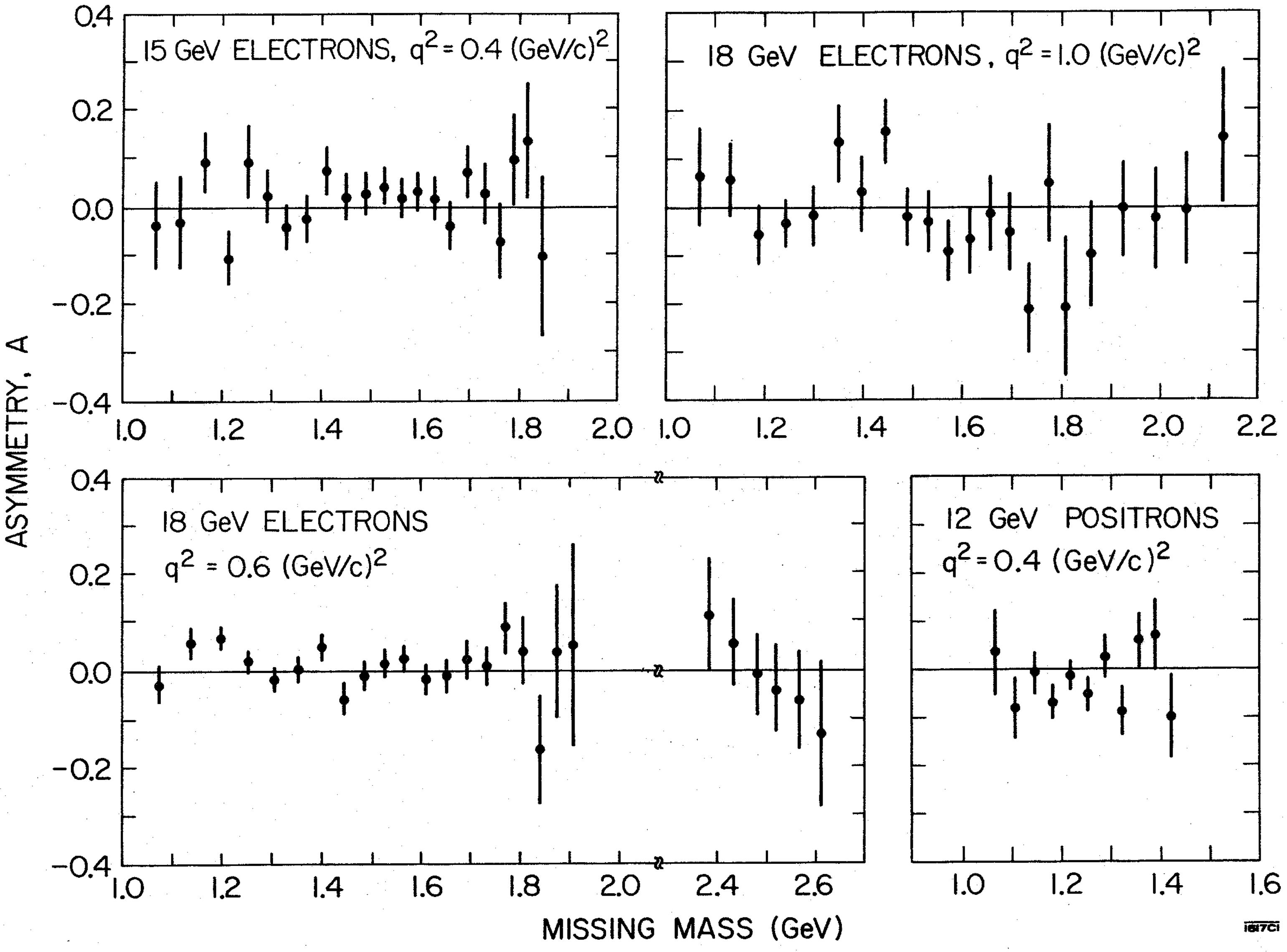
15 GeV ELECTRONS, $q^2 = 0.4\ (\mathrm{GeV}/c)^2$
18 GeV ELECTRONS, $q^2 = 1.0\ (\mathrm{GeV}/c)^2$
18 GeV ELECTRONS
$q^2 = 0.6\ (\mathrm{GeV}/c)^2$
12 GeV POSITRONS
$q^2 = 0.4\ (\mathrm{GeV}/c)^2$
ASYMMETRY, A
0.4
0.2
0.0
-0.2
-0.4
1.0
1.2
1.4
1.6
1.8
2.0
2.2
2.4
2.6
MISSING MASS (GeV)
1817C1

Fig. 1