TEST OF TIME-REVERSAL INVARIANCE IN ELECTROPRODUCTION INTERACTIONS USING A POLARIZED PROTON TARGET*

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Electrons have been scattered inelastically from an alcohol-water target containing protons polarized normal to the scattering plane. Scattered-electron energies corresponding to the excitation of the 1236-, 1512-, and 1688-MeV nucleon resonances were observed at four-momentum transfers between 0.2 and 0.7 $(\mathrm{BeV}/c)^2$. A search was made for changes in the intensity of the scattered electrons as the target polarization was reversed. None was seen.

This Letter reports the results of an experiment to test time-reversal (T) invariance in the inelastic scattering of high-energy electrons from a polarized proton target. A violation of T invariance in the electromagnetic interactions of hadrons[1] would be evidenced by a change in the intensity of scattered electrons upon reversal of the target polarization.[2] Such a violation of T invariance has been proposed to explain the observation of the CP-nonconserving decay $K_L^0 \to \pi^+\pi^-$.[3]

The test involved the measurement of an asymmetry in the doubly differential electron-proton scattering cross section, $d^2\sigma/d\Omega dE'$, denoted by

$$a = \frac{\sigma_\uparrow - \sigma_\downarrow}{\sigma_\uparrow + \sigma_\downarrow}\frac{1}{\vec{\mathrm{P}}\cdot\hat{n}}, \qquad (1)$$

where $\sigma_\uparrow$ ($\sigma_\downarrow$) is the doubly differential cross section with the target polarization parallel (antiparallel) to $\hat{n}$, the normal to the scattering plane. $\hat{n} = \vec{\mathrm{k}}\times\vec{\mathrm{k}}'/|k\times k'|$, where $\vec{\mathrm{k}}$ and $\vec{\mathrm{k}}'$ are the incident and scattered electron momenta, respectively. $\vec{\mathrm{P}}$ is the average nucleon polarization of the target.

T noninvariance implies the existence of a scalar-transverse interference term in the measured cross section. The phase difference δ between the scalar and transverse amplitude is related to the above asymmetry by[4]

$$a = \frac{[2\epsilon(1+\epsilon)]^{1/2}\sigma_{0T}\sin\delta}{\sigma} \equiv A\sin\delta, \qquad (2)$$

where σ is the cross section for an unpolarized target, σ_{0T} is the cross section due to the interference between the scalar and transverse amplitudes, and ϵ is the polarization of the transverse components of the virtual photon.

Since the magnitude of the asymmetry depends on the amount of scalar-transverse interference, the kinematic regions studied (Table I) were chosen with a view to maximizing σ_{0T}. At the 1236-MeV resonance, large scalar amplitudes have been reported[5] at four-momentum transfers between 0.1 and 0.3 $(\mathrm{BeV}/c)^2$. Similarly, at the 1512 resonance both scalar and transverse contributions are strongly indicated.[6] In the present experiment, we searched for asymmetries at π-N center-of-mass system energies ranging from 1130 to 1770 MeV, at four-momentum transfers between 0.2 and 0.7 $(\mathrm{BeV}/c)^2$.

An external electron beam from the Cambridge Electron Accelerator was directed at an alcohol-water target containing protons polarized normal to the plane of scattering. Unscattered electrons passed through a balanced ionization chamber, which monitored the beam position to within 0.1 mm, and into a Faraday cup (Fig. 1). A thin secondary-emission monitor was placed in front of the Faraday cup as an additional beam monitor. Electrons scattered at small angles were momentum analyzed in a half-quadrupole magnetic spectrometer[7] with a momentum acceptance $\Delta p/p$ of 16%. Separation of electrons from other scattering products was accomplished by means of a threshold gas Čerenkov counter and a lead-Lucite shower counter. Only the scattered electrons were detected. Data were stored, event by event, on magnetic tape using a PDP-1 on-line computer, which permitted experimental checks during data acquisition and detailed post-run analysis.

Free protons in the 92%-8% alcohol-water target,[8] which was saturated with porphyrexide, were dynamically polarized in a 25-kG field produced by a superconducting magnet wound with Ni-40Ti wire. The average polarization of the free protons was approximately 22% before exposure to the electron beam, but was reduced appreciably by irradiation. The decay of the polarization was consistent with an exponential de-

Table I. Kinematic regions investigated and the resulting asymmetries.

π-N Mass Region	4-Momentum Transfer	Incident Electron Energy	π-N Mass Region Accepted in Asymmetry Analysis	Asymmetry	χ^2	Degrees of Freedom	T-Noninvariance Phase
W(MeV)	q^2 (BeV/c)^2	E(BeV)	ΔW(MeV)	$\left(\frac{\sigma_\uparrow - \sigma_\downarrow}{\sigma_\downarrow + \sigma_\uparrow}\right)\frac{1}{\vec{P}\cdot\hat{n}}$			$\delta \pm \Delta\delta$
1170[a]	0.23	3.98	90	.058 ± .064	171	170	
1236	0.23	3.98	170	.038 ± .043	181	170	6.5° ± 7.2°
1470[b]	0.53	5.98	100	-.028 ± .119	126	136	-2.0° ± 8.8°
	0.73	5.97	100	.054 ± .069	661	704	4.0° ± 5.0°
1512	0.52	5.98	200	-.026 ± .082	149	136	-3.8° ±12.2°
	0.72	5.97	200	.036 ± .047	706	704	5.3° ± 6.9°
1688	0.49	5.98	160	.036 ± .073	168	136	
	0.68	5.97	160	-.005 ± .044	704	704	

[a]Subset of data at W = 1236 MeV. [b]Subset of data at W = 1512 MeV.

crease[9] with a decay constant of $\varphi_0 = (5.2 \pm 2.7) \times 10^{14}$ (minimum-ionizing particles)/cm^2. At a beam intensity of 2×10^{10} electrons/sec, the polarization in a small 0.15-cm × 1-cm section of the target, which was irradiated by the beam, was reduced by 35% in approximately 30 min. In order to irradiate the entire target uniformly, the 2.5-cm high target was moved 0.05 cm vertically after each pair of 3-min runs. One passage over the target lasted about 5 h and resulted in about 20% reduction in polarization. Some targets were used for a second such traversal.

For each kinematic region 180 3-min runs were taken with the target polarization reversed

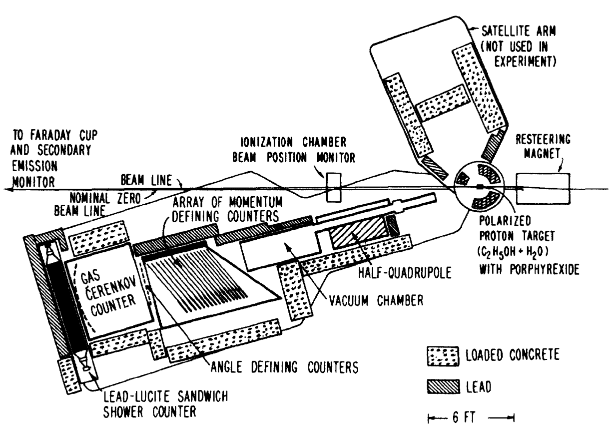

FIG. 1. Plan view of the apparatus (schematic).

according to the following pattern: ↑↓↓↑↓↑↑↓ in order to reduce the effects of systematic drifts in the apparatus. The polarization was reversed at fixed magnetic field by changing the 70-GHz microwave frequency used to saturate the forbidden transitions of the sample by approximately 214 MHz. No other changes were made in the apparatus. The incident beam energy, the electron scattering angle, and the efficiencies of the counters were carefully monitored during the course of the experiment in order to record any drifts in these parameters. In general, the changes in the cross section introduced by these drifts were much smaller than the 2% statistical error associated with the 2500 counts typically recorded in each 3-min run. In all cases, correcting the measured asymmetries for these variations produced a change of less than one-seventh of a standard deviation in the final averaged asymmetries.

We have checked the data for charged-pion contamination by imposing several different biases in the shower and Čerenkov counters. There were no significant changes in the asymmetries as the bias levels were varied.

Shown in Table I and Fig. 2 are the values of the average asymmetries obtained for the different π-N center-of-mass system energies studied. In all cases the asymmetries are consistent with zero and, therefore, with the hypothesis of T in-

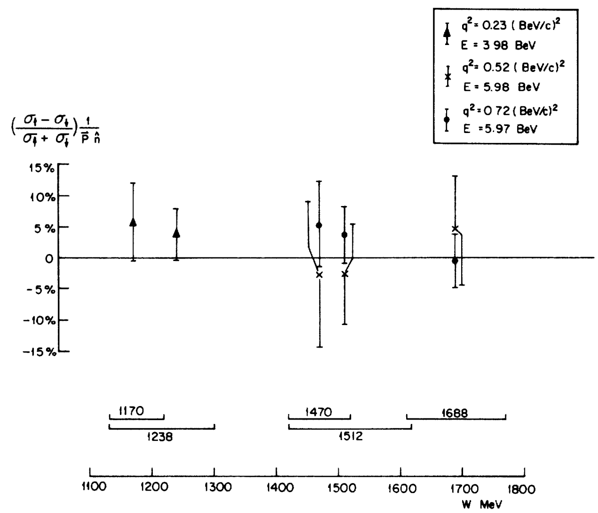

FIG. 2. Experimental asymmetries for different π-N center-of-mass system energies.

variance in the electromagnetic interactions of hadrons.

In order to obtain the limits on the T-noninvariance phase δ set by this experiment, it is necessary to estimate the value of A in Eq. (2). If one assumes complete interference between all parts of the transverse and the scalar cross sections, one obtains[4]

$$A=\{2\epsilon(1+\epsilon)\sigma_0\sigma_T\}^{1/2}/\sigma_{\text{unpolarized target}}. \quad (3)$$

However, in general, the scalar amplitude interferes with only one of the two transverse amplitudes. In the notation of Ref. 2, f_z interferes only with f_- and not with f_+. The relative magnitude of the two transverse amplitudes must be estimated from some other considerations. For production of the resonance at $W=1236$ MeV by a magnetic dipole transition, for example, the two transverse amplitudes are equal. If we also assume that the time-nonreversing amplitude occurs in the resonant amplitudes only and that the other background terms are invariant under time reversal, then A is given by

$$A=\{\tfrac{1}{2}\epsilon(1+\epsilon)\sigma_T{}^{\text{res}}\sigma_0{}^{\text{res}}\}^{\frac{1}{2}}/\sigma_{\text{unpolarized target}}, \quad (4)$$

where $\sigma_T{}^{\text{res}}$ ($\sigma_0{}^{\text{res}}$) is the doubly differential cross section arising from transverse (scalar) resonant amplitudes. Using Eq. (4), at the 1236-MeV resonance, we have made estimates of A using the electroproduction theory of Zagury[10] and the data of Lynch, Allaby, and Ritson.[5] At 1470 MeV, we have estimated A by using the total photoproduction cross section multiplied by a suitable form-factor dependence to estimate σ_T and a static threshold relation appropriate to a $P_{1/2}$ resonance to give the ratio $\sigma_0{}^{\text{res}}/\sigma_T{}^{\text{res}}$. To get $\sigma_0{}^{\text{res}}/\sigma_T{}^{\text{res}}$ at the 1512-MeV resonance, we have used values of $\sigma^{\text{res}}=(\sigma_T+\epsilon\sigma_0)^{\text{res}}$ obtained from the data of Cone et al.[6] together with estimates of σ_T from photoproduction data and a reasonable form-factor dependence. This is also consistent with the electroproduction analysis of Salin.[11] The resulting values of δ at center-of-mass system energies $W=1236$, 1470, and 1512 MeV are shown in the last column of Table I.

No attempt has been made to account for the effects of two-photon-exchange processes. However, based on measurements at the elastic peak,[12] any asymmetries introduced by these processes are expected to be negligible.

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K^+p BACKWARD SCATTERING IN THE REGION FROM 1.0 TO 2.5 GeV/c*

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Elastic scattering of K^+ mesons from protons in the backward direction has been measured to high accuracy. The data indicate that baryon exchange is extremely important for $P_{\mathrm{lab}}(K) > 1.8$ GeV/c. A phase-shift analysis of the data suggests the existence of a $P_{1/2}$ resonance in the K^+p system at a mass of approximately 2 GeV/c^2.

We report on results of backward elastic scattering of K^+ mesons from protons[1] with high statistical accuracy in the momentum region from 1.0 to 2.5 GeV/c. The angular region covered was from $\cos\theta_{\mathrm{c.m.}} = -1.00$ to -0.70 on the average. The partially separated beam of the Brookhaven alternating-gradient synchrotron was used yielding of the order of 10^4 kaons[2] per pulse with a π/K ratio varying between 1 and 4; $\Delta p/p$ was ± 0.01 at the higher momenta and ± 0.02 at low momenta.

The experimental apparatus is shown in Fig. 1 and consists of three arrays of four wire spark chambers each with magnetostrictive read-out.[3] Both x and y coordinates were determined in each chamber, and were recorded on magnetic tape through a PDP-8 computer which was used for on-line control and some simple checks.[3] The first array of chambers was positioned at 45° to the beam line and detected both the incoming and scattered kaon track. After traversing this first array the beam was incident on a $7\frac{1}{2}$-in. long liquid-hydrogen target. The scattered proton traversed the second array of chambers which was positioned normally to the beam line. The directional information on the incoming and two scattered tracks as well as the incident kaon momentum suffice to determine elastic events, which were selected on the basis of (1) coplanarity (± 0.015 for normalized coplanarity), (2) kine-

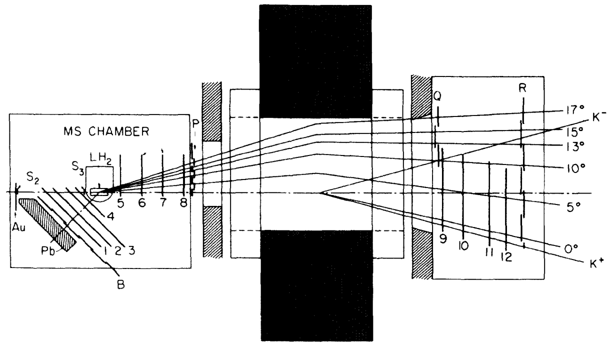

FIG. 1. The experimental apparatus drawn to scale. MS_{1-4}, MS_{5-8} and MS_{9-12} are digitized wire spark chambers. Arrays B, P, and R are the triggering counters. Typical trajectories through the system are shown.