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.

[19]T. Powell et al., following Letter [Phys. Rev. Letters 24, 753 (1970)].

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

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

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 $\boldsymbol{P}_T$ 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

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

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 $A=\boldsymbol{P}=0$ 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 $A=\boldsymbol{P}$ to all orders in the electromagnetic interaction. Four values of P have been reported[7] over the four-momentum-transfer range from 0.3 to 0.8 (GeV/c)^2, and are consistent with $P=0$. Several theoretical attempts[8] have been made to estimate the order of magnitude of the polarization due to the two-photon terms, and the predictions tend to be less than 1%.

Incident electron beams of 15 and 18 GeV from the Stanford linear accelerator were focused onto a polarized butanol target. The electrons which elastically scattered from the target were momentum selected using the 20-GeV/c magnetic spectrometer and were detected in a ten-scintillation-counter hodoscope. For one momentum setting of the spectrometer, the hodoscope covered a missing-mass range of approximately ±200 MeV about the elastic electron-proton scattering peak. Each hodoscope counter subtended about 60 MeV in missing mass. The elastic data were taken from a sum of the three missing-mass bins which centered around the kinematics for elastic electron-proton scattering. Some runs were made with the elastic peak positioned near one side of the hodoscope, while others were made with the elastic peak centered on the hodoscope. Electrons were detected by observing the pulse height in a total-absorption lead-scintillator shower counter. An upper limit of 0.2% can be placed upon the pion contamination in the data. The experimental details and method of analysis of this measurement were the same as those given in the preceding Letter.[9] The procedure for data-taking involved reversing the sign of the target polarization once every 3 minutes and recording the number of counts per unit beam-current charge recorded by the monitor. As the spin reversal was effected by applying only a small change in the frequency of the microwave power to the target, with all other conditions remaining fixed, systematic errors tended to cancel. In all, about 15 million events were obtained in the elastic region. As seen in Eq. (1), the measured asymmetry ϵ is diluted by the target polarization (P_T was about 0.02) and the fraction of counts due to hydrogen in the target (H_F was about 0.20). Because of this dilution, a 0.04% asymmetry in raw counts (ϵ) becomes a 1% asymmetry in A.

Errors can arise from the following: (1) lack of knowledge of the target polarization, (2) uncertainty in the determination of the hydrogen fraction, (3) monitoring errors, (4) statistical error in the total counts, and (5) other systematic effects.

The measurement of the target polarization employed standard NMR techniques.[10] Recent improvements[11] led us to believe that the polarization was known to within 5% ($=\Delta P_T/P_T$).

The hydrogen fraction H_F was determined as function of missing mass as follows:

(1) Data were taken at the kinematics corresponding to elastic electron-proton scattering using butanol, carbon, and polyethylene (CH_2) targets. A pure hydrogen spectrum was obtained from a CH_2-C subtraction, and the butanol spectrum was fitted by a linear combination of this hydrogen spectrum and the carbon spectrum. The prominence of the elastic peak from hydrogen improved the accuracy of the fit to the butanol spectrum.

(2) Spectra were taken at all kinematic conditions, both elastic and inelastic, using C and CH_2 targets. A second CH_2-C subtraction was effected, and the ratio of carbon scattering to hydrogen scattering for CH_2 was calculated for each missing-mass bin. Finally, this ratio was normalized to the butanol target using the fitting parameters obtained in step (1).

The quantity H_F was thus determined to about 20% of its value. However, since H_F is a normalizing factor, its error does not seriously affect the results. In Fig. 1, we show the measured spectrum obtained by scattering 15 GeV

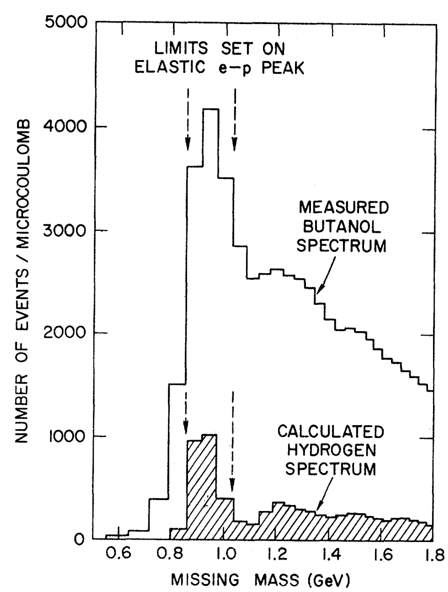

FIG. 1. The measured spectrum for scattering 15-GeV electrons (at 2.37° lab) from the polarized butanol target, and a calculated spectrum for scattering from the pure hydrogen in the target ($=H_F\times$butanol spectrum).

Table I. Asymmetry values A for the elastic scattering of electrons from a polarized proton target. The errors have been calculated from counting statistics which we believe represent the total errors.

Incident electron energy (GeV)	Electron scattering angle (deg)	Four-momentum transfer squared $(\mathrm{GeV}/c)^2$	Number of elastic events $(\times 10^6)$	Hydrogen fraction (H_F)	Asymmetry A
15.0	2.37	0.38	1.8	0.02	-0.004 ± 0.014
18.0	2.48	0.59	11.6	0.16	-0.005 ± 0.009
18.0	3.21	0.98	1.5	0.21	-0.003 ± 0.018

electrons from the butanol target together with a spectrum for pure hydrogen which was calculated by the above procedure.

The asymmetry A was calculated separately for each of the three different beam-current monitors which were used in the experiment. These asymmetries agreed with one another to within $\frac{1}{5}$ the size of the statistical errors. The monitor errors, therefore, can be neglected. From the study of "test" asymmetry values (see Ref. 9 for the details), we believe that our systematic errors are small and that the uncertainty in the measurement can be represented by the errors calculated from counting statistics.

The final asymmetry values at three values of four-momentum transfer squared (q^2) are shown in Table I, where the errors in A are calculated from counting statistics only, which are believed to be close to the total errors. Within the measurement errors, the values are consistent with

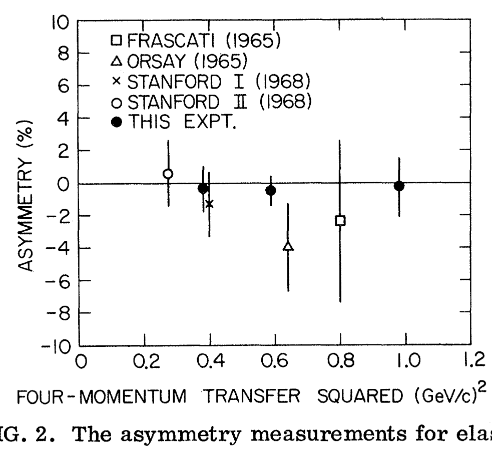

FIG. 2. The asymmetry measurements for elastic electron-proton scattering are shown versus four-momentum transfer squared. This experiment measured the asymmetry for scattering electrons from a polarized proton target. The other values (Ref. 7) were from analyzing the polarization of the protons recoiling from an unpolarized proton target. We have changed the sign of the latter data to be consistent with the definition of $\hat{n}$ given in Eq. (2) of this paper.

$A = 0$. These results are compared in Fig. 2 with the previous measurements[7] of P.

From the results of this experiment and from the measurements of Mar et al.[4] on the real part of two-photon exchange, one can conclude that the higher-order contributions to elastic electron-proton scattering have been found to lie between 0 and order α, in agreement with the theoretical estimates.[1,8]

We wish to thank John Jaros, Peter Robrish, and Stephen Shannon for assistance during the data taking. We are indebted to the accelerator crews and spectrometer facility group for their support during these measurements. We thank Professor Y. S. Tsai and Mr. R. Cahn for theoretical discussions.

*Work supported by the U. S. Atomic Energy Commission.

†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.

[1]S. D. Drell and M. A. Ruderman, Phys. Rev. 106, 561 (1957); S. D. Drell and S. Fubini, Phys. Rev. 113, 741 (1959); N. R. Werthamer and M. A. Ruderman, Phys. Rev. 123, 1005 (1961); D. Flamm and W. Kummer, Nuovo Cimento 28, 33 (1963); S. D. Drell and J. D. Sullivan, Phys. Letters 19, 516 (1965); M. Gourdin, Diffusion des Électrons de Haute Énergie (Masson et Cie., Paris, 1966); G. K. Greenhut, Phys. Rev. 184, 1860 (1969).

[2]M. N. Rosenbluth, Phys. Rev. 79, 615 (1950); S. D. Drell and F. Zachariasen, Electromagnetic Structure of Nucleons (Oxford University, Oxford, England, 1961).

[3]T. Janssens et al., Phys. Rev. 142, 922 (1966); H. J. Behrend et al., Nuovo Cimento 48A, 140 (1967).

[4]J. Mar et al., Phys. Rev. Letters 21, 482 (1968).

[5]Y. S. Tsai, Phys. Rev. 122, 1898 (1961).

[6]J. Bernstein, G. Feinberg, and T. D. Lee, Phys. Rev. 139, B1650 (1965).

[7]The normal to the scattering plane for the following measurements is defined as in Eq. (2), except that $\vec{p}_{in}$ is the momentum of the incident electron and $\vec{p}_{out}$ is the momentum of the recoil proton. Frascati: G. V. DiGiorgio et al., Nuovo Cimento 39, 474 (1965); Orsay: J. C. Bizot, J. M. Buon, J. LeFrançois, J. Perez-y-Jorba, and P. Roy, Phys. Rev. 140, B1387 (1965); Stanford I: D. E. Lundquist, R. L. Anderson, J. V. Allaby, and D. M. Ritson, Phys. Rev. 168, 1527 (1968); Stanford II: Dr. B. H. Wiik communicated to us a value of $P=(-0.006\pm0.020)$ measured at $q^2=0.27$ (GeV/c)^2 which was referred to in the paper by R. Prepost, R. M. Simonds, and B. H. Wiik, Phys. Rev. Letters 21, 1271 (1968).

[8]F. Guérin and C. A. Piketty, Nuovo Cimento 32, 971 (1964); G. K. Greenhut, thesis, Cornell University, 1968 (unpublished); J. Arafune and Y. Shimizu, Institute for Nuclear Study, Tokyo, Japan, Report No. INS-139, 1969 (unpublished).

[9]S. Rock et al., preceding Letter [Phys. Rev. Letters 24, 748 (1970)].

[10]C. D. Jeffries, Dynamic Nuclear Orientation (Interscience, New York, 1963).

[11]M. Borghini et al., "Polarized Proton Target for Use in Intense Electron and Photon Beams" (to be published).

SIMPLE MODEL FOR PROTON-PROTON SCATTERING*

G. G. Zipfel, Jr.
Institute for Theoretical Physics, State University of New York, Stony Brook, New York 11790
(Received 10 November 1969)

A semiclassical model for inelastic and elastic proton-proton scattering is presented. A fit to recent π production counter data is made. The resulting proton-proton elastic scattering and proton electromagnetic form factor are discussed. Reasonable agreement with the data is obtained.

Sometimes very simple models are useful tools in gaining insight into limited aspects of complicated processes. Here we present a model which explains some aspects of elastic and inelastic proton-proton scattering. The model is closely related in philosophy to one originally suggested by Lewis, Oppenheimer, and Wouthuysen[1,2] and goes as follows. Since boson—in particular, pion—production dominates the cross section, one assumes that the bosons are produced in states corresponding to a field coupled to a classical source. The structure of the source is related to the structure of the colliding protons. The model's phenomenological input is the source function.

The analysis of a field coupled to a classical source[3] shows that the average number of particles produced per unit volume in momentum space is given by

$$\bar{n}(\vec{k})=(2\pi)^{-3}(2\omega)^{-1}|f(\vec{k})|^2, \tag{1}$$

where

$$f(\vec{k})=\int d^4x\,\rho(x)\,e^{-ik\cdot x}, \tag{2}$$

$$k\cdot x=\vec{k}\cdot\vec{x}-\omega t,\quad \omega=(\vec{k}^2+m^2)^{1/2},$$

and m is the pion mass. In a collision of two protons the source, $\rho(x)$, implicitly contains a dependence on the impact parameter, $b_\perp$, of the protons. The average of $\bar{n}$ over $b_\perp$ is directly measured in counter experiments which determine the flux of outgoing particle in a given range of momentum and solid angle, all other variables being ignored. The classical source model also corresponds to particles which are produced in uncorrelated states with a Poisson number distribution. Thus, the probability p_0 that a collision will take place with no particle production is given by

$$p_0=e^{-\bar{n}(b_\perp)},$$

where

$$\bar{n}(\vec{b}_\perp)=\int d^3k\,\bar{n}(\vec{k},\vec{b}_\perp).$$

This immediately gives the absorption disk for proton-proton elastic scattering. The elastic differential cross section is given by

$$\left.\frac{d\sigma}{dt}\right|_{\text{elastic}}=\pi\left|\int_0^\infty db_\perp\,b_\perp(e^{-\bar{n}(b_\perp)/2}-1)J_0(b_\perp\sqrt{-t})\right|^2. \tag{3}$$