lines which are equally good fits to their experimental points.

Although dead-time effects modify quantities like the mean and variance of a counting distribution by small amounts of the order of $\bar{n}_0\tau/T$ with $\tau \ll T$, their effect on the distribution as a whole can be quite profound. Loosely speaking, the modification to the nth point in the distribution depends not simply on the value of τ/T but on that of $n\tau/T$. When detailed features of the distribution are being investigated, it is therefore essential to correct for dead-time effects.

[1]F. A. Johnson, T. P. McLean, and E. R. Pike, in Proceedings of the International Conference on the Physics of Quantum Electronics, Puerto Rico, 1965, edited by P. L. Kelley, B. Lax, and P. E. Tannenwald (McGraw-Hill Book Company, Inc., New York, 1965).

[2]F. T. Arecchi, Phys. Rev. Letters 15, 912 (1965); F. T. Arecchi, A. Berné, and P. Burlamacchi, Phys. Rev. Letters 16, 32 (1966).

[3]C. Freed and H. A. Haus, Phys. Rev. Letters 15, 943 (1965).

[4]A. W. Smith and J. A. Armstrong, Phys. Letters 19, 650 (1966).

[5]R. J. Glauber, Quantum Optics and Electronics, edited by C. De Witt, A. Blandin, and C. Cohen-Tannoudji (Gordon and Breach Publishers, Inc., New York, 1965), p. 65.

[6]In the technique of Arecchi, Berné, and Burlamacchi, Ref. 2, dead-time effects are avoided but are replaced by effects due to the output pulse-height distribution of a photomultiplier.

[7]I. De Lotto, P. F. Manfredi, and P. Principio, Energia Nucl. (Milan) 11, 557 (1964).

[8]L. Mandel, Progress in Optics, II, edited by E. Wolf (North-Holland Publishing Company, Amsterdam, 1963), p. 181.

[9]T. P. McLean and E. R. Pike, Phys. Letters 15, 318 (1965).

[10]F. A. Johnson, R. Jones, T. P. McLean, and E. R. Pike, to be published.

[11]Higher order factorial moments were first reported by C. Freed and H. Haus, in Proceedings of the International Conference on the Physics of Quantum Electronics, Puerto Rico, 1965, edited by P. L. Kelley, B. Lax, and P. E. Tannenwald (McGraw-Hill Book Company, Inc., New York, 1966), p. 715.

[12]The zero dead-time curve in Fig. 1 differs from that of Freed and Haus by a constant multiplicative factor which takes account for $n \gtrsim 10$ of the broad-band background from their source.

MEASUREMENTS OF NEUTRON FORM FACTORS*

P. Stein, M. Binkley, R. McAllister,† A. Suri, and W. Woodward

Laboratory of Nuclear Studies, Cornell University, Ithaca, New York

(Received 21 February 1966)

We have investigated the electromagnetic neutron form factors at momentum transfers of 5.5 F^{-2}, 10.0 F^{-2}, and 14.5 F^{-2} by measuring the differential cross sections for quasi-elastically scattered electrons by deuterium in coincidence with a scattered nucleon in the reaction $e+d\rightarrow e+p+n$.

Measurements were made of the ratio of the differential cross section $d^3\sigma/d\Omega_n d\Omega_e dE_e$ to the differential cross section $d^3\sigma/d\Omega_p d\Omega_e dE_e$ for two different electron scattering angles for each value of the momentum transfer q^2.

Durand[1] has shown that this ratio of differential cross sections from deuterium is nearly equal to the ratio of the differential cross sections for free electron-neutron and electron-proton scattering. This result is relatively insensitive to assumptions made about the wave function of the deuteron. An earlier experiment[2] of this type for $q^2 = 4.9$ F^{-2} has been reported.

The experiment was done using the internal electron beam of the Cornell electron synchrotron. In the $q^2 = 10.0$ F^{-2} experiment, the beam was incident upon a thin deuterated-polyethylene target. In the $q^2 = 5.5$ F^{-2} and the $q^2 = 14.5$ F^{-2} experiments, a liquid deuterium target was used. This target had 0.25-mil aluminum walls and was cooled with liquid helium.

The scattered electrons were analyzed in a vertically focusing quadrupole magnet. The electrons were detected by a momentum-defining scintillation counter in coincidence with a second scintillation counter and a totally absorbing lead glass Cherenkov counter.

The scattered nucleons were detected in coincidence with the scattered electron. The neutrons were detected by their interactions in a plastic scintillation counter 24 in. in diameter and 18 in. thick. Three to five inches of lead were placed between the neutron counter and the target. In all cases the neutron counter was centered around the direction corresponding to scattering from a free neutron and it subtended a cone of half-angle 3.8°, 3.7°, and 5.3°

for q^2 of 5.5 F^{-2}, 10.0 F^{-2}, and 14.5 F^{-2}, respectively.

The proton telescope consisted of two circular plastic scintillation counters in coincidence. The defining counter was positioned to subtend the same solid angle as the neutron counter. The kinematics were established from the geometry and range measurements of the recoil protons in e-p scattering using a hydrogen target.

The efficiency of the neutron counter was determined in a separate experiment using the neutrons from the reaction $\gamma + p \rightarrow \pi^+ + n$. Pions were detected by a magnetic spectrometer which determined a coincident neutron beam of known geometry and energy. The efficiency was measured as a function of the neutron energy, discriminator bias setting, and amount of absorber in front of the counter. The bias was determined relative to the pulse height of cosmic rays.

Since the efficiency of the neutron counter is quite bias sensitive, it was necessary to monitor the bias and gain of the counter continually during the course of the experiment. This was done by measuring cosmic rays between the beam pulses of the synchrotron. For our runs the bias was set so that we counted particles that lost about 40 MeV or more in the neutron counter. We obtained efficiencies of 16% to 21%.

During the experiment we displayed the outputs of the two proton counters and the neutron counter on a fast four-beam oscilloscope. The fourth trace displayed the rf wave form (86 Mc/sec) used to accelerate the electrons. Because of the bunching of the circulating electron beam, this provided an accurate timing base to determine the time of flight of the recoil nucleons. A common signal from the electron spectrometer was displayed on all four traces. The oscilloscope was triggered and a picture taken every time an electron was counted in the spectrometer. It was recorded on the film when a coincident neutron-pulse height exceeded the bias. From these pictures we determined the ratio of electron-neutron coincidences to electron-proton coincidences.

Background runs were made for all running conditions. It was determined that at $q^2 = 10.0$ F^{-2} the carbon in the deuterated polyethylene contributed about 10% of both the e-n and e-p coincidence rates. To within the statistics of our measurements the background was the same percentage for both. At $q^2 = 5.5$ F^{-2} and $q^2 = 14.5$ F^{-2} the background due to the aluminum walls of the target was found to contribute about 1% to both the e-n and e-p coincidence rates.

Investigations were also made of protons that counted in the neutron counter. Enough lead was placed in front of the neutron counter to range out all protons. However, a proton could count by charge-exchange scattering in the absorber in front of the neutron counter. Most of these cases were eliminated by noting if a proton had passed through the proton counters. Further subtractions were made by measuring the e-n coincidence rate when scattering from a hydrogen target. This "exchange" background amounted to approximately 1% of the real e-n rate.

It was also possible for neutrons to count in the proton counters. However, knowing the neutron-counter efficiency, the relative size of the neutron and proton counters, and the relative frequency of protons to neutrons, one obtains less than a 1% correction to the real e-p rate in all cases.

We have analyzed our data in terms of the form factors G_e and G_m:

$$G_{mn}^2 = \frac{D(\theta_2)R(\theta_2) - D(\theta_1)R(\theta_1)}{2\tau[\tan^2(\theta_2/2) - \tan^2(\theta_1/2)]},$$

$$G_{en}^2 = \tau(\tau+1)\Sigma(\theta_2) \times \frac{D(\theta_1)R(\theta_1)/D(\theta_2)R(\theta_2) - \Sigma(\theta_1)/\Sigma(\theta_2)}{1 - D(\theta_1)R(\theta_1)/D(\theta_2)R(\theta_2)} G_{mn}^2,$$

where

$$D(\theta) = (1+\tau)^{-1}G_{ep}^2 + \tau[(1+\tau)^{-1} + 2\tan^2(\theta/2)]G_{mp}^2;$$

$$\Sigma(\theta) = [(1+\tau)^{-1} + 2\tan^2(\theta/2)]; \quad \tau = q^2/4M^2;$$

and where $R(\theta)$ is the ratio of e-n to e-p scattering at angle θ. One should note that in calculating G_{en}^2 there is considerable cancelling of errors. G_{en}^2 depends mostly on the ratio of the e-n/e-p ratios at the two different angles; consequently, uncertainties in the absolute values of the counter efficiencies and solid angles cancel to this degree. If one takes G_{mn}^2 as known, these errors cancel completely.

At $q^2 = 5.5$ F^{-2} we give results only for G_{en}^2 because the absolute efficiency of the neutron counter was not determined for our running conditions. Hence the only measurement we can quote is the ratio of the ratios: $R(40°)/R(105°) = 0.553$ (±6.5%). Assuming[3] $G_{ep} = 0.584$, $G_{mp} = 1.60$, and $G_{mn} = 1.10$ we get as a result $G_{en}^2 = 0.0017 \pm 0.0070$. The only factor included

Table I. The neutron form factors are given as a function of the four-momentum transfer q^2. For comparison the values for G_{mn} from Hughes et al.[a] are given.

q^2 (F^{-2})	${G_{en}}^2$ This expt.	G_{mn} This expt.	G_{mn} Hughes[a]
5.5	$+0.0017 \pm 0.0070$	...	...
10.0	-0.0037 ± 0.0141	-0.825 ± 0.064	-0.825 ± 0.081[b]
14.5	-0.0055 ± 0.0088	-0.638 ± 0.042	-0.650 ± 0.072[b, c]

[a]See Ref. 6.

[b]Error includes 5% theoretical uncertainty.

[c]This value has been determined by extrapolation.

in the error was the 6.5% statistical error in the ratio of the ratios. As noted before, the other errors contribute little due to cancellation.

The following ratios were obtained for $q^2 = 10.0$ F^{-2}: At an electron angle of 50°, $R = 0.28$; at an electron scattering angle of 95°, $R = 0.39$. Again,[3] if $G_{ep} = 0.408$ and $G_{mp} = 1.14$ we get as results ${G_{en}}^2 = -0.0037 \pm 0.0141$ and $G_{mn} = -0.825 \pm 0.064$. The main contributions to the errors in ${G_{en}}^2$ were (a) 6% statistics in the ratio at 95°, (b) 4% statistics in the ratio at 50°, and additionally for G_{mn} (c) 5% uncertainty in the ratio of the efficiencies of the neutron and proton counters, (d) 8% error in the solid angle of the neutron counter.

At $q^2 = 14.5$ F^{-2} these ratios were obtained: At an electron scattering angle of 35°, $R = 0.297$; at an electron scattering angle of 90°, $R = 0.425$. Assuming that $G_{ep} = 0.326$ and $G_{mp} = 0.854$, we get as results ${G_{en}}^2 = -0.0055 \pm 0.0088$ and $G_{mn} = 0.638 \pm 0.042$. The principal errors were (a) 5% statistics in the ratio at 90°, (b) 5% statistics in the ratio at 35°, (c) 5% uncertainty in the ratio of the efficiencies of the neutron and proton counters, (d) 8% error in the absolute solid angle subtended by the neutron counter.

No corrections were made to take into account the effect of the spectator nucleon. The largest correction should be that due to the final-state interaction. Using Durand's[1] theory, Applequist has made an approximate evaluation of the final-state interaction correction for our geometry at $q^2 = 10$ F^{-2} and $q^2 = 14.5$ F^{-2}. In both cases the correction was considerably smaller than the experimental uncertainties. Also, no radiation corrections were made since they should cancel in the ratios.

Hughes et al.[6] have reported results which they say are consistent with ${G_{en}}^2 = 0$ for $q^2 > 6$ F^{-2}. Our measurements corroborate these results. For G_{mn} our values are also in agreement with those reported by Hughes et al. (see Table I).

We have previously[2,4] reported measurements which give the following values for the square of G_{en}: ${G_{en}}^2 = 0.0256 \pm 0.0128$ for $q^2 = 4.9$ F^{-2} and ${G_{en}}^2 = 0.0576 \pm 0.0240$ for $q^2 = 11.0$ F^{-2}. We are suspicious of some technical defects in these measurements and for this reason have considerably more confidence in the presently reported values.

*Work supported in part by the National Science Foundation and the U. S. Office of Naval Research.

†Now at Colorado School of Mines, Golden, Colorado.

[1]L. Durand, Phys. Rev. 115, 1020 (1959); 123, 1393 (1961).

[2]P. Stein, R. W. McAllister, B. D. McDaniel, and W. M. Woodward, Phys. Rev. Letters 9, 403 (1962).

[3]Obtained from data and results in C. de Vries, R. Hofstadter, A. Johansson, and Robert Herman, Phys. Rev. 134, B848 (1964); and J. S. Levinger and C. P. Wang, Phys. Rev. 136, B733 (1964).

[4]P. Stein, M. Binkley, R. McAllister, B. McDaniel, and W. Woodward, in Proceedings of the International Conference on Nucleon Structure at Stanford University, 1963, edited by R. Hofstadter and L. Schiff (Stanford University Press, Stanford, California, 1964).

[5]Marian Applequist, thesis, Cornell University, 1966 (unpublished).

[6]E. B. Hughes, T. A. Griffy, M. R. Yearian, and R. Hofstadter, Phys. Rev. 139, B458 (1965).