[1]In a subsequent short run the useful neutrino event rate has climbed to about 15 events per hour, still without focusing of the secondary hadrons.

[2]We assume that the average muon energy is $\frac{1}{2}$ of the neutrino energy. This assumption is consistent with the neutrino energy distribution determined for events observed in the calorimeter, after applying corrections for energy escape and calibration. We note that the IC has not yet been calibrated in a hadron beam. Cosmic-ray muons have been used to determine the energy loss for minimum ionizing tracks in order to calibrate crudely the visible energy measurement.

[3]E. A. Paschos and V. I. Zakharov, National Accelerator Laboratory Report No. NAL-THY-100 (to be published); J. D. Bjorken, Nuovo Cimento 68, 569 (1970).

[4]I. Budagov *et al.*, Lett. Nuovo Cimento 2, 689 (1969); A. Mann, V. Mehtani, B. Musgrave, Y. Oren, P. Schreiner, H. Yuta, R. Ammar, Y. Cho, M. Derrick, R. Engelmann, and L. Hyman, in Proceedings of the Sixteenth International Conference on High Energy Physics, National Accelerator Laboratory, Batavia, Illinois, 1972 (to be published). We explicitly assume that the quasielastic and Δ-production components remain constant with energy at high energy, as observed (approximately) in these experiments.

[5]The latest data from the CERN-Gargamelle collaboration were presented by P. Heusse, in Proceedings of the Sixteenth International Conference on High Energy Physics, National Accelerator Laboratory, Batavia, Illinois, 1972 (to be published); see also D. H. Perkins, *ibid*; I. Budagov *et al.*, Phys. Lett. 30B, 364 (1969).

[6]J. D. Bjorken and E. A. Paschos, Phys. Rev. 185, 1975 (1969).

[7]We have taken the π^+/π^- and K^+/K^- production ratio needed to determine the ratio of $\nu/\bar{\nu}$ flux from recent measurements at the CERN intersecting storage rings and proton synchrotron and interpolated the data to NAL energies. Since the π and K production approximately follow Feynman scaling in the approximate $(x, p_\perp)$ kinematic region for the NAL neutrino beam and over the s variation from proton-synchrotron to intersecting-storage-rings energies, we expect our estimate to be accurate to within ~20%. The relevant data were taken from G. Giacomelli, to be published; H. J. Muck *et al.*, Phys. Lett. 39B, 303 (1972); J. V. Allaby, F. Benon, A. N. Diddens, P. Duteal, A. Klovning, P. Meunier, J. P. Peigneux, E. J. Sacharidis, K. Schlupmann, M. Spiegel, J. P. Stroot, A. M. Thorndike, and A. M. Wetherell, CERN Report No. 70-12, 1970 (unpublished).

Comparisons of Deep-Inelastic *e-p* and *e-n* Cross Sections

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Cross sections for inelastic scattering of electrons from hydrogen and deuterium were measured for incident energies from 4.5 to 18 GeV, at scattering angles of 18°, 26°, and 34°, and covering a range of squared four-momentum transfers up to 20 $(\text{GeV}/c)^2$. Neutron cross sections were extracted from the deuterium data using an impulse approximation. Comparisons with the proton measurements show significant differences between the neutron and proton cross sections.

Deep-inelastic electron scattering has been used to study the structure of the proton[1,2] and neutron.[3] The investigation of neutron structure has been further extended in the present experiment. Comparisons of the proton and neutron cross sections provide important tests for many of the models suggested by the earlier proton measurements.

We have measured the differential cross section for electrons scattering from hydrogen and deuterium, detecting only the scattered electrons. Measurements were made at laboratory angles θ of 18°, 26°, and 34° and a range of scattered electron energy E' extending from that corresponding to the resonance region down to 1.5 GeV. The incident electron energy E varied from 4.5 to 18 GeV. A number of spectra, each covering a range of E' at a fixed value of E, were measured at each angle to permit model-insensitive radiative corrections to be made.

An electron beam at the Stanford Linear Accelerator Center (SLAC) passed through 7-cm-thick targets of liquid hydrogen or deuterium. The number of electrons incident on the target was measured by two toroidal charge monitors, which were periodically checked against a Faraday cup. Effects of beam heating on the liquid target densities were measured by the SLAC 1.6-GeV spectrometer which detected recoil protons from elastic e-p or quasielastic e-d scattering. The spectrometer was calibrated for each spectrum at very low beam currents. Scattered electrons were analyzed by the SLAC 8-GeV spectrometer, and were identified by a detection system similar to that used in earlier work.[2]

Corrections were made for dead-time losses and inefficiencies in electron identification. The errors associated with these corrections, typically $\pm 1\%$, were mainly statistical and were combined in quadrature with the statistical errors of the data. Yields from the empty targets were subtracted. Electron yields originating from π^0 decay and pair-production processes were determined by reversing the spectrometer polarity and measuring positron yields; these were subtracted also. Radiative corrections were then applied to the data. Radiative tails from the hydrogen elastic peak and the deuterium elastic and quasielastic peaks were calculated and subtracted from the hydrogen and the deuterium cross sections, respectively. The inelastic spectra were then radiatively corrected using a model-insensitive unfolding program. The statistical errors of the data were propagated through this procedure. For the ratio of deuterium to hydrogen most of the systematic errors in the radiative corrections cancel. Errors in this ratio associated with uncertainties in the elastic and quasielastic radiative tails do not cancel and range from a few tenths of a percent near the resonance region up to nearly $\pm 2\%$ at the smallest values of E' of the spectra.

Other systematic errors which did not cancel in the cross-section ratio of deuterium to hydrogen were target related. The total systematic error in the neutron-to-proton cross-section ratio, including uncertainities in the radiative corrections and deuteron effects, was about $\pm 6\%$.

The structure functions W_1 and W_2, which can be defined for the proton, neutron, or deuteron, are represented in the usual form[4]

$$d^2\sigma/d\Omega dE' = \sigma_M[W_2(q^2, \nu) + 2W_1(q^2, \nu)\tan^2\tfrac{1}{2}\theta],$$

where $\nu = E - E'$, $q^2 = 4EE'\sin^2\frac{1}{2}\theta$, and σ_M is the Mott cross section. The ratio of W_2 to W_1 is related to the ratio $R = \sigma_S/\sigma_T$ of the total photoabsorption cross sections for scalar and transverse virtual photons, σ_S and σ_T, by the expression

$$W_2/W_1 = q^2(1+R)/(q^2+\nu^2).$$

Information about the neutron is extracted from our measurements on deuterium using the impulse approximation. The method[5] used is that of West, with small modifications representing additional off-mass-shell corrections.[6] Both structure functions, or equivalently R and W_2, must be known in order to carry out this procedure. R for the proton previously had been determined[2] to be consistent with a constant value $R_p = 0.18 \pm 0.10$ over a kinematic range similar to that of the present experiment. Our preliminary results[7] are consistent with this value, and it has been used in our analysis.

In carrying out the West procedure we found it convenient to use the following form for the proton structure function $W_2^p(q^2, \nu)$ in fits to the experimental cross sections:

$$W_2^p(q^2, \nu) = \nu^{-1}A(W)\sum_{n=3}^{7} c_n(1-x')^n.$$

The mass of the hadronic final state is $W = (M^2 + 2M\nu - q^2)^{1/2}$, where M is the proton mass, $A(W)$ is an expression which is zero at the inelastic threshold and goes smoothly to 1.0 for W larger than approximately 2 GeV, and $x' = (1 + W^2/q^2)^{-1}$. The coefficients c_n were obtained by calculating the proton cross section using the above forms, averaging over the spectrometer acceptance, and fitting to the data. The resulting proton structure functions were integrated over the Fermi motion of the proton within the deuteron. The forms of these "smeared" proton structure functions were[5]

$$W_{1sm}^p(q^2, \nu) = \int f(p)[W_1^p(q^2, \nu') + W_2^p(q^2, \nu')(\vec{p}^{\,2} - p_3^2)/M]\, d^3p$$

$$W_{2sm}^p(q^2, \nu) = \int f(p)[(1 - p_3 q^2/M\nu' q_3)^2(\nu'/\nu)^2 + (2M^2)^{-1}(\vec{p}^{\,2} - p_3^2)q^2/q_3^2]W_2^p(q^2, \nu')\, d^3p,$$

where p is the four-momentum of the proton (now off the mass shell), $q = (0, 0, q_3, -\nu)$ is the four-momentum of the virtual photon, $\nu' = p\cdot q/M$, and $f(p)$ is the momentum distribution of a nucleon within the deuteron. The quantities W_1^p and W_2^p are identified with the observed on-mass-shell structure functions with the same values of q^2 and $W^2 = -(p+q)^2$.

TABLE I. Cross-section ratios. The errors quoted are statistical only.

x	σ_n/σ_p	$\nu W_{2p} - \nu W_{2n}$	Number of points	q^2 Range
0.090	0.961 ± 0.185	0.0116 ± 0.0583	2	1.5 - 2.0
0.110	0.903 ± 0.065	0.0286 ± 0.0210	6	1.8 - 3.3
0.130	0.846 ± 0.063	0.0505 ± 0.0206	4	2.0 - 3.7
0.150	0.773 ± 0.030	0.0768 ± 0.0101	7	1.3 - 4.2
0.170	0.851 ± 0.026	0.0459 ± 0.0082	7	1.3 - 4.6
0.190	0.811 ± 0.022	0.0612 ± 0.0074	7	1.5 - 5.0
0.210	0.759 ± 0.022	0.0793 ± 0.0073	9	1.6 - 5.6
0.230	0.712 ± 0.025	0.0958 ± 0.0082	6	2.2 - 5.8
0.250	0.730 ± 0.019	0.0865 ± 0.0063	11	1.0 - 7.3
0.270	0.754 ± 0.025	0.0762 ± 0.0076	7	1.5 - 8.2
0.290	0.699 ± 0.016	0.0892 ± 0.0048	9	1.9 - 7.1
0.310	0.672 ± 0.020	0.0936 ± 0.0058	7	2.0 - 9.1
0.330	0.651 ± 0.018	0.0979 ± 0.0050	9	1.6 - 7.6
0.350	0.624 ± 0.019	0.1018 ± 0.0051	7	2.1 -10.0
0.370	0.656 ± 0.021	0.0857 ± 0.0053	7	2.2 - 8.4
0.390	0.625 ± 0.019	0.0901 ± 0.0046	7	2.2 -11.0
0.410	0.629 ± 0.021	0.0810 ± 0.0046	5	4.6 - 9.1
0.430	0.642 ± 0.019	0.0734 ± 0.0039	9	2.3 -11.9
0.450	0.595 ± 0.020	0.0760 ± 0.0037	6	3.5 - 9.9
0.470	0.589 ± 0.069	0.0660 ± 0.0111	1	12.8 -12.8
0.490	0.569 ± 0.021	0.0675 ± 0.0032	7	5.3 -11.6
0.510	0.532 ± 0.030	0.0720 ± 0.0046	4	3.7 -13.7
0.530	0.547 ± 0.028	0.0574 ± 0.0036	4	7.5 -11.4
0.550	0.555 ± 0.026	0.0503 ± 0.0030	5	4.0 -14.6
0.570	0.538 ± 0.030	0.0515 ± 0.0034	4	5.7 -10.7
0.590	0.499 ± 0.030	0.0451 ± 0.0027	4	7.3 -15.5
0.610	0.514 ± 0.053	0.0393 ± 0.0043	3	5.6 -14.1
0.630	0.490 ± 0.033	0.0367 ± 0.0024	2	6.2 -11.7
0.650	0.446 ± 0.038	0.0326 ± 0.0022	4	9.6 -16.4
0.670	0.459 ± 0.049	0.0332 ± 0.0030	2	6.8 - 8.5
0.690	0.415 ± 0.049	0.0218 ± 0.0019	4	9.4 -17.3
0.710	0.422 ± 0.034	0.0206 ± 0.0012	3	10.2 -12.8
0.750	0.311 ± 0.064	0.0152 ± 0.0014	3	14.5 -18.2
0.790	0.357 ± 0.038	0.0094 ± 0.0006	2	13.4 -19.2

The smeared proton structure functions were combined to yield a smeared proton cross section σ_{ps}. Subtracting the smeared proton cross section from the deuteron cross section yielded by definition the smeared neutron cross section: $\sigma_{ns}=\sigma_d-\sigma_{ps}$. The "smeared" neutron-to-proton cross-section ratio was then $\sigma_{ns}/\sigma_{ps}=S_p\,\sigma_d/\sigma_p-1$, where S_p is the proton smearing correction, and is the ratio of the unsmeared to smeared proton cross sections, both calculated from our fit to $W_2{}^p$. The size of S_p varied from 0.893 ±0.012 to 1.032±0.003.

With the exception of Glauber corrections, which are known to be small, other corrections to the impulse approximation cannot be estimated accurately and are assumed to be small. The results are insensitive to the choice of wave function used to determine the momentum distribution of the bound nucleons, as long as the wave function is consistent with other known properties of the deuteron and the n-p interaction.

We removed the effects of smearing from the neutron-to-proton ratio by calculating S_n, the smearing correction for the neutron, and forming the unsmeared ratio $\sigma_n/\sigma_p=(\sigma_{ns}/\sigma_{ps})S_n/S_p$. The values of S_n were obtained as follows. The unsmeared structure function $W_2{}^n$ was assumed to have the same basic functional form as was assumed for the proton. The individual terms were then smeared and averaged over the spectrometer acceptance, and the c_n were determined by fitting the calculated values of σ_{ns} to the measured values. It was assumed for this purpose that the ratio of the scalar to transverse virtual photon-neutron total cross sections, R_n, was also equal to 0.18. This result is consistent with our observations that, to within the errors, $R_p=R_n$.[7,8] The effect of unsmearing was not large. The ratio S_n/S_p varied from 0.950±0.020 for the smallest measured value of ω to 1.002±0.003 at the largest measured value of ω, where ω is the Bjorken scaling variable $\omega=2M\nu/q^2$.

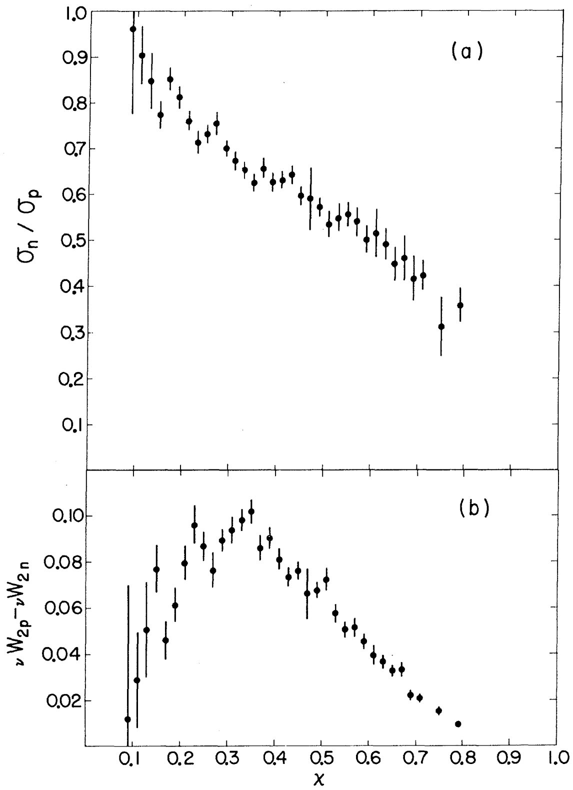

FIG. 1. (a) σ_n/σ_p versus $x = 1/\omega$. (b) $\nu(W_2^p - W_2^n)$ versus x, with the assumption $R_p = R_n = 0.18$. The errors shown are statistical. They do not include the 6% systematic error referred to in the text.

Values of σ_n/σ_p obtained from this experiment are given in Table I and plotted in Fig. 1(a) as a function of the variable $x = 1/\omega$. The values were obtained by calculating the ratio for all experimentally determined points outside the resonance region ($W > 2$ GeV) and then forming weighted averages of these points over small intervals in x.

The most prominent feature of Fig. 1(a) is the pronounced decrease in σ_n/σ_p as x increases. Quark models[9] have difficulty accounting for the small value of σ_n at large x, unless quark-quark correlations are included. Furthermore, a lower bound of 0.25 is imposed on σ_n/σ_p in the quark model.[10] While our results are consistent with this bound they do not rule out a smaller value. Regge[11] and resonance[12] models also have difficulty at large x. They predict values for the ratio in the neighborhood of 0.6 and 0.7, respectively, near $x = 1$. A relativistic parton model[13] in which the partons are associated with "bare" nucleons and mesons predicts a result for W_1^n/W_1^p which has an x dependence similar to that of the data. If the above assumption of equality between R_p and R_n is made, approximate agreement with our results is obtained. Our results are not in disagreement with a prediction of $W_2^n/W_2^p = 0.47$ at $x = 1.0$ from a duality model,[14] but since the model cannot be reliably extended far into the region $x < 1.0$, no more conclusive statement is possible.

The difference $\nu(W_2^p - W_2^n)$ determined with the assumption that $R_p = R_n = 0.18$ is plotted against x in Fig. 1(b). Significant nondiffractive behavior is evident: A peak is clearly seen in the vicinity of $x = 0.35$. The theories discussed above are only qualitatively successful in describing this behavior. These models all yield peaks at too small a value of x. A parton model coupled with duality[15] yields a peak in the right position but does not agree well with the data elsewhere. In addition it predicts a value of $\frac{2}{3}$ for the neutron-to-proton ratio. None of the models examined here can account quantitatively for the relative behavior of the neutron and proton cross sections determined in this experiment.

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[1]E. D. Bloom *et al.*, Phys. Rev. Lett. 23, 930 (1969); M. Breidenbach *et al.*, Phys. Rev. Lett. 23, 935 (1969).

[2]G. Miller *et al.*, Phys. Rev. D 5, 528 (1972).

[3]E. D. Bloom *et al.*, in Proceedings of 1970 International Conference on High Energy Physics, Kiev, September, 1970 (Atomizdat., Moscow, to be published); H. W. Kendall, in *Proceedings of the Eighth International Symposium on Electron and Photon Interactions at High Energies, Ithaca, New York, 1971*, edited by N. B. Mistry (Cornell Univ. Press, Ithaca, N.Y., 1972). Results from this experiment were presented in preliminary form at this conference. The data appearing in the present paper represent the result of improved analysis and supersede the conference results. J. S. Poucher, Ph.D. thesis, Massachusetts Institute of Technology, 1971 (unpublished).

[4]S. D. Drell and J. D. Walecka, Ann. Phys. (New York) 28, 18 (1964).

[5]W. B. Atwood and G. B. West, Phys. Rev. D 7, 773

(1973).
[6]A. Bodek, Ph.D. thesis, Massachusetts Institute of Technology, 1973 (unpublished).
[7]E. M. Riordan, Ph.D. thesis, Massachusetts Institute of Technology, 1973 (unpublished).
[8]E. M. Riordan *et al.*, to be published.
[9]J. Kuti and V. F. Weisskopf, Phys. Rev. D 4, 3418 (1971).
[10]O. Nachtman, Phys. Rev. D 5, 686 (1972).
[11]J. W. Moffat and V. G. Sneïl, Phys. Rev. D 3, 2848 (1971).
[12]G. Domokos *et al.*, Phys. Rev. D 3, 119 (1971).
[13]S. D. Frell and T. D. Lee, Phys. Rev. D 5, 1738 (1972).
[14]E. D. Bloom and F. J. Gilman, Phys. Rev. D 4, 2901 (1971).
[15]P. V. Landshoff and J. C. Polkinghorne, Nucl. Phys. B28, 240 (1971).

Observations on $\bar{p}d$ Annihilations at Rest into Two Pions

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The ratio $(\bar{p}d\to\pi^-\pi^0p_s)/(\bar{p}d\to\pi^-\pi^+n)$ at rest, with spectator momenta $\lesssim 300$ MeV/c, has been measured and found to be 0.68 ± 0.07. This implies that $(75\pm8)\%$ of the annihilations in deuterium into two pions come from odd $\bar{N}N$ orbital angular momenta, in disagreement with the S-state–dominance hypothesis. It has also been observed that the $\bar{p}d\to\pi^-\pi^0p_s$ production rate depends on the spectator momentum, which suggests energy-sensitive $\bar{N}N$ phenomena near threshold.

A fraction of our $\bar{p}d$ film, obtained using the 30-in. Brookhaven National Laboratory deuterium bubble chamber exposed to a stopping antiproton beam, has been analyzed to study the reactions

$$\bar{p}d\to\pi^+\pi^-n_s, \quad (1)$$

$$\bar{p}d\to\pi^-\pi^0p_s. \quad (2)$$

One part of the film, containing 2.5×10^5 annihilations, has been double scanned for these reactions concurrently, using the following acceptance criteria: (a) events with a single negative track having a projected length >15 cm and a projected momentum >500 MeV/c in all three views (*one-prong*); (b) events with two tracks, the negative one satisfying the criteria as in (a) and the positive being a stopping proton (*two-prong*); (c) events with two tracks, both of them satisfying the criteria as in (a) and, in addition, having a projected opening angle >164° (*collinear*). These criteria have been chosen so that the efficiencies for detecting Reactions (1) and (2) are independent of the spectator momenta up to ~300 MeV/c, while they reduce substantially the measuring effort. In addition, another part of the film was scanned and measured for one- and two-prong events without the momentum cut. These events are included in the analysis and are also used to normalize the high-momentum spectra obtained with the criteria (a) and (b) to the total number of one- and two-prong events. Reactions (1) and (2) have been identified on the basis of the measured momenta as follows.

Reaction (1).—In Fig. 1(a) the invariant mass squared (M^2) of the collinear tracks assumed to be pions is displayed versus the missing momentum $p_m=|\vec{p}_+ +\vec{p}_-|$. The signal for Reaction (1), centered at high M^2 and low (spectator) missing momentum, is well separated. The background is negligible for $M^2>2.95$ GeV^2 [Fig. 1(b)] and these events (305) are considered to belong to Reaction (1).

The $\pi^\pm$ momentum distribution of the $\pi^+\pi^-n$ events is shown in Fig. 1(d) and is fitted well by a Gaussian. The center of the peak (919 MeV/c) is in good agreement with the expected position for Reaction (1) at rest. The width (±53 MeV/c) is the combination of the measurement error and the uncertainty introduced by the unseen neutron. This uncertainty is ±17 MeV/c for a spectatorlike distribution and consequently the width is essentially due to the measurement errors. The missing momentum of the $\pi^+\pi^-$ (neutron momentum) is shown in Fig. 1(c). It fits