

## Measurement of the Ratio of Sea to Valence Quarks in the Nucleon

J. G. Heinrich, C. E. Adolphsen,<sup>(a)</sup> J. P. Alexander,<sup>(b)</sup> K. J. Anderson, J. S. Conway,<sup>(c)</sup> J. E. Pilcher,  
and A. Possoz<sup>(d)</sup>

*Enrico Fermi Institute and Department of Physics, The University of Chicago, Chicago, Illinois 60637*

E. I. Rosenberg

*Ames Laboratory and Department of Physics, Iowa State University, Ames, Iowa 50011*

C. Biino,<sup>(e)</sup> J. F. Greenhalgh,<sup>(f)</sup> W. C. Louis,<sup>(g)</sup> K. T. McDonald, S. Palestini,<sup>(e)</sup> F. C. Shoemaker,  
and A. J. S. Smith

*Joseph Henry Laboratories, Department of Physics, Princeton University, Princeton, New Jersey 08544*

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The ratio of sea to valence quarks for nucleons in tungsten has been measured for the fractional momentum range  $0.04 < x_N < 0.36$ . The determination is based on the relative production rate of muon pairs by  $\pi^+$  and  $\pi^-$  beams on a tungsten target. The results provide the most accurate determination to date of this ratio in the region  $x_N < 0.1$  and  $Q^2 > 20 \text{ GeV}^2$ , and are in good agreement with earlier measurements.

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Lepton pair production by  $\pi^+$  and  $\pi^-$  beams on a nuclear target affords a direct measurement of the ratio of sea to valence quarks in the nucleon. The method stems from the interpretation that lepton pair production at high energies proceeds through quark-antiquark annihilation.<sup>1</sup> In a kinematic regime where only valence quarks contribute and with a pure isoscalar target, the production ratio is  $\frac{1}{4}$  (the square of the relative antiquark charge in the  $\pi^+$  and  $\pi^-$  beams). In a regime where sea quarks from the nucleon also contribute, the ratio departs from  $\frac{1}{4}$  because of the antiquarks in the nucleon sea. It is this difference from  $\frac{1}{4}$  which provides a measurement of the nucleon sea-to-valence ratio and the ratio can be studied as a function of  $x_N$ , the fraction of the nucleon momentum carried by the annihilating quark.

The data for this measurement were obtained at Fermilab using  $\pi^+$  and  $\pi^-$  beams at a momentum of 250 GeV/c incident on a tungsten target. Both beams were derived from 800-GeV/c protons. The negative-beam intensity was  $4 \times 10^9$  per 20-s spill while the positive inten-

sity was  $(6-7) \times 10^9$ . The positive beam contained a proton contamination of 46% but, as shown below, this fraction can be determined from the data and leads to only a small correction.

The apparatus is shown in Fig. 1 and is described in detail in Ref. 2. It was built around two large dipole magnets. Hadrons produced in the tungsten target just upstream of the first magnet ( $p_T$  kick  $\approx 3.2 \text{ GeV}/c$ ) were attenuated by a beryllium and a carbon absorber located in the magnet gap. High-mass muon pairs focused by this system traversed an analyzing spectrometer ( $p_T$  kick  $\approx 0.86 \text{ GeV}/c$ ) located downstream. The spectrometer contained 25 planes of proportional or drift chambers for particle tracking and 8 scintillator planes for triggering. The trigger selected muon pairs with an estimated mass above  $2.0 \text{ GeV}/c^2$ . In changing from a negative to a positive pion beam, the currents in the two magnets were reversed but the setup was the same in all other respects. The apparatus was designed to have a large acceptance for muon pairs with a high longitudinal-

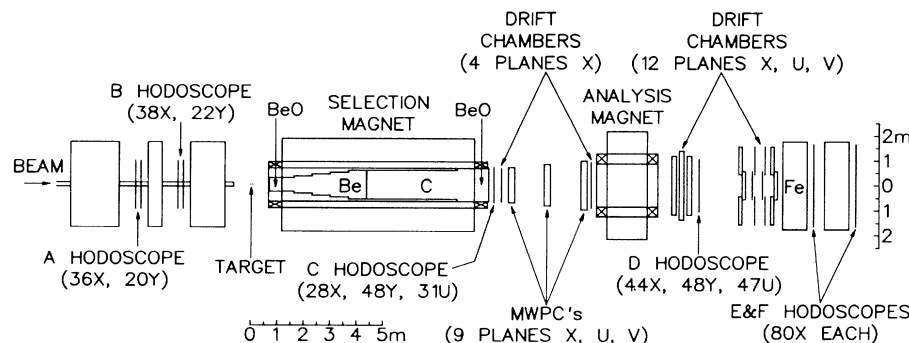


FIG. 1. Layout of the E615 apparatus.

momentum fraction ( $x_F$ ). Other results from this experiment are described in Ref. 3 and in references therein. The results reported here were based on  $\sim 5 \times 10^3$  and  $\sim 3 \times 10^4$   $\mu^+ \mu^-$  pairs with  $m_{\mu\mu} > 4.05$  GeV/ $c^2$  produced by the positive and negative beams, respectively.

An important monitor of both the beam and detector was provided by the large sample of  $J/\psi$  resonance decays which was collected together with the muon pairs in the continuum mass spectrum. A set of  $\sim 1.4 \times 10^6$   $J/\psi$  were obtained with the negative beam and  $\sim 4.8 \times 10^5$  with the positive one. These events were uniformly distributed in the two data samples and involved no special triggers or running conditions. The  $J/\psi$  data were used to determine the relative normalization of the positive and negative samples, the proton contamination of the positive beam, and any small shifts in the beam characteristics.

The cross-sectional ratios for  $J/\psi$  production by  $\pi^+$  relative to  $\pi^-$  and  $p$  relative to  $\pi^+$  have been well measured in the energy range of interest.<sup>4</sup> At 200 GeV the ratio  $\sigma(\pi^+)/\sigma(\pi^-)$  is unity to within 2% and  $\sigma(p)/\sigma(\pi^+)$  is a steep function of the longitudinal-momentum fraction  $x_F$ , decreasing to 5% at  $x_F$  of 0.7. Figure 2 shows the number of  $J/\psi$  events from the positive beam relative to that from the negative as a function of the longitudinal-momentum fraction  $x_F$ . The curve is the best fit based on the cross-sectional measurements of Ref. 4. It involves two parameters, the relative luminosity of the two samples and the proton fraction of the positive beam. The proton component in the positive case makes a negligible contribution at large  $x_F$  and the ratio in this region reflects the relative integrated pion luminosity of  $0.263 \pm 0.005$ . The rise in the curve at low  $x_F$  reflects the proton component of the positive beam. The data yield a value of  $45.5\% \pm 0.5\% \pm 4\%$ , relative to all hadrons. This is to be compared to the value of 42%

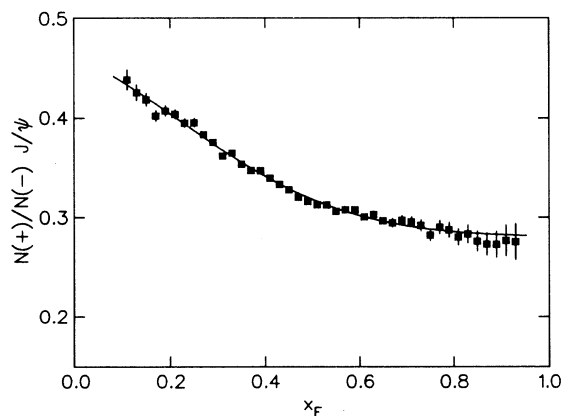


FIG. 2. Ratio of observed number of  $J/\psi$  events from positive-beam data relative to that from the negative beam. The curve is the results of the two-parameter fit described in the text.

$\pm 3\%$  interpolated from the measurements of Atherton *et al.* for 400-GeV/ $c$  protons.<sup>5</sup> The error on the latter figure represents the systematic uncertainty in the production angle of our positive beam. A careful study showed that the mean momentum of the positive beam was 0.4% lower than for the negative one. Small differences between beams of the two polarities may be expected. The production of the positive beam was more complicated since it was of the same polarity as the primary proton beam. The momentum spread of the beams was 10% FWHM.

Several selection criteria were applied to the continuum data. To unambiguously eliminate pairs produced by  $J/\psi$  and  $\Upsilon$  decays,  $m_{\mu\mu}$  was required to be between 4.05 and 8.55 GeV/ $c^2$ . The momentum fraction  $x_\pi$  of the annihilating quark or antiquark in the incident pion was required to be greater than 0.36 to insure no significant contribution from the pion sea. This requirement was based on measurements of the pion sea by Badier *et al.*<sup>6</sup> The above criteria constrained the range of  $x_N$  for the nucleon quark to the interval  $0.04 < x_N < 0.36$ .

The only detectable background in the data was associated with accidental coincidences between a muon in the beam and a soft muon from the experimental target. This source was easy to eliminate because it corresponded to apparent pairs with very asymmetric decay configurations in the  $\mu$ -pair rest frame. After requiring  $|\cos\theta^*| < 0.85$  for the  $\pi^-$  case and  $-0.75 < \cos\theta^* < 0.85$  in the  $\pi^+$  case, negligible background remained. The small difference in intervals was corrected by a Monte Carlo calculation. Here  $\cos\theta^*$  is the direction of the  $\mu^+$  in the  $t$ -channel reference frame.<sup>7</sup>

The ratio  $R = \sigma(\pi^+)/\sigma(\pi^-)$  was obtained from the data for intervals of  $x_N$ . This ratio was corrected for the proton contamination of the positive beam using the measured proton fraction and the proton structure function of Ref. 8. A Monte Carlo simulation was used to correct for minor differences associated with the pion beams. Since the geometry of the apparatus was unaltered in changing beam polarity and a comparison of the scintillator and wire-chamber efficiencies showed no differences, we conclude that the detection efficiency was the same in the two cases. Any difference in detector dead time was accounted for in the normalization, since the  $J/\psi$  samples were affected in the same way. Details of the analysis of the positive and negative data samples can be found in Ref. 3.

The form of the pion sea from Ref. 6 indicates that for  $x_\pi > 0.36$  the sea changes  $R$  by less than 3%. In this case the pion sea can be neglected and the cross-sectional ratio can be written as

$$R = \frac{(0.5 - \epsilon)V_p^u + (0.5 + \epsilon)V_p^d + 5S_p}{4(0.5 + \epsilon)V_p^u + 4(0.5 - \epsilon)V_p^d + 5S_p},$$

where  $\epsilon = Z/A - 1/2$  is the deviation of the target from isoscalar,  $V_p^u$  and  $V_p^d$  are the proton  $u$  and  $d$  valence-

quark  $x_N$  distributions, and

$$S_p = (0.5 + 0.6\epsilon)S_p^u + (0.5 - 0.6\epsilon)S_p^d$$

is the  $x_N$  distribution of the proton sea. In writing this expression for  $R$  we have used the relations that the sea-quark and -antiquark distributions are the same for each flavor and that the  $u$ - and  $d$ -quark distributions in the proton are the same as the  $d$ - and  $u$ -quark distributions in the neutron. We also use the fact that the valence quarks in the  $\pi^+$  and  $\pi^-$  beams are described by a single distribution. No strange-sea contribution appears because the pion contains no valence  $s$  quarks. The above expression for  $R$  can then be solved for the sea-to-valence ratio, and one obtains

$$\frac{S_p}{V_p^u + V_p^d} = \frac{2R - 0.5 + \epsilon(4R + 1)(V_p^u - V_p^d)/(V_p^u + V_p^d)}{5(1 - R)}$$

The term proportional to  $\epsilon$  is the isoscalar correction term. For the tungsten target used,  $\epsilon = -0.095$ . Given the measured values of  $R$ , the isoscalar correction term was evaluated using  $V_p^d/V_p^u \approx 0.571(1 - x_N)$ , which originates from neutrino scattering measurements on  $H_2$  and  $D_2$ .<sup>9</sup> Table I gives the measured values of  $R$  and the corresponding values for the sea-to-valence ratio.

We have investigated the extent to which quantum chromodynamic processes such as Compton-type quark-gluon scattering modify the assumption of electromagnetic annihilation used for the above analysis. The full first-order  $a_s$  cross-sectional expressions of Kubar *et al.*<sup>10</sup> were used together with the pion structure function of Conway *et al.*<sup>3</sup> and, for comparison, the two sets of nucleon-parton distributions from both Duke and Owens<sup>11</sup> and Eichten *et al.*<sup>12</sup> (EHLQ). We conclude the the Compton process slightly enhances the  $\pi^-$  cross section relative to the  $\pi^+$ , but that the effect is negligible in comparison to the experimental errors. For the Duke-Owens set 1 nucleon-parton distributions, the effect

TABLE I. Measured values of the  $\pi^+$ -to- $\pi^-$  cross-sectional ratio  $R$  and the inferred sea-to-valence ratio for nucleons in tungsten as a function of  $x_N$ .

$x_N$	$R$	Sea-to-valence ratio <sup>a</sup>
0.050	$0.620 \pm 0.029$	$0.338 \pm 0.054 \pm 0.037$
0.070	$0.575 \pm 0.021$	$0.259 \pm 0.031 \pm 0.025$
0.090	$0.533 \pm 0.022$	$0.202 \pm 0.027 \pm 0.020$
0.110	$0.504 \pm 0.025$	$0.167 \pm 0.027 \pm 0.018$
0.130	$0.453 \pm 0.031$	$0.115 \pm 0.028 \pm 0.013$
0.150	$0.432 \pm 0.039$	$0.096 \pm 0.032 \pm 0.011$
0.180	$0.382 \pm 0.036$	$0.057 \pm 0.025 \pm 0.009$
0.220	$0.355 \pm 0.049$	$0.038 \pm 0.031 \pm 0.007$
0.260	$0.279 \pm 0.067$	$-0.007 \pm 0.034 \pm 0.005$
0.300	$0.296 \pm 0.108$	$0.001 \pm 0.056 \pm 0.005$
0.340	$0.247 \pm 0.144$	$-0.025 \pm 0.065 \pm 0.004$

<sup>a</sup>The first error is statistical and the second is systematic.

amounts to a 4% increase in the sea-to-valence ratio in the lowest  $x_N$  interval. It becomes progressively smaller as  $x_N$  increases.

We have investigated the influence of various systematic effects. The systematic errors in Table I include a 15% uncertainty in the ratio  $V_p^d/V_p^u$ , a 20% uncertainty on the size of the proton subtraction in each bin, and a 2% uncertainty in the relative normalization of the positive- to negative-beam data. Except in the lowest two bins where the relative normalization dominates, the three sources are of about the same size. The systematic errors also include a component associated with quantum chromodynamic effects (only significant in the first two bins). Note that these systematic errors are small in comparison to the statistical ones. If no isoscalar correction is made ( $\epsilon = 0$ ), the sea-to-valence ratio moves upward by an amount less than or equal to the total errors.

Nuclear binding is known to affect quark distributions at the level of about 15% for the lowest  $x_N$  interval reported here.<sup>13</sup> This is less than the size of the errors for our present results. In addition, our results are for the ratio of two quark distributions and thus may be less sensitive to such effects. Further experiments would be needed, however, to substantiate this.

Figure 3 shows the sea-to-valence ratio measured by this experiment together with the ratio derived from Abramowicz *et al.*<sup>14</sup> [CERN-Dortmund-Heidelberg-Saclay (CDHS)] quark-distribution measurements ( $\nu$  and  $\bar{\nu}$  scattering on iron) in a comparable  $Q^2$  range. Curves from the quark-distribution parametrizations of

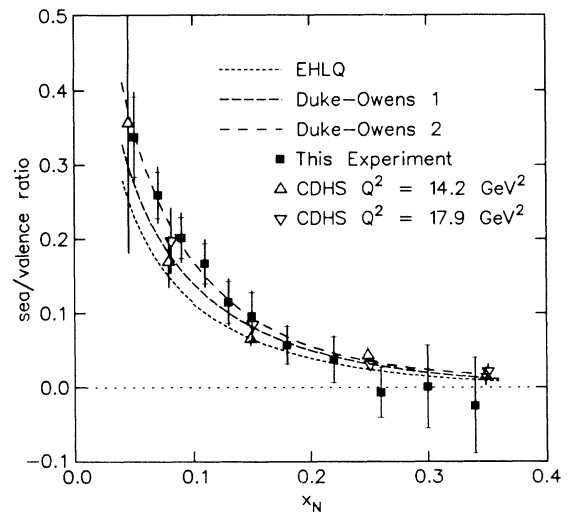


FIG. 3. The measured sea-to-valence ratio for  $0.04 < x_N < 0.36$ . The curves are predictions of the Duke-Owens (Ref. 11) and EHLQ (Ref. 12) quark-distribution parametrizations; the triangles are based on CDHS (Ref. 14) measurements of neutrino scattering on iron. The ticks on the error bars represent the statistical component alone and the total error bars represent statistical and systematic errors added in quadrature.

Duke and Owens<sup>11</sup> and EHLQ<sup>12</sup> are also shown. The results of this experiment favor the second Duke-Owens parametrization but other data are also important in constraining the parametrization. If one parametrizes the sea-to-valence ratio alone, the form  $(1-x_N)^a x_N^{-0.5}$  is in accord with commonly used functions for the sea and valence distributions. A  $\chi^2$  minimization gives  $0.120(1-x_N)^{7.5} x_N^{-0.5}$  with a  $\chi^2$  of 2 for 9 degrees of freedom.

The sea-to-valence ratio is expected to have a dependence on the  $m_{\mu\mu}^2$  range of the measurement. The mean  $m_{\mu\mu}^2$  associated with this measurement is a linear function of  $x_N$ :  $\langle m_{\mu\mu}^2 \rangle = 11.1 + 164.0 x_N \text{ GeV}^2/c^4$ . It should be noted that the sea-to-valence ratio is less sensitive to  $m_{\mu\mu}^2$  than the individual sea and valence distributions, since the sea and valence distributions evolve similarly as  $m_{\mu\mu}^2$  increases. According to the EHLQ parametrization, the increase in the ratio at a given value of  $x_N$  is expected to be about 8% as  $m_{\mu\mu}^2$  varies from 20 to 70  $\text{GeV}^2/c^4$ , the approximate range of these data.

A knowledge of the quark-distribution functions of the hadrons is essential for predicting cross sections for their scattering. The low- $x_N$ , high- $Q^2$  range in the nucleon structure function is of current interest in calculating cross sections at future multi-TeV hadron colliders. These results provide an improved measurement of the sea-to-valence quark ratio at low  $x_N$ . In addition, we have elucidated a new technique for measuring this ratio.

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<sup>(a)</sup>Present address: University of California at Santa Cruz, Santa Cruz, CA 95064.

<sup>(b)</sup>Present address: Cornell University, Ithaca, NY 14853.

<sup>(c)</sup>Present address: CERN, CH-1211 Geneva 23, Switzerland.

<sup>(d)</sup>Present address: Ecole Polytechnique Federal Lausanne, CH-1006 Lausanne, Switzerland.

<sup>(e)</sup>Present address: Istituto Nazionale di Fisica Nucleare, Sezione di Torino, Torino, Italy.

<sup>(f)</sup>Present address: Fonar Corp., Melville, NY 11747.

<sup>(g)</sup>Present address: Los Alamos National Laboratory, Los Alamos, NM 87545.

<sup>1</sup>G. Hogan *et al.*, Phys. Rev. Lett. **42**, 948 (1979); J. Badier *et al.*, Phys. Lett. **89B**, 145 (1979); B. Betev *et al.*, Z. Phys. C **28**, 9 (1985).

<sup>2</sup>C. Biino *et al.*, Nucl. Instrum. Methods Phys. Res., Sect. A **243**, 323 (1986).

<sup>3</sup>J. S. Conway *et al.*, Phys. Rev. D **39**, 92 (1989); J. S. Conway, Ph.D. dissertation, University of Chicago, 1987 (unpublished); J. G. Heinrich, Ph.D. dissertation, University of Chicago, 1988 (unpublished).

<sup>4</sup>J. Badier *et al.*, Z. Phys. C **20**, 101 (1983).

<sup>5</sup>H. W. Atherton *et al.*, CERN Report No. 80-70, 1980 (unpublished).

<sup>6</sup>J. Badier *et al.*, Z. Phys. C **18**, 281 (1983).

<sup>7</sup>The  $t$  channel is defined to be the  $\mu^+\mu^-$  pair rest frame with  $\theta^* = 0$  given by the beam direction.

<sup>8</sup>J. Badier *et al.*, Z. Phys. C **26**, 489 (1985).

<sup>9</sup>F. Eisele, Rep. Prog. Phys. **49**, 233 (1986).

<sup>10</sup>J. Kubar, M. Le Bellac, J. L. Meunier, and G. Plaut, Nucl. Phys. **B175**, 251 (1980).

<sup>11</sup>D. W. Duke and J. F. Owens, Phys. Rev. D **30**, 49 (1984).

<sup>12</sup>E. Eichten, I. Hinchliffe, K. Lane, and C. Quigg, Rev. Mod. Phys. **56**, 579 (1984).

<sup>13</sup>J. Ashman *et al.*, Phys. Lett. B **202**, 603 (1988).

<sup>14</sup>H. Abramowicz *et al.*, Z. Phys. C **17**, 283 (1983).