Measurement of the Strange Sea Distribution Using Neutrino Charm Production

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A high-statistics study by the Columbia-Chicago-Fermilab-Rochester Collaboration of opposite-sign dimuon events induced by neutrino-nucleon scattering at the Fermilab Tevatron is presented. A sample of 5044 ν_μ and 1062 $\bar{\nu}_\mu$ induced $\mu^\mp\mu^\pm$ events with $P_{\mu_1} \geq 9$ GeV/c, $P_{\mu_2} \geq 5$ GeV/c, $30 \leq E_\nu \leq 600$ GeV, and $\langle Q^2 \rangle = 22.2$ GeV$^2/c^2$ is observed. The data support the slow-rescaling model of charm production with a value of $m_c = 1.31 \pm 0.24$ GeV/c^2. The first measurement of the Q^2 dependence of the nucleon strange quark distribution $xs(x)$ is presented. The data yield the Cabibbo-Kobayashi-Maskawa matrix element $|V_{cd}| = 0.209 \pm 0.012$ and the nucleon fractional strangeness content $\eta_s = 0.064^{+0.008}_{-0.007}$.

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Charged-current neutrino-nucleon scattering produces a single muon at the leptonic vertex and changes the flavor of the initial quark at the hadronic vertex. Neutrino interaction with a strange or down quark may produce a charm quark, which fragments into a charmed hadron. The semileptonic decay produces a second muon, of opposite sign from the muon at the leptonic vertex. This distinctive opposite-sign dimuon signature serves as a unique and highly sensitive probe of charm particle production dynamics and the strange sea content of the nucleon. The strange quark sea distribution, presented here for the first time, is of particular interest in the exploration of higher-order corrections to nucleon structure [1], while the threshold behavior associated with the heavy charm mass is critical to the extraction of the weak mixing angle, $\sin^2\theta_W$, from the ratio of neutral-current to charged-current ν-N cross sections.

It is useful to define the kinematic variables $y = E_{\text{had}}/E_\nu$, $Q^2 = 4E_\nu E_{\mu_1}\sin^2(\theta_{\mu_1}/2)$, $x = Q^2/2ME_\nu y$, and $W^2 = M^2 + 2M(E_\nu - E_{\mu_1}) + Q^2$, where M is the nucleon mass, E_{had} is the energy of the hadronic system, E_ν is the neutrino energy, and E_{μ_1} and θ_{μ_1} are the energy and angle of the leading muon, respectively. E_{μ_2} similarly indicates the energy of the second muon. In practice, the following reconstructed variables are used:

$$E_{\text{vis}} = E_{\mu_1} + E_{\mu_2} + E_{\text{had}} ,$$

$$Q^2_{\text{vis}} = 4E_{\text{vis}}E_{\mu_1}\sin^2(\theta_{\mu_1}/2) ,$$

$$x_{\text{vis}} = Q^2_{\text{vis}}/2M(E_{\text{had}} + E_{\mu_2}) ,$$

and

$$W^2_{\text{vis}} = M^2 + 2M(E_{\text{vis}} - E_{\mu_1}) + Q^2_{\text{vis}} .$$

The mass of the charm quark, m_c, is expected to introduce a threshold energy suppression into the dimuon production rate. This effect is parametrized in the slow-rescaling model [2], wherein ξ, the momentum fraction carried by the struck quark, is related to the kinematic variable x by the expression $\xi = x(1 + m_c^2/Q^2)$. Representing the fractional momentum distribution of the strange and down quarks within the nucleon as $\xi s(\xi)$ and $\xi d(\xi)$ the cross section for neutrino production of dimuons on an isoscalar target may be written

$$\frac{d^2\sigma(\nu N \to \mu^-\mu^+ X)}{d\xi\, dy} = \frac{G^2 M E_\nu}{\pi}\{[\xi u(\xi) + \xi d(\xi)]|V_{cd}|^2 + 2\xi s(\xi)|V_{cs}|^2\}\left[1 - \frac{m_c^2}{2ME_\nu\xi}\right] D(z) B_c , \tag{1}$$

where the function $D(z)$, defined below, describes the fragmentation of a charm quark into a charmed hadron and B_c is the semileptonic branching ratio for charmed hadron decay. The analogous equation for antineutrinos is found by substituting $u(\xi)\to\bar{u}(\xi)$, $d(\xi)\to\bar{d}(\xi)$, and $s(\xi)\to\bar{s}(\xi)$.

This analysis combines data taken during two experiments, E744 and E770, which ran in 1985 and 1988, by the Columbia-Chicago-Fermilab-Rochester (CCFR) Collaboration at the Fermilab Tevatron using the quadrupole triplet neutrino beam [3]. The detector [4] combines a 690-ton steel/scintillator calorimeter target with a 420-ton toroidal magnetic spectrometer, with drift chambers for muon tracking.

Previously published results from E744 alone [5] described data for $30\le E_\nu\le 600$ GeV with $P_\mu\ge 9$ GeV/c and $\theta_\mu\le 250$ mrad for both muon tracks. By combining the E744 and E770 samples, requiring $E_{\rm had}\ge 10$ GeV, and lowering the cut on P_{μ_2} (the momentum of the second muon) to 5 GeV/c for $E_{\rm had}\le 130$ GeV a sample of 5044 ν_μ and 1062 $\bar{\nu}_\mu$ induced $\mu^\mp\mu^\pm$ events are observed, yielding more than a threefold increase in the event sample.

The dimuon events are divided into those from incident ν_μ or $\bar{\nu}_\mu$ by assuming that the leading muon has larger transverse momentum with respect to the direction of the hadron shower than the muon from charm decay. Monte Carlo studies, described below, indicate that this identification procedure introduces a 1.1% (32%) contamination in the ν_μ ($\bar{\nu}_\mu$) sample.

Muonic decays of nonprompt π and K mesons in the hadron shower of the charged-current events constitute the primary source of dimuon background. Hadronic test beam muon production data and Monte Carlo simulations predict a π/K decay background of 796.5 ± 11.5 ν_μ and 118.0 ± 2.1 $\bar{\nu}_\mu$ events [6].

Single-muon and dimuon events were simulated using Monte Carlo techniques. Quark and antiquark momentum densities were obtained from the CCFR structure functions [7] using a modified Buras-Gaemers parametrization [8]. The strange quark x dependence is parametrized as $xs(x)\propto(1-x)^\beta$, and it and the nonstrange sea distributions evolve together in Q^2, with the strange quark magnitude set by the parameter $\kappa=2S/(\bar{U}+\bar{D})$ [where $S=\int_0^1 xs(x)dx$, etc.]. The normalization of the dimuon Monte Carlo program is set by the ratio of charged-current single-muon events observed to those generated in the Monte Carlo simulation.

The parameters m_c, β, κ, and B_c are obtained from a multiparameter χ^2 minimization by comparing the data and Monte Carlo events binned in five $E_{\rm vis}$ and ten $x_{\rm vis}$ bins.

The largest source of systematic uncertainty is the charm quark fragmentation, which is modeled using the Peterson function [9] $D(z)\propto\{z[1-1/z-\epsilon/(1-z)]^2\}^{-1}$, where $z=P_D/P_c$ is the ratio of the charmed meson and quark momenta. The Monte Carlo distribution is fitted to the data for various fixed values of the adjustable Peterson parameter ϵ, and a study of the distribution of $z_{\rm vis}=E_{\mu_2}/(E_{\mu_2}+E_{\rm had})$ results in a measurement of $\epsilon=0.22\pm 0.05$. We combine this value with the E531 neutrino emulsion result [10] (analyzed for $W^2>30$ GeV^2) of $\epsilon=0.18\pm 0.06$ to yield a neutrino average $\epsilon=0.20\pm 0.04$. (This value is consistent with that from the ARGUS [11] and CLEO [12] e^+e^- experiments, which find $\epsilon=0.19\pm 0.03$ and 0.156 ± 0.015, respectively.) The uncertainty in ϵ is included directly in the fitting procedure through an additional term in the overall χ^2.

Other systematic errors are estimated by varying the fit parameters within their uncertainties. These include π/K decay background, the relative E_μ and $E_{\rm had}$ energy scale, dimuon data selection, $R_{\rm long}=\sigma_L/\sigma_T$, and the d/u quark ratio [13]. Assuming the Particle Data Group values [14] of $|V_{cd}|^2=0.0484\pm 0.0013$ and $|V_{cs}|^2=0.9494\pm 0.0016$, the multiparameter fit to the data, which have mean Q^2 of $\langle Q^2\rangle=22.2$ GeV$^2/c^2$, yields

$$\begin{aligned} &m_c=1.31^{+0.20+0.12}_{-0.22-0.11}\ \mathrm{GeV}/c^2,\\ &\kappa=0.373^{+0.048}_{-0.041}\pm 0.018\,, \qquad (2)\\ &\beta=9.45^{+0.60+0.36}_{-0.55-0.25},\quad B_c=0.105\pm 0.007\pm 0.005\,, \end{aligned}$$

where the first error is statistical and the second is systematic. The χ^2 of 42.5 for 46 degrees of freedom suggests excellent agreement between the data and Monte Carlo simulation.

The difference between the strange sea exponent $\beta=9.45$ and that of the total sea $\alpha=6.95\pm 0.19^{+0.23}_{-0.29}$ at $Q^2=22.2$ GeV$^2/c^2$, where $x\bar{q}(x)\propto(1-x)^\alpha$, provides a quantitative indication that the strange sea is softer than the $\bar{u}$ and $\bar{d}$ sea.

The value of κ in (2) is lower than previous CCFR results [5,15] as well as values reported by the CERN-Dortmund-Heidelberg-Saclay [16] and Fermilab-MIT-Michigan-Florida [17] Collaborations. This is due to a larger value of the nonstrange sea from the latest measured CCFR structure functions [7]. Defining the strange sea content of the nucleon as $\eta_s=2S/(U+D)$, the measured value of κ and $\bar{Q}/Q=0.198$ [7] at $Q^2=22.2$ GeV$^2/c^2$ combine to yield

$$\eta_s=0.064^{+0.008}_{-0.007}\pm 0.002\,.$$

This result is consistent with η_s from the previous publications.

In order to investigate the possible Q^2 variation of κ, the data are divided into three $E_{\rm vis}$ bins (30–150, 150–250, and 250–600 GeV). Fits to these samples with m_c, β, and B_c fixed to the values in Eq. (2) yield $\kappa=0.374\pm 0.019$, 0.375 ± 0.018, and 0.369 ± 0.023 for $\langle Q^2\rangle$ of 13.6, 23.7, and 31.1 GeV$^2/c^2$, respectively. (Two-parameter fits that vary κ and β and three-parameter fits that vary κ, β, and B_c are consistent with a constant κ but with larger errors.) This demonstrates that κ is independent of E_ν over a wide range of energies.

The ratio of dimuon to single-muon production provides a direct test of the slow-rescaling hypothesis. The

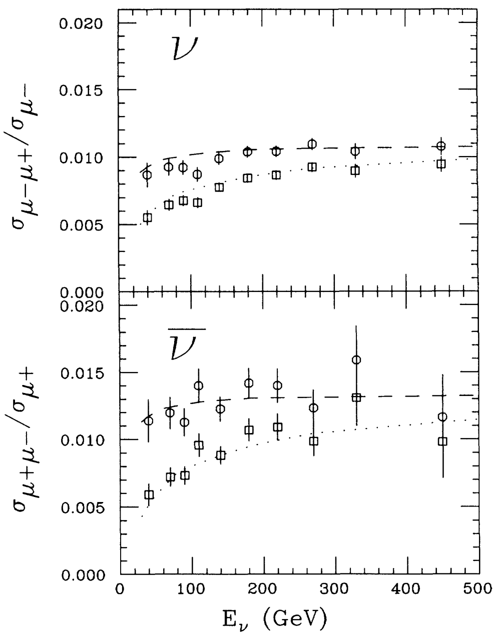

FIG. 1. Opposite-sign dimuon rates vs E_ν for ν_μ (top) and $\bar{\nu}_\mu$ (bottom) data. Rates corrected for acceptance, smearing, and kinematic cuts are indicated by squares. Those corrected for slow rescaling with $m_c=1.31$ GeV/c^2 are given by circles. The curves indicate the slow-rescaling model prediction with $m_c=1.31$ GeV/c^2 before (dotted) and after (dashed) correcting for the finite charm mass.

acceptance-corrected rates exhibit an energy dependence characteristic of heavy charm quark production. Once corrected for this threshold with $m_c=1.31$ GeV/c^2 the rates become less dependent on E_ν, exhibiting only the sharp, low energy threshold behavior associated with the production of heavy charmed mesons $[W^2>(m_D+M)^2]$. This strongly supports the validity of the slow-rescaling model for charm production in neutrino interactions, consistent with a charm mass of 1.31 GeV/c^2 (Fig. 1).

The strange quark momentum distribution $xs(x)$ is found from the observed dimuon event distributions assuming the leading-order formalism described above. The observed data are corrected for acceptance, missing energy associated with the decay neutrino, neutrino-antineutrino misidentification, and charm mass effects. The predicted down quark contribution to the dimuon sample is subtracted, resulting in an event sample due exclusively to the nucleon strange sea. The combined neutrino and antineutrino results for $xs(x)$ are displayed in Table I. Figure 2 shows the Q^2 variations in $xs(x)$ for each value of x (the lines are power-law fits to the data). While the scaling violations of the strange quark sea distribution function are similar to those seen for the nonstrange sea quarks [7], the quantitative behavior is not well understood and may be due to higher-order processes [1] or nonperturbative effects.

If the Cabibbo-Kobayashi-Maskawa (CKM) matrix elements are not assumed then the results of the fits in (2) can be rewritten in terms of the product

$$|V_{cd}|^2 B_c=(5.09\pm 0.32^{+0.17}_{-0.16})\times 10^{-3}.$$

Substitution of the neutrino world average charm branching ratio [15] $B_c=0.116\pm 0.010$ yields

$$|V_{cd}|=0.209\pm 0.011\pm 0.004.$$

In summary, the dimuon data support the slow-rescaling hypothesis for a value of $m_c=1.31\pm 0.24$ GeV/c^2. The charm mass error constitutes the single largest source of theoretical uncertainty in precision measurements of the weak mixing angle from the ratio of ν induced neutral-current to charged-current cross sections. This new result will reduce this uncertainty in $\sin^2\theta_W$ significantly, from 0.0034 to 0.0024. The CKM matrix element is found to be $|V_{cd}|=0.209\pm 0.012$. The nucleon strangeness content is measured to be $\eta_s=0.064^{+0.008}_{-0.007}$ and the strange sea is found to be softer than its nonstrange counterpart. These data indicate that the fractional strange quark content of the nucleon with respect to the nonstrange sea is constant over a range of Q^2. Scaling violations of the strange quark sea distribution function may indicate contributions from higher-

TABLE I. Strange quark sea distribution function $xs(x)$ and associated $\langle Q^2\rangle$ values, in units of GeV^2/c^2, for several x bins (x and $\langle Q^2\rangle$ have been corrected for acceptance, missing energy, etc., as mentioned in the text). Errors are statistical. An additional $^{+14\%}_{-12\%}$ scale error arises due to the uncertainty in κ.

	$30<E_{\rm vis}<600$ GeV		$30<E_{\rm vis}<150$ GeV		$150<E_{\rm vis}<250$ GeV		$250<E_{\rm vis}<600$ GeV	
x	$\langle Q^2\rangle$	$xs(x)$	$\langle Q^2\rangle$	$xs(x)$	$\langle Q^2\rangle$	$xs(x)$	$\langle Q^2\rangle$	$xs(x)$
0.015	2.4	0.0912 ± 0.0052	1.7	0.0875 ± 0.0099	3.3	0.1023 ± 0.0090	4.8	0.0966 ± 0.0097
0.045	6.8	0.0694 ± 0.0039	4.3	0.0784 ± 0.0074	9.6	0.0785 ± 0.0069	14.3	0.0598 ± 0.0067
0.080	11.9	0.0499 ± 0.0028	7.8	0.0541 ± 0.0052	17.0	0.0518 ± 0.0046	24.2	0.0484 ± 0.0052
0.125	17.9	0.0321 ± 0.0022	11.9	0.0319 ± 0.0039	26.6	0.0401 ± 0.0039	36.6	0.0232 ± 0.0037
0.175	24.4	0.0185 ± 0.0019	16.9	0.0231 ± 0.0035	36.2	0.0181 ± 0.0030	50.8	0.0132 ± 0.0032
0.225	30.2	0.0130 ± 0.0017	21.3	0.0147 ± 0.0033	45.6	0.0133 ± 0.0027	63.4	0.0090 ± 0.0026
0.275	36.0	0.0096 ± 0.0015	25.6	0.0117 ± 0.0029	57.1	0.0061 ± 0.0021	71.5	0.0093 ± 0.0025
0.350	43.9	0.0016 ± 0.0008	32.7	0.0007 ± 0.0014	66.7	0.0023 ± 0.0012	81.5	0.0012 ± 0.0010

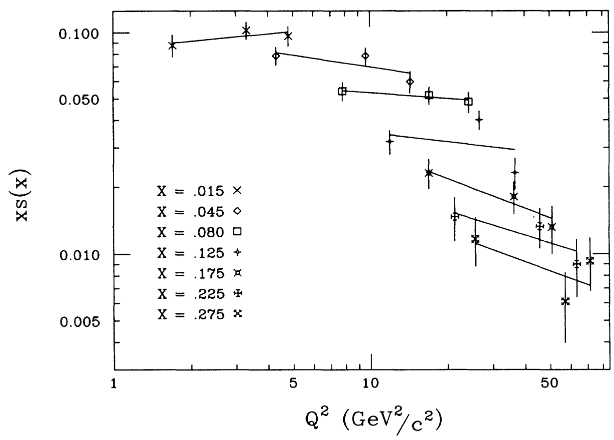

FIG. 2. Strange quark sea distribution function $xs(x)$ vs Q^2 for several values of x. The lines are power-law fits to the data. Errors are statistical. An additional $^{+14\%}_{-12\%}$ scale error arises due to the uncertainty in κ.

order processes or nonperturbative effects. This measurement of the Q^2 dependence of the strange sea distribution $xs(x)$ may be used to test perturbative-evolution predictions and evaluate flavor asymmetry in the quark sea of the nucleon.

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