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Evidence for New Quarks and New Currents*

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The quark-parton model is used to study neutrino scattering in the case where the mass of a heavy, produced quark is not neglected. Evidence for right-handed currents is found in the charged-current neutrino scattering data. The masses of produced heavy quarks are estimated.

There have been hints in the data of the Harvard University–University of Pennsylvania–University of Wisconsin–Fermilab (HPWF) and the California Institute of Technology–Fermilab (CT-F) collaborations[1-9] of new phenomena in charged-current neutrino scattering. By not neglecting the mass[10] of a heavy produced quark in the quark-parton model, it is possible to show that the $\bar{\nu}$ data contain substantial evidence of a quark d' of mass 4–5 GeV/c^2 with a right-handed coupling to u quarks. If there is a quark u' with a right-handed coupling to d quarks, its mass is greater than or equal to 3 GeV/c^2. The d' and u' quarks have charges $-\frac{1}{3}$ and $+\frac{2}{3}$, respectively.

Crucial to understanding the energy dependence of the $\bar{\nu}$ cross sections and of their anomalous y dependence is the manner in which scaling is reassumed after passing quark mass thresholds. The results described here correspond to a slow rescaling and are drastically different from previous work which assumed a fast rescaling.[11,12] Only with this slow rescaling is good agreement obtained with all available data.

In the quark-parton model, it is assumed that the structure functions $F(z)$ are functions only of the scaling variable z. z is defined as the fraction of the target nucleon's momentum which is carried by the struck quark. It is further assumed that the quarks are quasifree so that the produced quark is on mass-shell. If the exchanged W boson has momentum k, the struck quark has momentum zp, and the produced mass is neglected, then one finds

$$(k+zp)^2 \approx m_q^2 \approx 0 \rightarrow z \approx -k^2/2p\cdot k \equiv x. \tag{1}$$

The quantity x can be measured experimentally, so that in this case z is known.

However, for heavy, produced quarks ($m_q \gg 0.3$ GeV/c^2), it is not reasonable to neglect their mass and then z cannot be directly measured. Rather, when m_q is kept, it follows from Eq. (1) that

$$z \approx x\left(\frac{-k^2+m_q^2}{-k^2}\right) = x + \frac{m_q^2}{2MEy}, \tag{2}$$

where $y \equiv (E-E')/E$, E (E') is the incoming (outgoing) lepton energy, and M is the nucleon mass. Then calculating the cross section and observing that the Callan-Gross relation[13] must be written in terms of z not x, one obtains

$$\frac{d^2\sigma}{dx\,dy} = \frac{G^2ME}{\pi}\left\{1 - y + \frac{x}{z}\left[\frac{y^2}{2} \pm \left(y - \frac{y^2}{2}\right)\right]\right\} F_2(z)\theta(1-z), \tag{3}$$

where + (−) corresponds to ν ($\bar{\nu}$) scattering off quarks for left-handed currents and the opposite for right-handed currents. A very similar result is obtained by Georgi and Politzer[10] in an operator-product expansion calculation in an asymptotically free color gauge theory.

In the limits $m_q \to 0$ or $E \to \infty$, one finds $z \to x$ and Eq. (3) becomes the standard result:

$$\frac{d^2\sigma}{dx\,dy} = \frac{G^2ME}{\pi}\begin{Bmatrix} 1 \\ (1-y)^2 \end{Bmatrix} F_2(x). \tag{4}$$

Notice that "fast rescaling" means using Eq. (4) with heavy-quark terms multiplied by $\theta(1-z)$.

The results to be described are very insensitive to the parametrization of $F_2(z)$ for valence or sea contributions [for $F_2(z)$ consistent with the data]. The amount of sea, however, is very important in the standard four-quark model, though not in other models. The parametrization used was "solution 3" from Ref. 12 (with 6% sea) except for the standard model for which a parametrization with 11% sea was used.

A variety of models[14-17] were considered, and three models of the weak gauge group SU(2)⊗U(1) are discussed here. The standard four-quark model[14] has the weak charged couplings $(u,d)_L$ and $(c,s)_L$. The new model of Ref. 15 (the CHHP model) has those couplings plus others of which the important ones are $(u',d)_R$ and $(u,d')_R$, where primes denote heavy quarks and R denotes right-handed currents. The model of Ref. 16 (the HYM model) has the $(u,d')_R$ coupling but no $(u',d)_R$ coupling. The usual Cabibbo angle was always included.

HPWF has reported[2] an anomalous behavior of $d\sigma/dy$ for $\bar{\nu}$ scattering at small x. In the standard, CHHP, and HYM models, Eqs. (2) and (3) lead to such an effect. The anomalous behavior is simply the result of adding the right-handed contribution with constant (1) y dependence (asymptotically) to the original $(1-y)^2$ term. This effect is concentrated at small x for two reasons: (1) Part of the original and of the new contributions is produced off antiquarks in the sea, and (2) Eq. (3) gives a sharper x distribution for heavy-quark production. The CHHP and HYM models predict $\langle x\rangle_{\bar{\nu}}$ for dimuons larger than observed; however, only four events have been observed in $\bar{\nu}$ runs along with twelve events in ν runs which may have been due to $\bar{\nu}$ contamination.

The anomalous y dependence is more dramatic when the average value of y is shown as a function of energy.[9] This is done in Fig. 1, where the difference between the quark-parton model (with produced-quark mass not neglected) and the fast-rescaling assumption[11,12] is clearly quite large.

Figure 1 shows that the standard model does not account for the rapid change of $\langle y\rangle$ with energy. However, the CHHP and HYM models do account for this change. It is the right-handed coupling $(u,d')_R$ which is responsible for this change. The mass of d' from this and other fits is $m(d') = 4$ to 5 GeV/c^2. For the CHHP and HYM models, this result and those below are relatively insensitive to the amount of sea.

It has been assumed in the past that the ratio, R_c, of $\bar{\nu}$ to ν cross sections would rise quickly to 1.0 if $(u',d)_R$ and $(u,d')_R$ couplings were present. Such a fast rise is shown for fast rescaling in Fig. 2. However, Eqs. (2) and (3) lead to a much

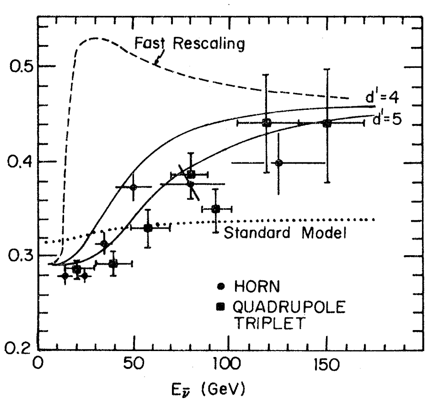

FIG. 1. The average value of y versus E in $\bar{\nu}N \to \mu^+X$. The curves show the results for (a) the standard model, (b) the CHHP model (same results for HYM model) with $m(d') = 4$ and 5 GeV/c^2, and (c) fast rescaling with $m(d') = 4.5$ GeV/c^2. The data are from Ref. 9.

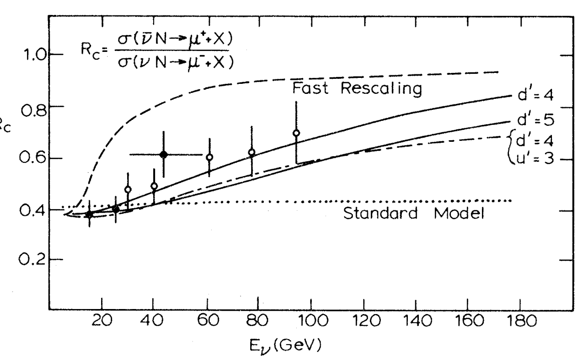

FIG. 2. The ratio R_c of $\bar{\nu}$ to ν scattering for $\nu N \to \mu X$ as a function of neutrino energy. The curves are the results for (a) the standard model, (b) the CHHP model with $m(u') = 3$ GeV/c^2 and $m(d') = 4$ GeV/c^2, (c) the HYM model with $m(d') = 4$ and 5 GeV/c^2 (solid curves), and (d) fast rescaling with $m(d') = 4.5$ GeV/c^2. These data are from Ref. 2.

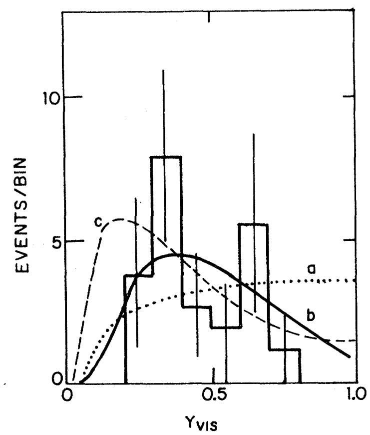

FIG. 3. The cross section $d\sigma/dy$ versus $y_{vis} \approx y$ for $\nu N \to \mu^- \mu^+ X$. The curves are the results for (a) the standard model, (b) the CHHP model with $m(u') = 3$ GeV/c^2, and (c) fast rescaling for $m(u') = 3$ GeV/c^2. The data are from Ref. 5.

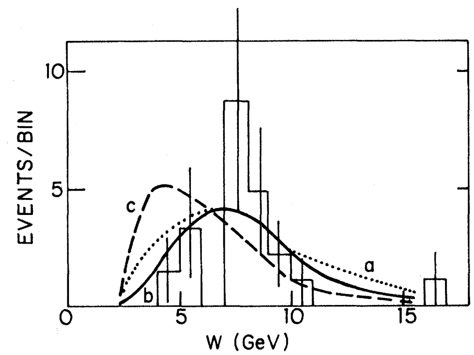

FIG. 4. The cross section versus W_{min} for $\nu N \to \mu^- \mu^+ + X$. The curves are the results for (a) the standard model, (b) the CHHP model with $m(u') = 3$ GeV/c^2, and (c) fast rescaling with $m(u') = 3$ GeV/c^2. The data are from Ref. 5.

slower rise. The HYM model and the CHHP model with $m(u') \gtrsim 3$ GeV/c^2 are consistent with the data, while the standard model gives a poor fit.

The standard model can fit the experimental dimuon rate[3,5,6] for ν and $\bar{\nu}$ scattering (with reasonable branching ratios of charmed particles to muons) if it is assumed (1) that the mass of the c quark is at most 1.5 GeV/c^2, (2) that the sea is at least 11% of valence, and (3) that there are as many s quarks in the sea as $\bar{u}$ quarks. The CHHP and HYM models fit the dimuon rate even if those assumptions are relaxed.

Most of the dimuon distributions[5,6] do not distinquish between various models, in part because of large error bars. However, $d\sigma/dy$ for neutrinos, shown in Fig. 3, will, when more data are available, allow an estimation of the u' mass [since the coupling $(u', d)_R$ is relevant here].

The dimuon distribution[5,6] for the total invariant mass W recoiling against the μ^- (in ν scattering) does not discriminate between various models. This is because it primarily reflects the energy spectrum of the incoming neutrinos. However, Eqs. (2) and (3) lead to results consistent with the data (see Fig. 4) whereas the fast-rescaling assumption gives different results.

A more detailed analysis of charged-current neutrino scattering in these and other models will be presented elsewhere.[18]

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Time-Dependent Hartree-Fock Calculation of the Reaction $^{16}O + ^{16}O$ in Three Dimensions

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We have solved the time-dependent Hartree-Fock equations in three dimensions for the heavy-ion reaction $^{16}O+^{16}O$ at energies $E_{lab}/A_{proj}=8$, 16, and 24 MeV and impact parameters $b=0$, 2, 4, 6, and 8 fm. The potential used is a simplified form of the Skyrme interaction. An angular-momentum window for complete fusion is predicted. A multifluid flow pattern similar to that of atomic physics is observed and seems to cast doubts on the validity of the simplified axiality and rigid clutching assumptions currently made.

The time-dependent Hartree-Fock (TDHF) formalism[1] has been found to yield encouraging results in the calculation of head-on (two-dimensional) collisions of nuclear heavy ions such as $^{12}C+^{12}C$[2] and $^{16}O+^{16}O$.[3] Much more interesting results on reaction cross sections require, however, that the ions collide with a finite impact parameter in the semiclassical context implied by the single-Slater-determinant nature of the TDHF prescription. One must therefore do a complete three-dimensional calculation or make simplifying assumptions[4] concerning the behavior of the collision in a rotating frame. It is important to check these assumptions by doing the more complete calculation. We have therefore solved the TDHF equations discussed below, on a three-dimensional grid consisting of $16\times 24\times 24$ points with a spacing of 1 fm, for the reaction $^{16}O+^{16}O$, at various energies and impact parameters given in Table I. We first describe briefly the combined techniques of fast Fourier transform and predictor-corrector method used to solve the Schrödinger equation. We then discuss our results and finally we point out their implication for heavy-ion calculations and for the search of a rotating-frame simplified model.

The TDHF model assumes that the time-dependent wave function of the colliding ions is given by a single Slater determinant whose occupied single-particle orbits $\psi_\lambda(\vec{r},t)$ obey the TDHF single-particle Schrödinger equation

$$i\hbar\frac{\partial\psi_\lambda(\vec{r},t)}{\partial t}=h\psi_\lambda(\vec{r},t),\quad \lambda=1,\ldots,A_1+A_2, \quad (1)$$

where A_1 and A_2 are the number of particles in each ion and h is the single-particle Hamiltonian which we have taken for simplicity as

$$h=\hbar^2k^2/2m-a\rho(r)+b\rho^2(r), \quad (2)$$

with $a=+817.5$ MeV fm^3 and $b=3241.5$ MeV fm^6. These two parameters correspond to a simplified version of the Skyrme interaction,[1,3] while the first term is the free kinetic energy operator. We assume $Z=N$ and spin saturation so that each space wave function applies to four nucleons; thus

$$\rho(r,t)=4\sum_{\lambda=1}^{N_1+N_2}|\psi_\lambda(r,t)|^2. \quad (3)$$

Whereas the potential energy part of h in Eq. (2) is bounded, the kinetic energy is not. The kinetic energy can be removed from the Schrödinger