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From recent developments in the area of nuclear parity nonconservation we extract evidence for (1) SU(3)/soft-pion breaking in weak pionic vertices, and (2) larger values of quark masses than have been used in previous evaluations of "penguin" matrix elements.

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Nuclear parity nonconservation has long been of interest in that it provides a unique probe of the strangeness-conserving nonleptonic weak interactions. During the early part of the last decade, there was much interest in this subject, as it was believed that such experiments would provide information about the fundamental structure of the weak interaction, specifically concerning the existence and composition of weak neutral currents.¹ However, computational difficulties associated with nuclear structure and inability to handle the complexities of the strong interactions soon changed this early optimism to pessimism—and even skepticism.

Only recently has the gloom begun to lift. Careful experimental work has produced a number of solid results on nuclei whose structure is amenable to theoretical calculation.² On the theoretical side, work by us together with Desplanques (DDH) has developed a calculational framework based upon the quark model by means of which parity-nonconservation amplitudes may be evaluated, albeit with substantial uncertainties.³ In addition, Haxton, Gibson, and Henley (HGH) and Brown, Richter, and Godwin (BRG)⁴ have applied full two-body shell-model codes to nuclei near $A = 20$ thereby relating experiment to the parity-nonconservation amplitudes. While these calcula-

tions are not yet definitive,⁵ we will in this Letter adopt the results of Ref. 4, although later in the paper we comment on the effect of possible uncertainties.

It is our purpose here to combine these three developments in order to overview the field of nuclear parity nonconservation and to ask whether any new physics involving the nonleptonic weak interactions may be inferred at long last. We believe the answer to be in the affirmative.

We assume, following the usual approach, that the weak parity-nonconserving force can be written as the sum of single-meson-exchange amplitudes for ρ, ω, π between two nucleons. The weak meson-nucleon coupling can then be written in terms of the parameters

$$h_M^{(I)} \sim \langle MN | H_w(\Delta I) | N \rangle,$$

$$f_\pi \sim \langle \pi N | H_w(\Delta I = 1) | N \rangle,$$

where $H_w(\Delta I)$ is the parity-nonconserving weak Hamiltonian carrying isospin $\Delta I = 0, 1, 2$. Specific definitions of these couplings are given in Ref. 3.

The results of the calculations by HGH and BRG are consistent and imply that the experiments involving ^{18}F , ^{19}F , and ^{21}Ne are under-

standable in terms of²

$$f_\pi - 0.12h_\rho^{(1)} - 0.17h_\omega^{(1)} = (3.2 \pm 1.1)g_\pi, \quad (1a)$$

$$h_\rho^{(0)} + 0.56h_\omega^{(0)} = (-9.4 \pm 2.7)g_\pi. \quad (1b)$$

Here g_π is the familiar partial conservation of axial-vector current (PCAC)-SU(3) value⁶ for f_π ,

$$g_\pi = -(2/3)^{1/2} \tan \theta_C [-S(\Xi_-^-) + 2S(\Lambda_-^0)] \cong 3.8 \times 10^{-8}, \quad (2)$$

$\theta_C \approx 13^\circ$ being the Cabibbo angle, while $S(\Lambda_-^0)$, $S(\Xi_-^-)$ are the parity-nonconservation (S-wave) amplitudes for the $\Delta S = 1$ hyperon decays in parentheses.

One striking feature about the values presented in Eq. (1) is the rather modest value of f_π . Indeed, with use of values for $h_\omega^{(1)}$ and $h_\rho^{(1)}$ presented by DDH,³ Eq. (1a) becomes

$$f_\pi = (2.6 \pm 1.1)g_\pi, \quad (3)$$

whereas previous theoretical estimates had quoted values of⁷ $7g_\pi$ or even as large as $25g_\pi$,⁸ the large difference from the old sum-rule value arising from the contribution of weak neutral currents which were not included in the SU(3)-PCAC estimate for g_π quoted in Eq. (2).

Within the quark-model picture, there exist three classes of contributions to f_π . There is one piece which *can* be related via PCAC and SU(3) to the $\Delta S = 1$ hyperon decays via a sum rule. Denoting this by the superscript S we find^{3,8}

$$f_\pi^{(S)} = g_\pi \left[1 + \frac{1 - 2 \sin^2 \theta_W}{\sin^2 \theta_C} \left(\frac{K^{0.48} - K^{0.24}}{K^{0.48} + K^{0.24}} \right) \right]. \quad (4)$$

Here θ_W is the Weinberg angle, while

$$K = 1 + \frac{g(\mu^2)}{16\pi^2} b \ln \frac{M_w^2}{\mu^2} = \frac{\alpha_s(\mu)}{\alpha_s(M_w)} \quad (5)$$

is the usual strong-interaction-renormalization-group enhancement factor. Reasonable estimates place K in the range $3 < K < 7$ for which we find the values of $f_\pi^{(S)}$ listed in Table I.

An additional contribution to f_π arises from those pieces of H_w ($\Delta S = 0$) which *cannot* be related via SU(3) to the $\Delta S = 1$ charged-current Hamiltonian. This additional term can itself be separated into two components— $f_\pi^{(Q)}$, which can be evaluated directly between baryons in a quark model, and $f_\pi^{(P)}$, which can be Fierz transformed into a product of scalar and pseudoscalar densities and which can be evaluated with use of a “factorization” or vacuum intermediate-state as-

TABLE I. Numerical values, in units of $g_\pi = 3.8 \times 10^{-8}$, for the three contributions to f_π , described in the text, for various values of the strong-interaction parameter K .

	$K=3$	$K=4$	$K=7$
$f_\pi^{(S)}$	4.8	5.7	7.2
$f_\pi^{(Q)}$	1.9η	0.6η	-2.8η
$f_\pi^{(P)}$	$6.3S$	$8.1S$	$12.6S$

sumption. For the former, we find³

$$f_\pi^{(Q)} = \sin^2 \theta_W \frac{4}{3\sqrt{6}} \eta E(K) \frac{S(\Lambda_-^0)}{\sin \theta_C \cos \theta_C} = 22.3\eta E(K) g_\pi \sin^2 \theta_W, \quad (6)$$

where η is a ratio of two reduced matrix elements that is unity in a nonrelativistic quark model and approximately $\frac{2}{3}$ in the MIT bag model with massless quarks,³ and

$$E(K) = -0.33K^{0.85} + 0.03K^{0.43} + 1.61K^{-0.13} - 0.31K^{-0.35}. \quad (7)$$

Numerical values of $f_\pi^{(Q)}$ are given in Table I for various values of K . Finally, $f_\pi^{(P)}$ is evaluated with use of the same “factorization” techniques which have been applied to “penguin” diagrams in $\Delta S = 1$ weak decays.⁹ We find³

$$f_\pi^{(P)} = \frac{1}{3} \sin^2 \theta_W F(K) \times \frac{2}{3} G \frac{F_\pi m_\pi^2 S}{m_u + m_d} \quad (8a)$$

$$= 0.28F(K)S \frac{F_\pi}{m_u + m_d} g_\pi, \quad (8b)$$

where $G (\approx 10^{-5} m_p^{-2})$ is the weak-coupling constant, $F_\pi = 94$ MeV is the pion decay constant,

$$S = \langle p | \bar{u}d | n \rangle \quad (9)$$

is a renormalization constant which is unity in a nonrelativistic quark model and $\sim \frac{1}{2}$ in the MIT bag model with massless quarks,³ m_u and m_d are the current-algebra masses for the u and d quarks, respectively, and

$$F(K) = 1.04K^{0.85} - 0.19K^{0.43} - 0.09K^{-0.13} + 0.24K^{-0.35}. \quad (10)$$

It is conventional to use the Weinberg mass estimates¹⁰ $m_u = 4.2$ MeV and $m_d = 7.5$ MeV (we will return to this point later) which yields the values for $f_\pi^{(P)}$ listed in Table I. Putting the three con-

tributions together then gives

$$6.3S + 1.9\eta + 4.8 < f_\pi < 12.6S - 2.8\eta + 7.2, \quad (11)$$

which is clearly inconsistent—even if we use the MIT bag values for S and η —with the experimental value for f_π [Eq. (3)].

We believe there are several reasons which account for this discrepancy. Consider first the estimate for $f_\pi^{(S)}$. Derivation of this result requires the assumption of SU(3) symmetry. However, it has been pointed out¹¹ that the combination which appears in the sum rule is quite sensitive to SU(3)/soft-pion breaking and could well give corrections of order 100% to the naive result for symmetry-breaking corrections of order (20–30)%. Indeed a valence-quark calculation of g_π vanishes because of the absence of strange quarks in the nucleon.¹¹ DDH have detailed other reasons why one expects $f_\pi^{(S)}$ to be reduced, perhaps appreciably, from its sum-rule value. The experimental result for f_π seems to indicate that these expectations are borne out.

In the case of $f_\pi^{(P)}$ it appears that experiment is indicating that the conventional estimates of m_u and m_d are too small. In fact, they *should* be larger if one notes a distinction made by Weinberg in his estimates.¹⁰ The quoted values are for Lagrangian masses multiplied by a renormalization constant, $m_u^* = m_u Z_m = 4.2$ MeV and $m_d^* = m_d Z_m = 7.5$ MeV, where $Z_m N_q$ is the number of quarks q in H . In fact, $Z_m = S$ [Eq. (9)] in quark models. Thus for $S = \frac{1}{2}$, $m_u + m_d = 23.4$ MeV, reducing $f_\pi^{(P)}$ to the range $1.6 < f_\pi^{(P)} < 3.2$. This may be acceptable. Further reduction is possible if one derives the quark masses from the nucleon σ term

$$\langle N | \sigma | N \rangle = \langle N | m_u \bar{u}u + m_d \bar{d}d | N \rangle \approx 51 \text{ MeV}, \quad (12)$$

yielding $\frac{1}{2}(m_u^* + m_d^*) = 17$ MeV, and $\frac{1}{2}(m_u + m_d) \approx 34$ MeV, a value consistent with estimates in the bag model.¹² The sigma term evaluation involves chiral SU(2) while Weinberg's estimate uses chiral SU(3). The result for $f_\pi^{(P)}$ is especially interesting in that it has implications for "penguin" operators in $\Delta S = 1$ nonleptonic processes. Using the above method of evaluation, with $S = 1$, Shifman, Wainshtein, and Zakharov⁹ first suggested that penguins explained a good deal of nonleptonic physics. However, the above analysis implies that the strength of penguins is at least a factor of 4 weaker, in baryons, than previously thought.

For $3 < K < 7$ we note the values of $f_\pi^{(Q)}$ are small and thereby consistent with the experimental number.

In conclusion, we have carried through an analysis indicating two effects: (1) SU(3) breaking, etc., for $f_\pi^{(S)}$; and (2) larger values for m_u and m_d than used in the canonical estimates for $f_\pi^{(P)}$. The specific results depend on the nuclear physics calculations of HGH and BRG.⁴ There have been some very recent experiments which question the validity of a similar nuclear calculation—that of the pion-exchange matrix element in $\frac{1}{2}^+ \rightarrow \frac{1}{2}^-$ Ne¹⁹ β decay.¹³ If the HGH and BRG calculations were too large by a factor of 3, as suggested by these experiments, the value of f_π would be very close to the "best estimate" of DDH. In this case, both of the above effects could *not* be present simultaneously, although the presence of either of them could still be compatible with the data.

It is of interest to see if even more can be learned from analysis of the isoscalar results. In this case it is convenient, instead of dealing with $h_\rho^{(0)}$ and $h_\omega^{(0)}$ directly to analyze these experiments in terms of two-quark model parameters (b_v, c_v) defined by DDH as reduced matrix elements for specific quark diagrams discussed in Ref. 3. Dependence of our analysis on K is found to be rather weak and thus we shall use, for simplicity, the value $K \cong 4$. In terms of b_v and c_v , Eq. (1b) reveals

$$+ 18.8g_\pi + 4.4b_v - 2.9c_v = (-9.4 \pm 2.7)g_\pi. \quad (13)$$

Here $18.8g_\pi$ is the conventional factorization prediction.¹⁴ Thus we see already that, as emphasized by DDH, there *must* be additional contributions to $h_\rho^{(0)}$ and $h_\omega^{(0)}$ which arise from nonfactorizable terms: $b_v, c_v \neq 0$.¹⁵ These additional parameters were first introduced by McKellar and Pick,¹⁶ who utilized the symmetry $[SU(6)]_w$. Using exact SU(6) they were able to relate b_v and c_v to experimental $\Delta S = 1$ hyperon decay amplitudes. However, DDH have argued that such SU(6)-breaking effects are expected to substantially reduce b_v from its nonrelativistic SU(6) value. A crude estimate which uses the MIT bag model gave a value of b_v which was consistent with Eq. (14) for the case of very massive (i.e., nonrelativistic) quarks, but which was much smaller for ultrarelativistic (massless) quarks. We expect the correct answer to lie somewhere between these two extremes, probably closer to the mass-

FIG. 1. The values for the parameters b_v and c_v in the vector-meson sector allowed by (1) the analysis of ^{18}F , ^{19}F , and ^{21}Ne ; (2) pp scattering at 15 MeV; and (3) the parameter X_N^F from the analysis of heavy nuclei by Desplanques and Missimer (Ref. 20). The error bars represent the width of the error bands parallel to the lines. Also included are the naive $[\text{SU}(6)]_w$ value and the "best" estimate of DDH.

less quark value. In the result

$$4.4b_v - 2.9c_v = \begin{cases} -153g_\pi, & \text{exact SU(6) (Ref. 16)} \\ (-28.2 \pm 2.7)g_\pi, & \text{from Eq. (13)} \end{cases} \quad (14)$$

this expectation seems to be borne out, although since we have at present no corresponding way in which to estimate SU(6) breaking for c_v , it is difficult to say anything definite.¹⁷

Most experiments are sensitive primarily to $h_\rho^{(0)}$ and thereby measure roughly the same combinations of b_v and c_v . In Fig. 1, we plot Eq. (13), along with the constraints³ of recent polarized- pp -scattering asymmetry results^{18,19} and the result of the heavy-nuclei analysis of Desplanques and Missimer²⁰ [we have introduced a conservative 25% error estimate in the latter and have used the experimental value of f_π , Eq. (3)]. We note that the allowed regions are consistent—a very welcome and reassuring effect. A result which is extremely inconsistent with these values is the Lobashov experiment on $np \rightarrow d\gamma$,²¹ which would, if correct, require a completely new theory of parity violation (the effects seen are a factor of 100 too large). Confirmation of this result is urgently needed.

We conclude then that the field of nuclear parity nonconservation is perhaps moving into a new era—one where consistent experimental results can be expected to continue to reveal exciting physics unavailable by other means.

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Experimental Test of the Drell-Yan Model in $p + W \rightarrow \mu^+ + \mu^- + X$

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We report a high-statistics study of the reaction $p + W \rightarrow \mu^+ + \mu^- + X$ with use of an intense 400-GeV/c proton beam, a magnetized-iron beam dump, and a wide-acceptance detector. Using data near $x_F = 0$, we have extracted the nucleon sea-quark distribution and find it to be a factor 1.6 ± 0.3 larger than that obtained by inelastic charged-current neutrino scattering. We then compare the Drell-Yan prediction with our data including the previously unexplored region of large x_F and find excellent agreement for a wide range of μ -pair invariant mass.

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Hadronic production of dimuons with large invariant mass has contributed both to the discovery of quarkonium states and, via the Drell-Yan mechanism, to the elaboration of the quark-parton model. We report here results from continuum μ -pair production by 400-GeV/c protons at Fermilab. The experiment was characterized by high intensity and a very large acceptance which allow us to extract sea-quark distributions which we use to test the Drell-Yan model in important kinematic regimes not covered by other experiments.

The apparatus has been described previously¹; here we include only features particularly relevant to this measurement. A 400-GeV/c proton beam ($\sim 2 \times 10^{11}$ protons per 1-sec pulse) impinged on a 32-cm tungsten (W) target. Muons produced in the target penetrated 5.5 m of magnetized iron with a field of 2.15 T before reaching the detector. The detector consisted of two identical arrays of

large solid angle placed symmetrically on the left and right sides of the beam direction. The position of these arrays with respect to the beam-line direction could be varied. Each array contained two planes of crossed x - y hodoscope counters plus another smaller plane of "wedge" counters to reject low-transverse-momentum muons. Also, in each array, nine multiwire proportional chambers (MWPC's) with 2-mm wire spacing determined each muon straight-line trajectory in the detector.

Data were recorded under three sets of conditions. Our lowest μ -pair invariant-mass events were recorded with the two detector arrays as close to the beam line direction as possible. The intermediate- and high-mass events were taken simultaneously with the detector arrays moved away from the beam line direction so that each array accepted muons whose laboratory angle was ≥ 18 mrad. The high-mass events differed from