Isospin Violation in Quark-Parton Distributions

G. Preparata

Dipartimento di Fisica, Università di Milano, Milano, Italy
and Instituto Nazionale di Fisica Nucleare, Sezione di Milano, via Celoria 16, 20133 Milano, Italy

P. G. Ratcliffe

Instituto Nazionale di Fisica Nucleare, Sezione di Milano, via Celoria 16, 20133 Milano, Italy

J. Soffer

Centre de Physique Theorique, Centre National de la Recherche Scientifique, Luminy Case 907,
13288 Marseille CEDEX 9, France

(Received 31 July 1990)

The analysis of very recent and accurate deep-inelastic-scattering data leads us to conclude that isospin is strongly violated in the proton sea-quark distributions. Such findings have severe implications for reliable global parton-distribution fitting programs.

PACS numbers: 12.40.Aa, 11.50.Li, 13.15.−f, 13.60.Hb

(1) Parton sum rules.—One of the most fundamental results of the quark-parton model (QPM) is the derivation of several sum rules relating to the various deep-inelastic-scattering (DIS) structure functions. The validity of these sum rules is a direct consequence of the applicability of the light-cone operator-product expansion (OPE) to deep-inelastic processes, i.e., where the Q^2 of the electromagnetic or weak probe is much larger than typical hadronic mass scales. The OPE results for the various (unpolarized) structure functions can be summarized as follows: The Adler sum rule (ASR),[1]

$$\int_0^1 \frac{dx}{2x}[F_2^{\bar{\nu}p}(x)-F_2^{\nu p}(x)]=1\,, \tag{1.1}$$

and the Gross-Llewellyn Smith sum rule (GLSSR),[2]

$$\tfrac{1}{2}\int_0^1 dx[F_3^{p}(x)+F_3^{n}(x)]=3\left(1-\frac{\alpha_s}{\pi}\right). \tag{1.2}$$

Note that while the former is free from perturbative-QCD corrections, the latter receives corrections coming from gluon radiation.

From the relationship of the structure functions to quark-parton distributions it is readily seen that these sum rules simply count the numbers of valence-type quarks in certain combinations. In terms of quark-parton distributions inside a proton the sum rules can be expressed as follows: The Adler sum rule,

$$\int_0^1 dx[u(x)-d(x)-\bar{u}(x)+\bar{d}(x)]=1\,, \tag{1.3}$$

and the Gross-Llewellyn Smith sum rule,

$$\int_0^1 dx[u(x)+d(x)-\bar{u}(x)-\bar{d}(x)]=3\left(1-\frac{\alpha_s}{\pi}\right). \tag{1.4}$$

Note that, since the valence distributions are $q_v(x)=q(x)-\bar{q}(x)$, the noncontribution of the sea quarks to the GLSSR and ASR is guaranteed by the charge-conjugation properties of the weak current which lead to direct cancellation flavor by flavor of quark and antiquark distributions in the sea. In particular, there is no contribution to the sum rules from strange quarks since, if we neglect electroweak effects, $\int s(x)=\int\bar{s}(x)$ and any difference in the x dependence can only lead to safely negligible differences when comparing the behavior of the distributions in x.

If one assumes isospin invariance in the sea, i.e., that $\bar{u}(x)=\bar{d}(x)$, a further sum rule relating to charged-lepton DIS may be obtained from the ASR, namely, the Gottfried sum rule (GSR),[3]

$$\int_0^1 \frac{dx}{x}[F_2^{ep}(x)-F_2^{en}(x)]=\tfrac{1}{3}\,, \tag{1.5}$$

which translated into parton language is

$$\int_0^1 dx\,\tfrac{1}{3}\,[u(x)-d(x)+\bar{u}(x)-\bar{d}(x)]=\tfrac{1}{3}\,. \tag{1.6}$$

We should point out that such an assumption, while seemingly very plausible, has no sound theoretical footing.

The important question of small-x_B convergence may be addressed via Regge theory which indicates that the valence distributions should behave as $x_B^{-1/2}$. In the case of sea distributions it should be noted that in the above sum rules (including the GLSSR) the potentially divergent Pomeron contribution cancels by virtue of its flavor independence.

(2) Experimental results.—Over the past decade or so the data on the various sum rules have improved to the point where any deviation from the expected values should now be discernible. However, in the light of the poor determination of the ASR (Ref. 4) and very recent high-statistics data on the other two sum rules we shall in fact restrict our discussion to the GSR and GLSSR.

In the case of the GSR, for some years the central value has been consistently determined at 0.24;[5] unfortunately, large experimental errors have until now rendered this discrepancy insignificant. Recently, the New Muon Collaboration (NMC) at CERN (Ref. 6) has reported a much improved result:

$$\mathrm{GSR}=0.240\pm0.034(\mathrm{stat})\pm0.021(\mathrm{syst})\,. \qquad (2.1)$$

This value is the result of a point-by-point integration in x_B and extrapolation to $x_B=0$. We have made a fit to the data on $F_2^p(x)-F_2^n(x)$ using the form $ax^b(1-x)^c$, see Fig. 1, from which the values of the parameters are $a=0.47\pm0.15$, $b=0.77\pm0.13$, and $c=2.09\pm0.32$. It should be pointed out that in making this fit we have ignored the highest x_B bin with its unlikely negative value, the inclusion of which would, of course, only lower the estimated integral. Our fit leads to $\mathrm{GSR}=0.24\pm0.02$ (where the error is statistical only). We note that this value is in perfect agreement with (2.1) and that the experimentally quoted statistical error may in fact be an overestimate in that it neglects certain knowledge of the structure-function behavior in x_B. The latest NMC value (still preliminary) for the integral from $x_B=0.004$ to 1.0 is

$$\mathrm{GSR}(0.004\text{–}1.0)=0.230\pm0.013(\mathrm{stat})\pm0.027(\mathrm{syst})\,, \qquad (2.2)$$

and using our fit to the data we estimate the contribution from below 0.004 to be 0.009. Moreover, using only the NMC F_2^n/F_2^p ratio and the world-average fit to F_2 on deuterium the following value has been obtained:[7]

$$\mathrm{GSR}=0.219\pm0.008(\mathrm{stat})\pm0.021(\mathrm{syst})\,. \qquad (2.3)$$

To quantify the discrepancy between theory and experiment, in Fig. 1 we compare the data with a parametrization obtained from a global fit to the DIS data, namely, Martin-Roberts-Stirling (MRS) B.[8] The experimental points lie consistently below the theoretical curve and the integral obtained by the NMC falls short of the prediction by more than 2 standard deviations or, in other words, is some 25% less than the sum rule itself. This changes using the world-average fit to F_2 on deuterium, as mentioned above, to nearly 3 standard deviations or some 30% of the sum rule.

Turning now to the GLSSR we observe a similarly improved situation with regard to the experimental accuracy. Recent data have been presented by the Columbia-Chicago-Fermilab-Rochester (CCFR) Collaboration at Fermilab[9] which has measured deep-inelastic neutrino-iron scattering to very high precision. The value they obtain is

$$\mathrm{GLSSR}=2.66\pm0.03(\mathrm{stat})\pm0.08(\mathrm{syst})\,, \qquad (2.4)$$

which agrees excellently with the prediction of 2.63 for $\Lambda_{\mathrm{QCD}}=250$ MeV and mean $Q^2=3$ GeV^2. In Fig. 2 we display the GLSSR data for $xF_3(x)$ together with an experimental fit of the form $ax^b(1-x)^c$, for which $a=4.88\pm0.20$, $b=0.697\pm0.015$, and $c=2.635\pm0.067$, and the MRS B parametrization.

Given the accuracy of the predictions and experimental determinations of these two related sum rules, one must now address the problem of a large discrepancy, not only between predictions and experiment but also

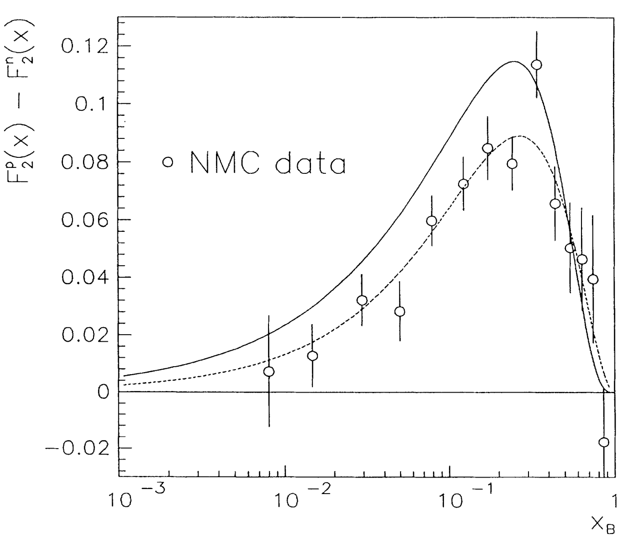

FIG. 1. Preliminary NMC data for the GSR for $p_{\mathrm{lab}}=280$ GeV and $Q^2=4$ GeV^2. The dashed line is a fit to the data using the parametrization given in the text and the solid line is from the global parametrization of MRS B.

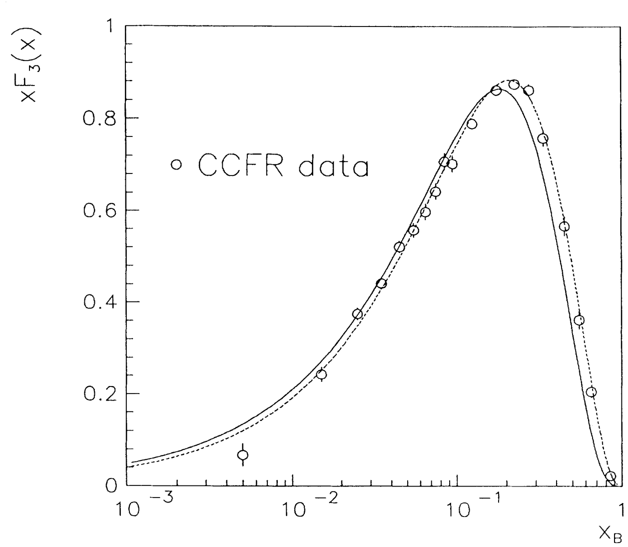

FIG. 2. Preliminary CCFR data for the GLSSR. The curves are as in Fig. 1.

then apparently between the two experiments.

(3) Escape routes.— The immediate problem is to explain the theoretical overestimate of the GSR. An obvious possibility might be to push the discrepancy into the very-small-x_B region. Experimentally though, the systematic errors are dominated by the overall normalization uncertainty and the extrapolation errors for both the GLSSR and GSR are very small.

On the other hand, one might envisage a deviation from the expected $x_B^{-1/2}$ behavior with a more singular behavior only setting in at $x_B \sim 10^{-3}$ or even lower, i.e., below that of the experimental coverage. Such a possibility, however, would demand a similar mismatch for the GLSSR which, as observed above, is well-satisfied experimentally and is on a sounder theoretical footing than the GSR. The saturation of the GLSSR for $x_B > 0.01$ leaves then essentially no space for the large contribution below 0.01 required to satisfy the GSR.

Given the severe restrictions imposed by the GLSSR data, the only serious alternative is to admit isospin violation in the sea. We note that this is not a new idea, having been proposed by Field and Feynman in 1977.[10] The physical principle behind the suggestion is the Pauli exclusion of up quark states in the sea due to the excess of up valence quarks in the proton. However, the magnitude and functional form suggested in Ref. 10 are not at all sufficient to explain the present data. It should also be pointed out that such a violation arises quite naturally in the physically intuitive approach developed by Preparata and has already been discussed in the context of the ratio F_2^n/F_2^p and a very successful prediction of G_1^p, the polarized structure function.[11] In this approach one would expect a violation quite compatible in size and x_B dependence with that suggested by the data under discussion.

Indeed the required difference between the up and down sea, as deduced from the fits shown in Fig. 1, is well represented by the form

$$\bar{d}(x) - \bar{u}(x) = ax^b(1-x)^c, \tag{3.1}$$

where $a=1$, $b=0$, and $c=7$. The fact that $b=0$ demonstrates that the Pomeron contribution is absent, as expected, and the exponent c is typical of sea-distribution behavior. The question that arises naturally is whether or not such a large violation is acceptable within the confines of the existing semi-inclusive neutrino DIS data.[4,12] An earlier analysis of the sea distributions extracted from these data[13] led to a non-Pomeron contribution per flavor of the form of Eq. (3.1) with parameters $a=0.53$, $b=0$, and $c=8.25$. Thus clearly the required magnitude of isospin violation can be very comfortably accommodated within the non-Pomeron piece of the sea.

Finally, it is important to underline that this level of isospin violation is necessarily primordial in origin, given that perturbative violation is a next-to-leading logarithmic effect and, as such, at the low Q^2 values of interest is entirely negligible.

Comments and conclusions.— A few comments are in order before drawing our final conclusions. While already rather precise, the NMC data should improve in statistics and the collaboration expects to reduce the corresponding error by a factor of 2 in the near future. For some time it has been observed that the strange sea is suppressed by about a factor of 2 with respect to the down sea;[14] clearly, in the light of our analysis this could, at least in part, be attributed to dominance of the sea by the down quark. An important implication of our findings is that, so far, all global parton-distribution fits to the DIS data must have been seriously biased by the implicit assumption of isospin invariance and will thus require revision.

Moreover, isospin violation is not expected to affect the ASR (for the same reasons that the GLSSR is protected) and so an experimental test of this prediction would provide a vital cross-check of our interpretation.

In conclusion, then, the GSR data imply a strong violation of isospin in the proton sea, which is furthermore shown not to be in contradiction with any other experimental data. Indeed it precisely resolves what might have been an apparent discrepancy between the GSR and GLSSR data, which are thus now shown to be perfectly compatible.

We should like to thank S. Mishra, H. Schellman and R. Windmolders for helpful discussions and clarification of various experimental points.

Note added.— After completing this paper we became aware of a more recent global fit[15] which also includes the NMC data. While the resulting distribution functions might give adequate descriptions of both the GLSSR and the GSR (by delaying the onset of Regge behavior to *very* small x), we still feel that this is an awkward solution to the problem and we maintain that isospin breaking in the proton sea remains the most likely explanation of the data.

[1] S. L. Adler, Phys. Rev. **143**, 1144 (1966).

[2] D. Gross and C. Llewellyn Smith, Nucl. Phys. **B14**, 337 (1969).

[3] K. Gottfried, Phys. Rev. Lett. **18**, 1154 (1967).

[4] The WA25 Collaboration, D. Allasia *et al.*, Z. Phys. C **28**, 321 (1985).

[5] T. Sloan, G. Smadja, and R. Voss, Phys. Rep. **162**, 45 (1988).

[6] The NMC, R. Windmolders, in Proceedings of the Twelfth International Conference on Particles and Nuclei (PANIC 90), Cambridge, Massachusetts, June 1990 (to be published).

[7] The NMC, in Proceedings of the Twenty-Fifth Rencontre de Moriond (Hadronic Interactions), March 1990 (to be published).

[8] A. D. Martin, R. G. Roberts, and W. J. Stirling, Phys. Lett. B **206**, 327 (1988).

[9] The CCFR Collaboration, W. C. Leung *et al.*, in Proceed-

ings of the Twenty-Fifth Rencontre de Moriond (Hadronic Interactions), Ref. 7.

[10]R. D. Field and R. P. Feynman, Phys. Rev. D **15**, 2590 (1977).

[11]G. Preparata, in *High-Energy Physics with Polarized Beams and Polarized Targets,* edited by C. Joseph and J. Soffer (Birkhäuser Verlag, Boston, 1981); A. Giannelli, L. Nitti, G. Preparata, and P. Sforza, Phys. Lett. B **150**, 214 (1985).

[12]CERN-Dortmund-Heidelberg-Saclay Collaboration, H. Abramowicz *et al.*, Z. Phys. C **25**, 29 (1984).

[13]G. Preparata and J. Soffer, Phys. Rev. Lett. **61**, 1167 (1988); **62**, 1213(E) (1989).

[14]The CCFR Collaboration, C. Foudas *et al.*, Phys. Rev. Lett. **64**, 1207 (1990).

[15]P. N. Harriman, A. D. Martin, R. G. Roberts, and W. J. Stirling, Phys. Rev. D **42**, 798 (1990).