Origin of the violation of the Gottfried sum rule

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Using generalized Sullivan processes to generate sea-quark distributions of a nucleon at $Q^2=4 \text{ GeV}^2$, we find that the recent finding by the New Muon Collaboration on the violation of the Gottfried sum rule can be understood quantitatively, including the shape of $F_2^p(x)-F_2^n(x)$ as a function of x . The agreement may be seen as a clear evidence toward the validity of a recent suggestion of Hwang, Speth, and Brown that the sea distributions of a hadron, at low and moderate Q^2 (at least up to a few GeV^2), may be attributed primarily to generalized Sullivan processes.

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In a recent article, Preparata, Ratcliffe, and Soffer [1] discussed the significance of the finding [2] by the New Muon Collaboration (NMC) on the violation of the Gottfried sum rule (GSR) [3]. The GSR has to do with the integral

$$I_G \equiv \int_0^1 \frac{dx}{x} [F_2^{ep}(x) - F_2^{en}(x)] , \quad (1)$$

which is, in the context of the quark-parton model,

$$I_G = \frac{1}{3} \int_0^1 dx [u_p(x) - d_p(x) + \bar{u}_p(x) - \bar{d}_p(x)] \\ = \frac{1}{3} + \frac{2}{3} \int_0^1 dx [\bar{u}_p(x) - \bar{d}_p(x)] , \quad (2)$$

where $u_p(x)$ is the u -quark distribution in the proton and similarly for the other quark distributions $d_p(x)$, $\bar{u}_p(x)$, and $\bar{d}_p(x)$. In obtaining Eq. (2), one has used *isospin invariance* in relating the distributions in a neutron to those in a proton, i.e., $u_n(x)=d_p(x)$, $d_n(x)=u_p(x)$, $s_n(x)=s_p(x)$, etc., in order to obtain an expression that involves only parton distributions in a proton. The Gottfried sum rule [3] may then be derived by assuming *isospin independence* of the sea distributions in the *proton*:

$$\bar{u}_p(x) = \bar{d}_p(x) , \quad (3)$$

so that $I_G = \frac{1}{3}$. Here we emphasize that *isospin invariance*, or *isospin symmetry*, is *not* violated even if Eq. (3) is *not* true, since as a member of an isospin doublet the proton already has different valence u - and d -quark distributions. Thus, perhaps the preliminary value [2] reported by the NMC group, at $\langle Q^2 \rangle = 4 \text{ GeV}^2$, should not be considered as a major surprise:

$$\int_{0.004}^1 \frac{dx}{x} [F_2^{ep}(x) - F_2^{en}(x)] = 0.230 \pm 0.013(\text{stat}) \\ \pm 0.027(\text{syst}) . \quad (4a)$$

Analogously, 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 [4]:

$$\int_0^1 \frac{dx}{x} [F_2^{ep}(x) - F_2^{en}(x)] = 0.240 \pm 0.016 . \quad (4b)$$

As emphasized by Preparata, Ratcliffe, and Soffer [1], the observed deviation of the Gottfried sum I_G from $\frac{1}{3}$ is at variance with the standard hypothesis used by many of us for years:

$$\bar{u}_p(x) = \bar{d}_p(x) \approx 2\bar{s}_p(x) . \quad (5)$$

Such a difference may be considered a *surprise* but, as mentioned earlier, the deviation of the GSR from the value of $\frac{1}{3}$ is *not* a signature for violation of isospin invariance or isospin symmetry. It is therefore helpful to caution that the words used by some authors, such as “isospin violation” by Preparata, Ratcliffe, and Soffer [1] or “isospin symmetry violation” by Anselmino and Predazzi [5], are in fact quite misleading and should perhaps be avoided in the future.

As the standard hypothesis Eq. (5) is nullified by the NMC data, Eqs. (4a) and (4b), it implies that almost all of the existing parametrized parton distributions, as well as the analyses of the high-energy experiments in extracting the sea quark distributions for the nucleon or other hadrons, suffer from the commonly accepted *bias*. In this regard, we wish to echo the criticisms raised by Preparata, Ratcliffe, and Soffer [1].

Nevertheless, we wish in this paper to point out the fact that, as a result of our studies [6] related to a very different aspect concerning the sea distributions of a proton, we, together with G. E. Brown, have come to propose that the sea distributions of a hadron at low or moderate Q^2 (at least up to a few GeV^2) may be attributed primarily to generalized Sullivan processes [7] and, apart from the fact that good agreement with the Chicago-Columbia-Fermilab-Rochester (CCFR) data [8] and the phenomenologically parametrized sea distributions may easily be reproduced, the NMC data on the deviation of the Gottfried sum I_G from the value of $\frac{1}{3}$ may be explained using the proposed meson-exchange picture for parton distributions. In view of the importance of the

subject, we wish to present our detailed results concerning the origin of the violation of the Gottfried sum rule. In addition to the agreement on the integrated value on the Gottfried sum I_G , we shall see that the detailed x dependence of $F_2^{ep}(x) - F_2^{en}(x)$ may be reproduced *without* any further adjustment of the input parameters adopted in our earlier studies [6]. We believe that the agreement may be taken as the *first* clear evidence toward the suggestion that the sea distributions of a hadron, at low and moderate Q^2 (at least up to a few GeV^2), may be attributed primarily to generalized Sullivan processes. This then gives the sea distributions which are not biased by the standard hypothesis Eq. (5) and may be used as input for QCD evolutions to higher Q^2 .

There is little doubt concerning the significance of the observation, as first made by Sullivan [7], that, in deep-inelastic scattering (DIS) of a nucleon by leptons, the process in which the virtual photon strikes the pion emitted by the nucleon and smashes the pion into debris scales like the original process where the virtual photon strikes and smashes the nucleon itself. In other words, the process will contribute by a finite amount to cross sections in the Bjorken limit, $Q^2 \rightarrow \infty$ and $\nu \equiv E_l - E_l' \rightarrow \infty$ with $x \equiv Q^2/(2m_N \nu)$ held fixed. This in turn implies that a certain part of the sea quark distributions in a nucleon is due to the meson cloud surrounding the nucleon. Thomas [9] was the first one who suggested, in 1983, to use the difference $\frac{1}{2}(\bar{u} + \bar{d}) - \bar{s}$ for setting a limit on the size of a nucleon. Conceptually, the work of Frankfurt, Mankiewicz, and Strikman [10], or that of Kumano [11], was based on the idea of Thomas. What has been missing in the argument, unfortunately, is that Sullivan processes involving couplings to kaons such as the KNA vertex contribute to the $\bar{s}$ sea; such a fact may invalidate the entire argument altogether. By considering generalized Sullivan processes that involve low-lying mesons and baryons, we have shown that [6] the original argument of Thomas, which we feel is a very helpful suggestion, can no longer give rise to a limit on the nucleon size or on the πNN or $\pi N\Delta$ form factors.

Our early work [6] was intended originally to incorporate kaons and other relevant mesons as generalized Sullivan processes but it was soon recognized that the meson-baryon picture in fact provides a reasonable account for the observed sea quarks in a nucleon even at $Q^2 \approx 20 \text{ GeV}^2$. Thus, we have compared the model predictions directly with the experimental data such as the CCFR results [8] or the observed strength of the s or $\bar{s}$ quarks. It was indeed the case [6] that the πNN form factor in the range of about 1 GeV (when parametrized in a monopole form) yields results in good agreement with the experimental data, thereby confirming the validity of the conjecture of using the meson-exchange picture for generating the major portion of the sea distributions of a hadron at moderate Q^2 . Not only the strengths of the various sea distributions, but also their shapes at the x region that by far is relevant experimentally are reproduced [6] using the meson-baryon picture.

The idea of linking the original Sullivan processes to the apparent violation of the Gottfried sum rule has been considered independently (and almost simultaneously) by

several authors: by Henley and Miller [12], by Kumano [11], by Signal, Schreiber, and Thomas [13], and by us [6]. Henley and Miller [12] considered only effects caused by the πNN vertex while Kumano [11] and Signal, Schreiber, and Thomas [13] considered both the πNN and $\pi N\Delta$ vertices. Note that the effects caused by the $\pi N\Delta$ vertex tend to cancel those due to πNN vertex and thus need to be treated with care [13,6]. With both the πNN and $\pi N\Delta$ vertices properly taken into account, the conclusion [13,6] is that only about one-half of the observed deviation of the Gottfried sum I_G from the value of $1/3$ may be accounted for, should the soft form factor as used in Refs. [9–11] be adopted. Thus, the success in not only obtaining the agreement on the integrated value of the GSR but also reproducing the detailed x dependence of $F_2^{ep}(x) - F_2^{en}(x)$, on the basis of the same input parameters adopted earlier [6], is in our opinion a true success of the meson-baryon picture and may be taken as clear evidence toward the suggestion that the sea distributions of a hadron, at low and moderate Q^2 (at least up to a few GeV^2), may be attributed primarily to generalized Sullivan processes.

Specifically, we use identical input parameters adopted earlier [6] (in the dipole scenario) and obtain

$$\int_{0.002}^1 \frac{dx}{x} [F_2^{ep}(x) - F_2^{en}(x)] = \begin{cases} 0.251 & (\text{EHLQ [14]}) \\ 0.177 & (\text{HMSR [15]}) \\ 0.235 & (\text{NC [16]}) \\ 0.235 & (\text{CC [16]}) \end{cases} \quad (6)$$

Here the first two calculations are carried out by using the phenomenologically parameterized valence distributions [14,15] (both at $Q^2 = 4 \text{ GeV}^2$) while the third and fourth entries are obtained when we adopt the valence distributions (at $Q^2 = 10 \text{ GeV}^2$) which Mattison *et al.* [16] extracted from weak reactions involving neutral currents (NC) or charge currents (CC). Only the first number (EHLQ) has been reported earlier [6]. It is useful to stress the point that, as the sea quark distributions are now calculated from generalized Sullivan processes, our results are controlled essentially by the input valence distributions (together with the form factors chosen to reproduce the strength of the observed sea). Such input is considered to be the most reliable piece of the various parton distributions.

To investigate the situation in much greater detail, we plot in Fig. 1 the structure function difference $F_2^p(x) - F_2^n(x)$ as a function of x . The five curves are the predictions using five different input valence distributions for the nucleon: a dash-dotted curve from the distribution extracted from the neutral-current neutrino data [16], a dashed curve from the charge-current neutrino data [16]; a dotted curve from the input valence distribution of Harriman, Martin, Sirling, and Roberts (HMSR) [15], a long dash curve from the valence distributions of Dukes and Owens [17]; and a solid curve from the valence distributions of Eichten, Hinchliffe, Lane, and Quigg (EHLQ) [14].

We should emphasize that, despite the fact that the integrated value as listed in Eq. (6) may come close to the data, it is *nontrivial* to reproduce as well as the shape of

the experimental data as a function of x . The curves shown in Fig. 1 reflect directly the shape of the proposed valence distribution convoluted according to Sullivan processes. It is clear that the shape of the EHLQ valence distributions performs better than that of the HMSR ones. The QCD evolution softens the valence distributions slightly (from $Q^2=4$ to 10 GeV^2) so that the results from the NC and CC neutrino data are more or less consistent with the EHLQ prediction. For the purpose of the present paper, the result from the old Duke-Owens distributions may now be disregarded owing to a very recent update of parton distributions from Owens [17]. On the other hand, the EHLQ result may now be taken more seriously in light of a recent work of Eichten, Hinchliffe, and Quigg [18]. In any event, the general agreement may be taken as an *additional* evidence toward the suggestion that the sea distributions of a hadron, at low and moderate Q^2 (at least up to a few GeV^2), may be attributed primarily to generalized Sullivan processes. This then gives the sea distributions which are not biased by the standard hypothesis Eq. (5) and may be used as the input for QCD evolutions to higher Q^2 . (See Fig. 2.)

We may remark that in principle one may in fact *first* evolve the input valence distribution to higher Q^2 and *then* calculate the sea quark distributions via Sullivan processes. The results remain the same for practical purposes. In other words, QCD evolution and convolution for Sullivan processes are two concepts compatible with each other. This must be so since contributions from Sullivan processes remain there in the Bjorken limit. What is intriguing is that the contribution from Sullivan processes never goes away—it scales or it does not vanish in the Bjorken limit. In other words, one could in principle tell that a quark actually comes from some parton via QCD evolution and that this parton belongs to the core of the hadron or to some hadron in the cloud.

FIG. 1. The structure function difference $F_2^p(x) - F_2^n(x)$ shown as a function of x . The five curves are our predictions using five different input valence distributions for the nucleon: a dash-dotted curve from the distribution extracted from the neutral-current neutrino data [16], a dashed curve from the charge-current neutrino data [16], a dotted curve from the input valence distribution of Harriman, Martin, Stirling, and Roberts [15], a long dash curve from the valence distributions of Dukes and Owens [17], and a solid curve from the distributions of Eichten, Hinchliffe, Lane, and Quigg [14].

It is known that the meson-baryon picture with a relatively hard πNN form factor (such as the one expected from our calculations) provides a quantitative understanding of *nuclear physics* phenomena such as the electromagnetic form factors of the deuteron, those of the triton or the helium-3, and the near-threshold electrodisintegration of the deuteron, all up to a few GeV^2 . Accordingly, we have in mind that the conjecture of generating sea quark distributions in a hadron via generalized Sullivan processes is valid at a few GeV^2 and the QCD evolution then takes us to higher Q^2 . The issue is when we should start doing QCD evolution via Altarelli-Parisi equations. In our opinion, the Q^2 must be high enough (or the resolution is good enough) in order to see the substructure (or occurrence of subprocesses) at the quark-gluon level. In this paper we take it to be 4 GeV^2 , which we believe is a reasonable guess. For Q^2 below such value, we believe that quarks and gluons exist only by associating themselves with hadrons and thus Sullivan processes provide a natural way for obtaining parton distributions at these Q^2 .

At this juncture, it may be useful to discuss a very recent work of Eichten, Hinchliffe, and Quigg [18], who advocate the view of understanding the violation of the Gottfried sum rule in an effective chiral quark model [19]. It is clear that such a view is quite similar to what we have described in this paper, except that we insist on the confinement aspect that, at low and moderate Q^2 , quarks and gluons exist only by associating themselves with hadrons and couplings of quarks to pions [18,19] are subject to potentially strong renormalizations due to QCD. On the other hand, it was pointed out [20] that the contribution from the unmeasured region of very small x , $\int_0^{\delta} (dx/x) [F_2^p(x) - F_2^n(x)]$, might make up the deviation of the Gottfried sum I_G from $\frac{1}{3}$. Nevertheless, preliminary data from the Fermilab E665 experiment [21], which covers the range of x down to ≈ 0.001 , suggest that the NMC extrapolation is not grossly in error. In addition, it is difficult [18] to use this ansatz in reproducing exactly the observed smooth shape of

FIG. 2. The structure function difference $F_2^p(x) - F_2^n(x)$ as a function of x in the case of EHLQ [14] is decomposed into two contributions: the dotted curve from the valence contribution $\frac{1}{3}[u_v(x) - d_v(x)]$ and the dashed curve from the calculated sea distribution $\frac{2}{3}[\bar{u}(x) - \bar{d}(x)]$.

$F_2^p(x) - F_2^n(x)$ at small x . Therefore, it seems preferable to adopt the interpretation of the observed violation of the Gottfried sum rule in terms of pions (or more generally in terms of the meson-baryon picture).

It might also be argued that a model in terms of a cloud of off-shell pions and an off-shell baryon core may be intrinsically vaguely defined. This seems a legitimate concern if we follow Sullivan's original derivation, as it is not clear how to go beyond the specific approximation. Nevertheless, the problem is not a serious one since differences between parton distributions of an off-shell hadron and those of an on-shell one are effects of higher twists and thus can be neglected in the leading approximation. Indeed, it is possible to adopt the infinite-momentum-frame (IMF) perturbation theory, as elaborated extensively by Drell, Levy, and Yan [22], to derive the formulas for Sullivan processes—the results are quite similar to those obtained from Sullivan's original derivation and it becomes clear how the approximation may be improved order by order. Alternatively, the light-cone perturbation theory [23] may be adopted in this context, yielding the results identical to the IMF perturbation theory in the infinite momentum limit. These observations point to the fact that the model can be consistently and clearly defined.

Our earlier work [6] already indicates that the meson-baryon picture in fact provides a reasonable account for the observed sea quarks in a nucleon even at $Q^2 \approx 20 \text{ GeV}^2$. In particular, the model predictions compare very

well with the existing experimental data, such as the CCFR results [8] or the observed strength, as well as the shape (as a function of x), of the s or $\bar{s}$ quarks. This is in accord with the observation of Eichten, Hinchliffe, and Quigg [18] that parton distributions which incorporate in the fit the NMC data reproduce adequately all the important features of the existing parton-distribution data. (That is, there is no inherent inconsistency between the NMC result and the existing data.) Thus, generalized Sullivan processes provide a simple and natural interpretation of the observed violation of the Gottfried sum rule, while maintaining the overall consistency with the other existing data related to parton distributions.

In summary, we have shown, by using generalized Sullivan processes to generate sea quark distributions of a nucleon at $Q^2 = 4 \text{ GeV}^2$, that the recent finding [2,4] by the NMC group on the violation of the Gottfried sum rule [3] can be understood quantitatively. In our opinion, such agreement may be seen as a clear evidence toward the validity of a recent suggestion of Hwang, Speth, and Brown [6] that the sea distributions of a hadron, at low and moderate Q^2 (at least up to a few GeV^2), may be attributed primarily to generalized Sullivan processes.

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