Gottfried Sum from the Ratio F_2^n/F_2^p

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Experimental results obtained at the CERN Super Proton Synchrotron on the structure-function ratio F_2^n/F_2^p in the kinematic range $0.004 < x < 0.8$ and $0.4 < Q^2 < 190$ GeV^2, together with the structure function F_2^d determined from a fit to published data, are used to derive the difference $F_2^p(x) - F_2^n(x)$. The value of the Gottfried sum $\int (F_2^p - F_2^n)\,dx/x = 0.240 \pm 0.016$ is below the quark-parton-model expectation of $\frac{1}{3}$.

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The Gottfried sum[1] written in terms of the proton and neutron structure functions F_2 is defined[2] as $S_G = \int_0^1 (F_2^p - F_2^n)dx/x$. In the quark-parton model, F_2 is expressed in terms of the quark momentum distributions, $q_i(x)$, and the Gottfried sum is

$$S_G = \int_0^1 \sum_i e_i^2 [q_i^p(x) + \bar{q}_i^p(x) - q_i^n(x) - \bar{q}_i^n(x)]dx \,, \qquad (1)$$

where e_i is the charge (in units of e) of a quark of flavor i. The integral represents the difference between the sum of the squares of the quark charges in the proton and the neutron.

Separating the quark distributions into valence and sea components, and performing the integral over the former, one has

$$S_G = \tfrac{1}{3} + \int_0^1 \sum_i e_i^2 [2\bar{q}_i^p(x) - 2\bar{q}_i^n(x)]dx \,, \qquad (2)$$

where $\bar{q}_i(\text{sea}) = q_i(\text{sea})$. Under the assumption of isospin symmetry between the proton and the neutron, Eq. (2) reduces to

$$S_G = \tfrac{1}{3} + \tfrac{2}{3} \int_0^1 [\bar{u}(x) - \bar{d}(x)]dx \,, \qquad (3)$$

where $\bar{u} \equiv \bar{u}^p = \bar{d}^n$ and $\bar{d} \equiv \bar{d}^p = \bar{u}^n$. Perturbative QCD corrections to the first term are calculated to be small.[3] Then for a flavor-symmetric sea ($\bar{u} = \bar{d}$) the second term vanishes and the expected result is $\frac{1}{3}$ (the Gottfried sum rule). Previous experimental results on this sum rule were obtained by the European Muon Collaboration[4] (EMC) and the Bologna-CERN-Dubna-Munich-Saclay Collaboration[5] (BCDMS). In each case the result was lower than but compatible with $\frac{1}{3}$, within the large systematic errors due to the extrapolation of $F_2^p - F_2^n$ into the unmeasured region $x < 0.02$ (EMC) and $x < 0.06$ (BCDMS).

In this Letter we report on the value of S_G determined from $F_2^p - F_2^n$ expressed as $F_2^p - F_2^n = 2F_2^d(1-F_2^n/F_2^p)/(1+F_2^n/F_2^p)$. The ratio $F_2^n/F_2^p \equiv 2F_2^d/F_2^p - 1$ was determined from the deuteron/proton cross-section ratio measured in this experiment. The absolute deuteron structure function F_2^d was taken from a fit to published data from other experiments.

We have measured deep-inelastic muon scattering on hydrogen and deuterium targets, which were simultaneously exposed to the beam at incident muon energies of 90 and 280 GeV. The use of a complementary-target setup reduces the systematic errors in F_2^n/F_2^p due to beam-flux and spectrometer-acceptance uncertainties. The data cover the kinematic range down to $x = 0.004$ and $Q^2 = 0.4$ GeV^2. A description of the New Muon Collaboration (NMC) apparatus and how the ratio F_2^n/F_2^p was derived from the data can be found in Ref. 6, where results from 65% of the 280-GeV data were presented.

The parametrization of F_2^d used to evaluate S_G and to calculate radiative corrections was obtained from a fit to the SLAC,[7] BCDMS,[5] EMC-NA28,[8] and Chicago-Harvard-Illinois-Oxford[9] (CHIO) data in the deep-inelastic region and to the SLAC data[10] in the baryon-resonance region.[11] The normalizations of the data sets were not adjusted, nor were their systematic errors included in the weights. The resulting values of F_2^d are given in Table I. An upper (lower) limit of F_2^d was obtained from a fit with each data set simultaneously raised (lowered) by its quoted normalization error, which was also included in the weights. These limits were taken as a measure of the systematic uncertainty on F_2^d.

The ratio of the structure functions F_2^n/F_2^p was determined from the measured cross-section ratio assuming the longitudinal-to-transverse virtual-photon absorption cross-section ratio to be the same for hydrogen and deuterium.[12] Radiative corrections were calculated using the method of Mo and Tsai.[13] Since these corrections depend on the structure functions, an iterative method was used, modifying F_2^p while keeping F_2^d fixed. The results for F_2^n/F_2^p are presented in Fig. 1(a) for 90 and 280 GeV separately. The systematic errors were estimated as the quadratic sum of the uncertainties due to the radiative corrections, incoming and scattered muon momenta, and the assignment of events to the wrong target. They are dominated by uncertainties in the radiative corrections at low x and in the muon momenta at high x.

TABLE I. The structure function F_2^d with systematic errors, the values of the ratio F_2^n/F_2^p derived from the linear fit in $\log Q^2$, and the cumulative integral $S_G(x_{\min}-0.8) = \int_{x_{\min}}^{0.8}(F_2^p - F_2^n)dx/x$, both with statistical errors. All values are at $Q^2 = 4$ GeV^2. The values of the ratio and of F_2^d are at the middle of each x interval.

$x_{\min}-x_{\max}$	F_2^d	F_2^n/F_2^p	$S_G(x_{\min}-0.8)$
0.004–0.01	0.349 ± 0.025	0.985 ± 0.017	0.227 ± 0.007
0.01–0.02	0.356 ± 0.022	0.959 ± 0.009	0.222 ± 0.005
0.02–0.04	0.359 ± 0.018	0.928 ± 0.006	0.212 ± 0.005
0.04–0.06	0.355 ± 0.014	0.921 ± 0.007	0.194 ± 0.004
0.06–0.10	0.346 ± 0.010	0.876 ± 0.006	0.182 ± 0.004
0.10–0.15	0.329 ± 0.008	0.837 ± 0.007	0.160 ± 0.004
0.15–0.20	0.307 ± 0.006	0.801 ± 0.009	0.136 ± 0.004
0.20–0.30	0.268 ± 0.005	0.722 ± 0.010	0.117 ± 0.004
0.30–0.40	0.210 ± 0.004	0.629 ± 0.017	0.082 ± 0.004
0.40–0.50	0.153 ± 0.003	0.463 ± 0.028	0.055 ± 0.003
0.50–0.60	0.103 ± 0.002	0.412 ± 0.046	0.030 ± 0.003
0.60–0.80	0.048 ± 0.006	0.312 ± 0.067	0.014 ± 0.002

The bands at the bottom of Fig. 1(a) show their sizes.

In order to determine the ratio F_2^n/F_2^p at fixed Q^2, the data were parametrized as a linear function of $\log Q^2$ in every x bin. The value of $Q^2 = 4$ GeV^2 was chosen since it is covered by our measurement in the range of $0.004 < x < 0.5$; only for larger values of x was it neces-

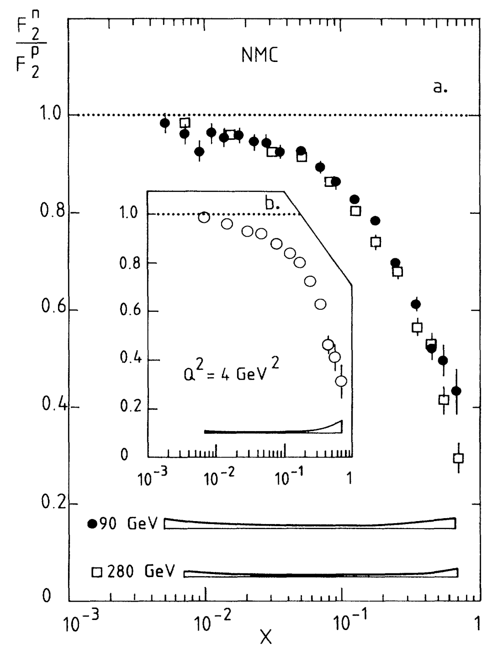

FIG. 1. (a) The ratio F_2^n/F_2^p as a function of x averaged over Q^2 as measured at 90- and 280-GeV incident muon energy. The average Q^2 changes from point to point and is different for the two data sets. (b) The F_2^n/F_2^p ratio at $Q^2 = 4$ GeV^2. The bands show the systematic uncertainties.

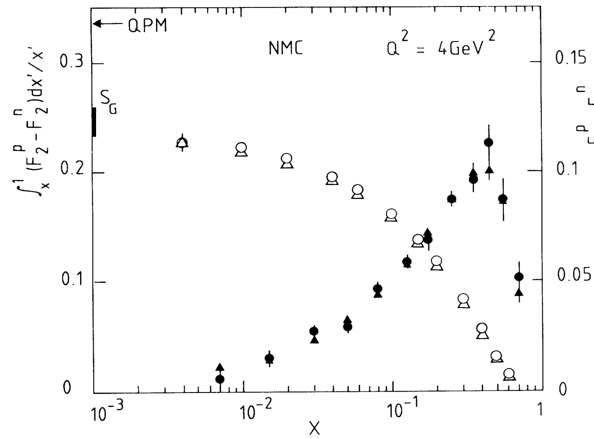

FIG. 2. The difference $F_2^p(x) - F_2^n(x)$ (solid symbols and the scale to the right) and $\int_{x_{\min}}^1 (F_2^p - F_2^n) dx/x$ (open symbols and the scale to the left) at $Q^2 = 4$ GeV^2. The circles are from the linear fit in $\log Q^2$ and triangles from the procedure of Ref. 7. The extrapolated result S_G is indicated by the bar. The simple quark-parton-model (QPM) prediction is also shown.

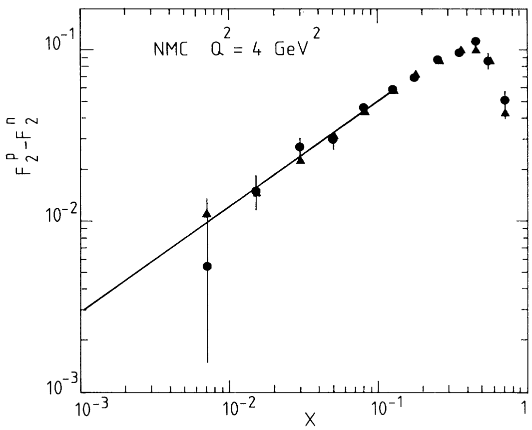

FIG. 3. The difference $F_2^p(x) - F_2^n(x)$ at $Q^2 = 4$ GeV^2 from the linear fit in $\log Q^2$ (solid circles) and the fitted function ax^b used in the extrapolation to $x = 0$. For comparison the triangles from Fig. 2 are also plotted.

sary to extrapolate the fitted lines. The results are shown in Fig. 1(b) and in Table I.

Figure 2 shows the results for $F_2^p - F_2^n$ and the cumulative integral $S_G(x_{\min} - 0.8) = \int_{x_{\min}}^{0.8} (F_2^p - F_2^n) dx/x$ which is also given in Table I. The errors shown are statistical only. The value of the Gottfried sum in the measured region at $Q^2 = 4$ GeV^2 is

$$S_G(0.004 - 0.8) = 0.227 \pm 0.007(\text{stat}) \pm 0.014(\text{syst}).$$

The individual systematic errors are given in Table II; the total is their quadratic sum. Although the error in F_2^d also contributes to the uncertainty in the radiative corrections, we treated the systematic errors independently. Also shown in Fig. 2 are the results derived from a simultaneous fit to F_2^n/F_2^p over all x and Q^2, using a function proposed in Ref. 7 [Eq. (5.47) on p. 141]. These results differ from those from the independent linear fits mainly at large x where extrapolation is necessary; the difference in the integral, however, is negligible. If the structure function F_2^d given in Ref. 14 is used to evaluate $F_2^p - F_2^n$ from our data, the value of the integral

TABLE II. The contribution ΔS_G to the systematic error on the value of the integral $\int_{0.004}^{0.8} (F_2^p - F_2^n) dx/x$ at $Q^2 = 4$ GeV^2.

Source	ΔS_G
Radiative corrections	0.006
Beam and scattered muon momentum	0.008
Position of the interaction vertex	0.007
Uncertainty in F_2^d	0.006
Other sources	0.003
Total error	0.014

is also not significantly changed.

The contribution to S_G from $x > 0.8$ was estimated, assuming a smooth extrapolation of F_2^n/F_2^p to the value of 0.25 at $x = 1$, to be $S_G(0.8 - 1.0) = 0.002 \pm 0.001$. More important is the contribution from the extrapolation to $x = 0$. At small x, the deep-inelastic region overlaps the Regge region and it has been suggested that the shape of the parton distributions may be given by the intercept α of the appropriate Regge trajectory:[15] $q(x) \sim \nu^{\alpha} \sim x^{-\alpha}$. In the extrapolation to $x = 0$ we have therefore assumed that $F_2^p - F_2^n$, a flavor nonsinglet, behaves as ax^b. The fit in the region $x = 0.004$–0.15 shown in Fig. 3 gives the values $a = 0.21 \pm 0.03$ and $b = 0.62 \pm 0.05$. This yields $S_G(0 - 0.004) = 0.011 \pm 0.003$. A similar fit to the second set of points (triangles in Fig. 2) yields a consistent result with a slightly lower contribution to S_G. The quoted errors include the uncertainties in the fitted parameters and those from the systematic errors listed in Table II.

Summing the contributions from the measured and unmeasured regions and adding the errors quadratically, we obtain the value for the Gottfried sum

$$S_G = 0.240 \pm 0.016,$$

which is significantly below the simple quark-parton-model result of $\frac{1}{3}$.

A number of factors might change this result. We have considered the influence of target-mass effects, higher twist, and nuclear effects in deuterium. Target-mass corrections[16] to the Gottfried sum were found to be negligible. The influence of possible higher twists on the ratio F_2^n/F_2^p and F_2^d was estimated in the range $x = 0.06$–0.8 following the analysis of Ref. 14. Correction for this would increase S_G by about 10%. Shadowing of the virtual photon in the deuteron would imply a larger F_2^n/F_2^p than observed, leading to a lower value of S_G. Fermi motion should not affect the Gottfried sum which in the quark-parton model is sensitive to the squared quark charges, independent of their momentum distributions.[17] Indeed, if one applies the Fermi-smearing correction as estimated by EMC (Ref. 4), one finds a negligible effect.

It is possible to make parametrizations[18] of parton distributions which agree with our results on the ratio[6] and are constrained to fulfill the Gottfried sum rule.[19] With these parametrizations, one-third of the sum comes from the region $x < 0.004$. In Ref. 20, however, it is pointed out that the experimental results on iron for the Gross–Llewellyn Smith sum rule may preclude a large contribution below $x = 0.01$.

Within the quark-parton model, our result implies [see Eq. (2)] an excess of $\int \sum_i e_i^2 \bar{q}_i^n dx$ over $\int \sum_i e_i^2 \bar{q}_i^p dx$. This may be interpreted as more sea in the neutron than in the proton, or, using isospin symmetry as an excess of $d\bar{d}$ sea-quark pairs in the proton [Eq. (3)]. Isospin-symmetry-breaking effects are likely to be small since they are at the level of a few MeV which is well below the QCD scale. Taking isospin to be a good symmetry, our result is then $\int (\bar{u} - \bar{d}) dx = -0.140 \pm 0.024$.

It has been pointed out[21,22] that the nonperturbative processes of nucleon dissociation into π-N and π-Δ can lead to such a flavor-asymmetric sea. Here the process $p \to n + \pi^+$ is favored over $p \to \Delta^{++} + \pi^-$, which in quark terms corresponds to favoring $u \to d + u\bar{d}$ over $d \to u + \bar{u}d$. The effect of the Pauli principle, hindering the emission of $u\bar{u}$ compared to $d\bar{d}$ pairs in the proton,[2] has been discussed in the bag model.[22] In hard QCD processes, however, the effect of the Pauli principle is unimportant.[3] In another approach[23] our result could be due to a small admixture of vector diquarks, without requiring a flavor-asymmetric sea. A more detailed investigation of a number of the above effects and a review of the literature is given in Ref. 24.

In summary, we have derived the Gottfried sum from our data on F_2^n/F_2^p and a fit to F_2^d data from other experiments, and find a result significantly below the simple quark-parton-model prediction of $\frac{1}{3}$. While a flavor-asymmetric sea appears to be a likely explanation, other effects should also be considered.

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