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Flavor asymmetry of the nucleon

R. Bijker
Instituto de Ciencias Nucleares, Universidad Nacional Autónoma de México,
Apartado Postal 70-543 México, D.F. 04510, México
e-mail:bijker@nucleares.unam.mx

E. Santopinto
I.N.F.N. and Dipartimento di Fisica,
via Dodecaneso 33, Genova, I-16146, Italy,
e-mail:santopinto@ge.infn.it

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The flavor asymmetry of the nucleon sea is discussed in an unquenched quark model for baryons in which the effects of quark-antiquark pairs ($u\bar{u}$, $d\bar{d}$ and $s\bar{s}$) are taken into account in an explicit form. The inclusion of $q\bar{q}$ pairs leads automatically to an excess of $\bar{d}$ over $\bar{u}$ quarks in the proton, in ageement with experimental data.

Keywords: Protons and neutrons; quark models; flavor symmetries; Gottfried sum rule.

Se discute la asimetría de sabor del nucleón en una extensión del modelo de cuarks en que se toman en cuenta de manera explícita los efectos de creación de pares cuark-anticuark ($u\bar{u}$, $d\bar{d}$ y $s\bar{s}$). La inclusión de los pares $q\bar{q}$ lleva inmediatamente a un exceso de cuarks $\bar{d}$ sobre $\bar{u}$ en el protón, de acuerdo con los datos experimentales.

Descriptores: Protones y neutrones, modelos de cuarks, simetría de sabor, regla de suma de Gottfried

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1. Introduction

The flavor content of the nucleon sea provides an important test for models of nucleon structure. A flavor symmetric sea leads to the Gottfried sum rule $S_G = 1/3$ [1], whereas any deviation from this value is an indication of the $\bar{d}/\bar{u}$ asymmetry of the nucleon sea. The first clear evidence of a violation of the Gottfried sum rule came from the New Muon Collaboration (NMC) [2], which was later confirmed by Drell-Yan experiments [3] and a measurement of semi-inclusive deep-inelastic scattering [4]. All experiments show evidence that there are more $\bar{d}$ quarks in the proton than there are $\bar{u}$ quarks. The experimental results and theoretical ideas on the flavor asymmetric sea are summarized in several review articles [5].

In the constituent quark model (CQM), the proton is described in terms of a uud valence-quark configuration. Therefore, a violation of the Gottfried sum rule implies the existence of higher Fock components (such as $uud - q\bar{q}$ configurations) in the proton wave function. Additional indications for the importance of multiquark components are provided by parity-violating electron scattering experiments, which have shown evidence for a nonvanishing strange quark contribution, albeit small, to the charge and magnetization distributions of the proton [6], and by CQM studies of baryon spectroscopy [7]. Whereas most models (see *e.g.* [8-11]) reproduce the mass spectrum of baryon resonances reasonably well, they show very similar deviations for other properties, such as for example the electromagnetic and strong decay widths of $\Delta(1232)$ and $N(1440)$, the spin-orbit splitting of $\Lambda(1405)$ and $\Lambda(1520)$, the low Q^2 behavior of transition form factors, and the large η decay widths of $N(1535)$, $\Lambda(1670)$ and $\Sigma(1750)$. All of these results point towards the need to include exotic degrees of freedom (*i.e.* other than qqq), such as multiquark $qqq - q\bar{q}$ or gluonic $qqq - g$ configurations. As an illustration we show in Fig. 1, the transverse electromagnetic transition form factors of the $N(1520)$ resonance for different CQMs. The problem of missing strength at low Q^2 can be attributed to the lack of explicit quark-antiquark degrees of freedom, which become more important in the outer region of the nucleon.

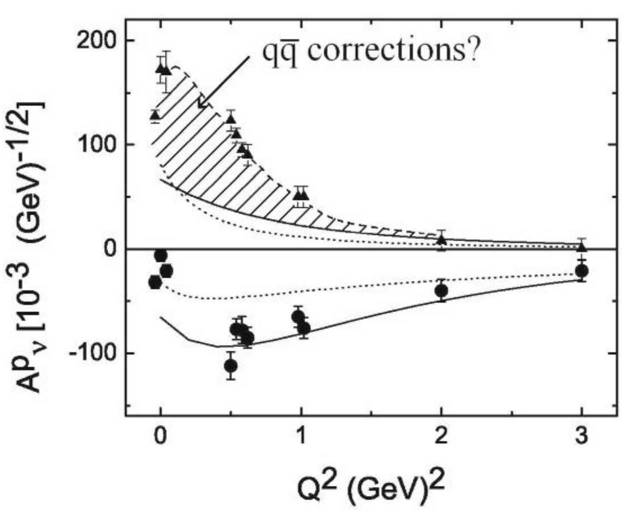

FIGURE 1. Transition form factors for the $N(1520)$ resonance. Experimental data are compared with theoretical predictions from the collective $U(7)$ model [10] (dotted line) and the hypercentral model [11] (solid line).

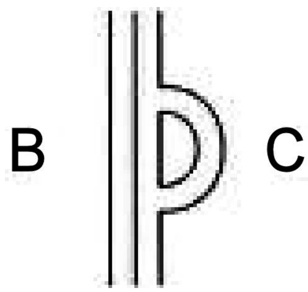

FIGURE 2. One-loop diagram at the quark level.

Theoretically, the role of $q^4\bar{q}$ configurations in the nucleon wave function was studied in an application to the electromagnetic form factors [12]. Mesonic contributions to the spin and flavor structure of the nucleon are reviewed in Ref. 5.

In another, CQM based, approach the importance of $s\bar{s}$ pairs in the proton was studied in a flux-tube breaking model based on valence-quark plus glue dominance to which $s\bar{s}$ pairs are added in perturbation [13]. The pair-creation mechanism is inserted at the quark level and the one-loop diagrams are calculated by summing over a complete set of intermediate baryon-meson states BC (see Fig. 2). For consistency with the OZI-rule and to retain the success of the CQM in hadron spectroscopy, it was found necessary to sum over a complete set of intermediate states, including both pseudoscalar and vector mesons, rather than just a few low-lying states [13,14].

In order to address the violation of the Gottfried sum rule, we first generalize the model of [13] to include $u\bar{u}$ and $d\bar{d}$ loops as well. The formalism of the ensuing unquenched quark model is reviewed briefly before discussing an application to the flavor asymmetry of the nucleon sea.

2. Unquenched quark model

In the flux-tube model for hadrons, the quark potential model arises from an adiabatic approximation to the gluonic degrees of freedom embodied in the flux tube [15]. The role of quark-antiquark pairs in meson spectroscopy was studied in a flux-tube breaking model [16] in which the $q\bar{q}$ pair is created with the $^3P_0$ quantum numbers of the vacuum. Subsequently, it was shown by Geiger and Isgur [14] that a *miraculous* set of cancellations between apparently uncorrelated sets of intermediate states occurs in such a way that they compensate each other and do not destroy the good CQM results for the mesons. In particular, the OZI hierarchy is preserved and there is a near immunity of the long-range confining potential, since the change in the linear potential due to the creation of quark-antiquark pairs in the string can be reabsorbed into a new strength of the linear potential, *i.e.* in a new string tension. As a result, the net effect of the mass shifts from pair creation is smaller than the naive expectation of the order of the strong decay widths. However, it is necessary to sum over large towers of intermediate states to see that the spectrum of the mesons, after unquenching and renormalizing, is only weakly perturbed. An important conclusion is that no simple truncation of the set of meson loops is able to reproduce such results [14].

The extension of the flux-tube breaking model to baryons requires a proper treatment of the permutation symmetry between identical quarks. As a first step, Geiger and Isgur investigated the importance of $s\bar{s}$ loops in the proton by taking into account the contribution of the six different diagrams of Fig. 3 with $q\bar{q} = s\bar{s}$ and $q_1q_2q_3 = uud$, and by using harmonic oscillator wave functions for the baryons and mesons [13]. In the conclusions, the authors emphasized that, in order to investigate the origin of the violation of the Gottfried sum rule and the spin crisis of the proton, it is necessary to extend their calculation to include $u\bar{u}$ and $d\bar{d}$ loops as well. In this contribution, we take up this challenge and present a generalization of the formalism of [13] in which quark-antiquark contributions can be studied

- for any initial baryon resonance,
- for any flavor of the quark-antiquark pair, and
- for any model of baryons and mesons.

These extensions were made possible by two developments: the solution of the problem of the permutation symmetry between identical quarks by means of group-theoretical techniques, and the construction of an algorithm to generate a complete set of intermediate states for any model of baryons and mesons. While the first improvement allows the evaluation of the contribution of quark-antiquark pairs for any initial baryon $q_1\ q_2\ q_3$ (ground state or resonance) and for any flavor of the $q\bar{q}$ pair (not only $s\bar{s}$, but also $u\bar{u}$ and $d\bar{d}$), the second one permits the carry out the sum over intermediate states up to saturation for any model of baryons and mesons, as long as their wave functions are expressed in the basis of harmonic oscillator wave functions.

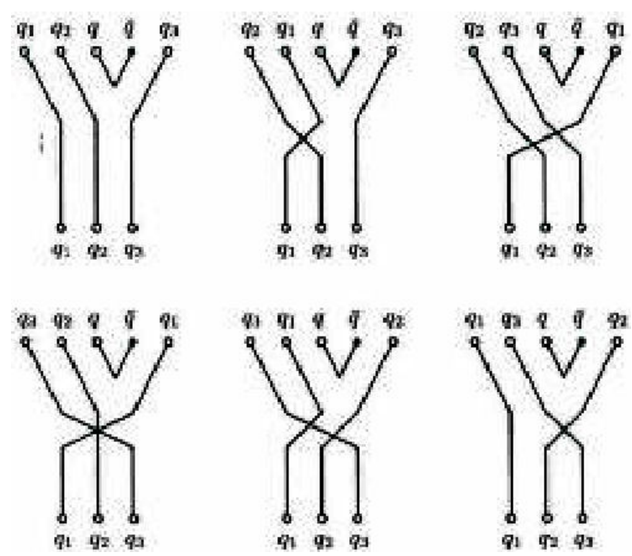

FIGURE 3. Quark line diagrams for $A \rightarrow BC$ with $q_1q_2q_3 = uud$ and $q\bar{q} = s\bar{s}$

The ensuing unquenched quark model is based on an adiabatic treatment of the flux-tube dynamics to which $q\bar{q}$ pairs with vacuum quantum numbers are added as a perturbation [13]. The pair-creation mechanism is inserted at the quark level and the one-loop diagrams are calculated by summing over a complete set of intermediate states. Under these assumptions, to leading order in pair creation, the baryon wave function is given by

$$\mid \psi_A \rangle = \mathcal{N} \left[\mid A \rangle + \sum_{BClJ} \int d\vec{k} \, \mid BC\vec{k}\, lJ \rangle \right.$$
$$\left. \times \, \frac{\langle BC\vec{k}\, lJ \mid T^{\dagger} \mid A \rangle}{M_A - E_B - E_C} \right] , \qquad (1)$$

where A denotes the initial baryon and B and C the intermediate baryon and meson, $\vec{k}$ and l represent the relative radial momentum and orbital angular momentum of B and C, and J is the total angular momentum $\vec{J} = \vec{J}_B + \vec{J}_C + \vec{l}$. The operator $T^{\dagger}$ represents the quark-antiquark pair-creation operator with the $^3P_0$ quantum numbers of the vacuum [17]

$$T^{\dagger} = -\, 3 \sum_{ij} \int d\vec{p}_i \, d\vec{p}_j \, \delta(\vec{p}_i + \vec{p}_j) \, C_{ij} \, F_{ij} \, \Gamma(\vec{p}_i - \vec{p}_j)$$
$$\times \, [\chi_{ij} \times \mathcal{Y}_1(\vec{p}_i - \vec{p}_j)]^{(0)} \, b_i^{\dagger}(\vec{p}_i) \, d_j^{\dagger}(\vec{p}_j) \, . \qquad (2)$$

Here, $b_i^{\dagger}(\vec{p}_i)$ and $d_j^{\dagger}(\vec{p}_j)$ are the creation operators for a quark and antiquark with momenta $\vec{p}_i$ and $\vec{p}_j$, respectively. The quark pair is characterized by a color singlet wave function C_{ij}, a flavor singlet wave function F_{ij} and a spin triplet wave function χ_{ij} with spin $S = 1$. The solid harmonic $\mathcal{Y}_1(\vec{p}_i - \vec{p}_j)$ indicates that the quark and antiquark are in a relative P wave.

Since the operator $T^{\dagger}$ creates a pair of constituent quarks, a Gaussian quark-antiquark creation vertex function was introduced by which the pair is created as a finite object with an effective size, rather than as a pointlike object. In momentum space it is given by

$$\Gamma(\vec{p}_i - \vec{p}_j) = \gamma_0 \, \mathrm{e}^{-r_q^2 (\vec{p}_i - \vec{p}_j)^2/6} \, . \qquad (3)$$

The width has been determined from meson decays to be approximately $0.25 - 0.35$ fm [13, 14, 18]. Here we take the average value, $r_q = 0.30$ fm. Finally, the dimensionless constant γ_0 is the intrinsic pair creation strength which has been determined from strong decays of baryons as $\gamma_0 = 2.60$ [19].

The strong coupling vertex

$$\langle BC\vec{k}\, lJ \mid T^{\dagger} \mid A \rangle \, , \qquad (4)$$

was derived in explicit form in the harmonic oscillator basis [17]. In the present calculations, we use harmonic oscillator wave functions in which there is a single oscillator parameter for the baryons and another one for the mesons which, following [13], are taken to be $\beta_{\rm baryon} = 0.32$ GeV [8] and $\beta_{\rm meson} = 0.40$ GeV [16], respectively.

In general, matrix elements of an observable $\hat{\mathcal{O}}$ can be expressed as

$$\mathcal{O} = \langle \psi_A \mid \hat{\mathcal{O}} \mid \psi_A \rangle = \mathcal{O}_{\rm val} + \mathcal{O}_{\rm sea} \, , \qquad (5)$$

where the first term denotes the contribution from the valence quarks

$$\mathcal{O}_{\rm val} = \mathcal{N}^2 \langle A \mid \hat{\mathcal{O}} \mid A \rangle \, , \qquad (6)$$

and the second term that from the $q\bar{q}$ pairs

$$\mathcal{O}_{\rm sea} = \mathcal{N}^2 \sum_{BClJ,B'C'l'J'} \int d\vec{k} d\vec{k}' \, \frac{\langle A \mid T \mid B'C'\vec{k}'l'J' \rangle}{M_A - E_{B'} - E_{C'}}$$
$$\times \, \langle B'C'\vec{k}'l'J' \mid \hat{\mathcal{O}} \mid BC\vec{k}lJ \rangle$$
$$\times \, \frac{\langle BC\vec{k}lJ \mid T^{\dagger} \mid A \rangle}{M_A - E_B - E_C} \, . \qquad (7)$$

We developed an algorithm based upon group-theoretical techniques to generate a complete set of intermediate states of good permutational symmetry, which makes it possible to perform the sum over intermediate states up to saturation, and not just for the first few shells as in Ref. 13. Not only does this have a significant impact on the numerical result, but it is necessary for consistency with the OZI-rule and the success of CQMs in hadron spectroscopy.

3. Flavor asymmetry

The first clear evidence for the flavor asymmetry of the nucleon sea was provided by NMC at CERN [2]. The flavor asymmetry is related to the Gottfried integral for the difference of the proton and neutron electromagnetic structure functions

$$S_G = \int_0^1 dx \frac{F_2^p(x) - F_2^n(x)}{x}$$
$$= \frac{1}{3} - \frac{2}{3} \int_0^1 dx \left[\bar{d}(x) - \bar{u}(x) \right]$$
$$= \frac{1}{3} \left[1 - 2(N_{\bar{d}} - N_{\bar{u}}) \right] \, . \qquad (8)$$

Under the assumption of a flavor symmetric sea $\bar{d}(x) = \bar{u}(x)$ one obtains the Gottfried sum rule $S_G = 1/3$. The final NMC value is 0.2281 ± 0.0065 at $Q^2 = 4$ (GeV/c)^2 for the Gottfried integral over the range $0.004 \leq x \leq 0.8$ [2], which implies a flavor asymmetric sea. The violation of the Gottfried sum rule has been confirmed by other experimental collaborations [3, 4]. Table I shows that the experimental values of the Gottfried integral are consistent with each other within the quoted uncertainties, even though the experiments were performed at very different scales, as reflected in the average Q^2 values. Theoretically, it was shown that in the

TABLE I. Experimental values of the Gottfried integral.

Experiment	$\langle Q^2 \rangle$	x range	S_G
NMC	4	$0.004 < x < 0.80$	0.2281 ± 0.0065
HERMES	2.3	$0.020 < x < 0.30$	0.23 ± 0.02
E866/NuSea	54	$0.015 < x < 0.35$	0.255 ± 0.008

framework of the cloudy bag model the coupling of the proton to the pion cloud provides a mechanism to produce a flavor asymmetry due to the dominance of $n\pi^+$ among the virtual configurations [20].

In the unquenched quark model, the flavor asymmetry can be calculated from the difference of the number of $\bar{d}$ and $\bar{u}$ sea quarks in the proton

$$\hat{\mathcal{O}} = \hat{N}_{\bar{d}} - \hat{N}_{\bar{u}} \; . \tag{9}$$

Even in absence of explicit information on the (anti)quark distribution functions, the integrated value can be obtained directly from Eq. (9). The effect of the quark-antiquark pairs on the Gottfried integral is a reduction of about one third with respect to the Gottfried sum rule, corresponding to an excess of $\bar{d}$ over $\bar{u}$ quarks in the proton which is in qualitative agreement with the NMC result.

An explicit calculation with harmonic oscillator wave functions for the baryons and mesons in which the sum over intermediate states includes four oscillator shells, shows a proton asymmetry $A_{\rm asym}(p) = N_{\bar{d}} - N_{\bar{u}} = 0.21$ which corresponds to $S_G = 0.19$, in remarkable agreement with the experimental value. It is important to note that in this calculation the parameters were taken from the literature [13,19], and that no attempt was made to optimize their values. Due to isospin symmetry, the neutron has a similar excess of $\bar{u}$ over $\bar{d}$ quarks $A_{\rm asym}(n) = N_{\bar{u}} - N_{\bar{d}} = 0.21$.

4. Summary and conclusions

In this contribution, we discussed the importance of quark-antiquark pairs in baryon spectroscopy. To this end, we developed an unquenched quark model for baryons in which the contributions from $u\bar{u}$, $d\bar{d}$ and $s\bar{s}$ loops are taken into account in a systematic way. The present model is an extension of the flux-tube breaking model of Geiger and Isgur [13], and is valid for any initial baryon resonance, any flavor of the quark-antiquark pair and any model of baryons and mesons.

The model was applied to the flavor asymmetry of the nucleon sea. In a first calculation with harmonic oscillator wave functions for both baryons and mesons in which the parameters were taken from the literature [13,19], it was shown that the inclusion of $q\bar{q}$ pairs leads automatically to an excess of $\bar{d}$ over $\bar{u}$ quarks in the proton. The value that we obtained for the violation of the Gottfried sum rule is in amazing agreement with the experimental data. We emphasize that no attempt was made to optimize the parameters in the calculations.

The first applications of the unquenched quark model to the flavor asymmetry of the nucleon sea and the proton spin [21] are very promising and encouraging. We believe that the inclusion of the effects of quark-antiquark pairs in a general and consistent way may provide a major improvement to the constituent quark model, which increases considerably its range and applicability. In future work, the present unquenched quark model will be applied systematically to several problems in light baryon spectroscopy, such as the electromagnetic and strong couplings, the elastic and transition form factors of baryon resonances, their sea quark content and their flavor decomposition [22].

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1. K. Gottfried, *Phys. Rev. Lett.* **18** (1967) 1174.
2. P. Amaudruz *et al.*, *Phys. Rev. Lett.* **66** (1991) 2712; M. Arneodo *et al.*, *Nucl. Phys. B* **487** (1997) 3.
3. A. Baldit *et al.*, *Phys. Lett. B* **332** (1994) 244; R.S. Towell *et al.*, *Phys. Rev. D* **64** (2001) 052002.
4. K. Ackerstaff *et al.*, *Phys. Rev. Lett.* **81** (1998) 5519.
5. S. Kumano, *Phys. Rep.* **303**, 183 (1998); J. Speth and A.W. Thomas, *Adv. Nucl. Phys.* **24** (1998) 83; G.T. Garvey and J.-C. Peng, *Prog. Part. Nucl. Phys.* **47** (2001) 203.
6. A. Acha *et al.*, *Phys. Rev. Lett.* **98** (2007) 032301.
7. See *e.g. N* Physics, Proceedings of the Fourth CEBAF/INT Workshop*, Eds. T.-S.H. Lee and W. Roberts (*World Scientific*, 1997); N. Isgur, *Nucl. Phys. A* **623** (1997) 37c.
8. N. Isgur and G. Karl, *Phys. Rev. D* **20** (1979) 1191.
9. S. Capstick and N. Isgur, *Phys. Rev. D* **34** (1986) 2809; R. Bijker, F. Iachello and A. Leviatan, *Ann. Phys. (N.Y.)* **236** (1994) 69; *ibid.* **284** (2000) 89 ; *Phys. Rev. D* **55** (1997) 2862; M. Ferraris, M.M. Giannini, M. Pizzo, E. Santopinto and L. Tiator, *Phys. Lett. B* **364** (1995) 231; M. Aiello, M. Ferraris, M.M. Giannini, M. Pizzo and E. Santopinto, *Phys. Lett. B* **387** (1996) 215. L.Ya. Glozman and D.O. Riska, *Phys. Rep.* **268** (1996) 263; L.Ya. Glozman, W. Plessas, K. Varga and R.F. Wagenbrunn, *Phys. Rev. D* **58** (1998) 094030; U. Löring, K. Kretzschmar, B.Ch. Metsch, H.R. Petry, *Eur. Phys. J. A* **10** (2001) 309; U. Löring, B.Ch. Metsch, H.R. Petry, *Eur. Phys. J. A* **10** (2001) 447.

10. R. Bijker, F. Iachello and A. Leviatan, *Phys. Rev. C* **54** (1996) 1935 .
11. M. Aiello, M.M. Giannini and E. Santopinto, *J. Phys. G: Nucl. Part. Phys.* **24** (1998) 753.
12. Q.B. Li and D.O. Riska, *Nucl. Phys. A* **791** (2007) 406.
13. P. Geiger and N. Isgur, *Phys. Rev. D* **55** (1997) 299.
14. P. Geiger and N. Isgur, *Phys. Rev. Lett.* **67** (1991) 1066; *Phys. Rev. D* **44** (1991) 799; *ibid.* **47** (1993) 5050.
15. N. Isgur and J. Paton, *Phys. Rev. D* **31** (1985) 2910.
16. R. Kokoski and N. Isgur, *Phys. Rev. D* **35** (1987) 907.
17. W. Roberts and B. Silvestre-Brac, *Few-Body Systems* **11** (1992) 171.
18. B. Silvestre-Brac and C. Gignoux, *Phys. Rev. D* **43** (1991) 3699.
19. S. Capstick and W. Roberts, *Phys. Rev. D* **49** (1994) 4570.
20. A.W. Thomas, *Phys. Lett. B* **126** (1983) 97;
E.M. Henley and G.A. Miller, *Phys. Lett. B* **251** (1990) 453.
21. R. Bijker and E. Santopinto, *AIP Conference Proceedings* **947** (2007) 168.
22. R. Bijker and E. Santopinto, *work in progress.*