Spin and flavor content of octet baryons

Roelof Bijker\(^1\) and Elena Santopinto\(^2\)
\(^1\) Instituto de Ciencias Nucleares, Universidad Nacional Autónoma de México, AP 70-543, 04510 Mexico DF, Mexico
\(^2\) I.N.F.N., Sezione di Genova, via Dodecaneso 33, 16164 Genova, Italy
E-mail: bijker@nucleares.unam.mx

Abstract. We discuss the spin and flavor content of the proton in an unquenched quark model. It is shown that the inclusion of hadron loops leads automatically to an excess of \(\bar{d}\) over \(\bar{u}\) and introduces a sizeable contribution of orbital angular momentum to the spin of the proton. Whereas the flavor asymmetry and the orbital angular momentum are dominated by pion loops, the contribution of the sea quark spins to the proton spin arises almost entirely from (excited) vector meson loops.

1. Introduction
In the constituent quark model (CQM) hadrons are described in terms of system of constituent (or valence) quarks and antiquarks, \(qqq\) for baryons and \(q\bar{q}\) for mesons. Despite the success of the quark model there is strong evidence for the existence of exotic degrees of freedom (other than valence quarks) in hadrons, in particular for the need to include the effects of quark-antiquark pairs (hadron loops). The importance of these quark-antiquark configurations (or higher Fock components in baryon wave functions) is evident from measurements of the \(\bar{d}/\bar{u}\) asymmetry in the nucleon sea [1], parity-violating electron scattering experiments [2, 3], the proton spin crisis [4], as well as from analysis of helicity amplitudes [5] and strong couplings of baryon resonances [6, 7].

The aim of this contribution is to study the spin and flavor content of the proton in an unquenched quark model in which the effects of quark-antiquark pair creation \((\bar{u}u, \bar{d}d\) and \(ss))\) are taken into account in an explicit form via a \(^3P_0\) coupling mechanism [8, 9, 10]. The numerical results for the flavor asymmetry [9] and the proton spin [8] are analyzed by means of a simple exactly solvable meson-cloud model. Finally, we show some predictions for other octet baryons as well.

2. Unquenched quark model
The impact of \(q\bar{q}\) pairs in hadron spectroscopy was originally studied by Törnqvist and Zen czykowski in a quark model extended by the \(^3P_0\) model [11]. Subsequently, the effects of hadron loops in mesons was studied by Geiger and Isgur in a flux-tube breaking model in which the \(q\bar{q}\) pairs are created in the \(^3P_0\) state with the quantum numbers of the vacuum [12, 13]. It was shown that cancellations between apparently uncorrelated sets of intermediate states occur in such a way that the modification in the linear potential can be reabsorbed, after renormalization, in the new strength of the linear potential [12]. In addition, the quark-antiquark pairs do not destroy the good CQM results for the mesons [12] and preserve the OZI hierarchy [13] provided
Figure 1. One-loop diagram at the quark level.

that the sum be carried out over a large tower of intermediate states. The basic idea of the importance to carry out a sum over a complete set of intermediate states was already contained in [11]. An extension to baryons was presented in [14] in which the effects of $s\bar{s}$ loops in the proton were studied combining harmonic oscillator wave functions for baryons and mesons and a $3P_0$ pair creation mechanism.

The present approach is motivated by earlier studies on extensions of the quark model that employ a $3P_0$ model for the $q\bar{q}$ pair creation [11, 14]. Our approach is based on a CQM to which the quark-antiquark pairs with vacuum quantum numbers are added as a perturbation [8, 9, 14]. 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 in Fig. 1). Under these assumptions, the baryon wave function consists of a zeroth order three-quark configuration $|A\rangle$ plus a sum over all possible higher Fock components due to the creation of $3P_0$ quark-antiquark pairs

$$
|\psi_A\rangle = \mathcal{N} \left[ |A\rangle + \sum_{BCIJ} \int d\vec{k} \ |BC\vec{k}lJ\rangle \frac{(BC\vec{k}lJ | T^\dagger | A\rangle}{M_A - E_B - E_C} \right].
$$

(1)

Here A denotes the initial baryon, B and C represent the intermediate baryon and meson, and $M_A$, $E_B$ and $E_C$ are their respective energies, $\vec{k}$ and $l$ 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 $T^\dagger$ creates a quark-antiquark pair in the $3P_0$ state with the quantum numbers of the vacuum: $L = S = 1$ and $J = 0$, color singlet and flavor singlet [8, 9, 15]. Therefore, the $SU(3)$ flavor symmetry of the valence quark configuration $|A\rangle$ is broken by the quark-antiquark pairs via the energy denominator, but the $SU(2)$ isospin symmetry is still preserved. In the special case of the closure limit in which the energy denominator of Eq. (1) is a constant, the flavor symmetry of the valence quark configuration is recovered.

In order to calculate the effects of quark-antiquark pairs on an observable, one has to evaluate the contribution of all possible intermediate states. By using a combination of group theoretical and computational techniques, the sum over intermediate states is carried out up to saturation and not only for the first few shells as in previous studies [11, 14]. In addition, the contributions of quark-antiquark pairs can be evaluated for any initial baryon (ground state or resonance) and for any flavor of the $q\bar{q}$ pair (not only $s\bar{s}$ as in [14], but also $u\bar{u}$ and $d\bar{d}$), and for any model of baryons and mesons, as long as their wave functions are expressed in the basis of harmonic oscillator wave functions [8, 9].

The unquenching of the quark model has to be done in such a way as to maintain the phenomenological successes of the CQM. In applications to mesons, it was shown that the inclusion of quark-antiquark pairs does not destroy the good CQM results [12] and preserves
Table 1. Contributions to the flavor asymmetry of the proton [9]. \( N^2 = 1 + a^2 + b^2 + c^2 + d^2 \) is the normalization factor of the wave function of Eq. (3).

|                      | Unquenced QM 0-4 \( \hbar \omega \) | 0 \( \hbar \omega \) | Meson-Cloud Eq. (4) |
|----------------------|-------------------------------------|----------------------|---------------------|
| \( N\pi \)          | 0.195                               | 0.177                | 2\( a^2/3N^2 \)     |
| \( \Delta\pi \)     | -0.016                              | -0.010               | -\( b^2/3N^2 \)     |
| \( N\pi\eta\eta_1 \)| -0.028                              | -0.018               | -2\( a(c + d\sqrt{2})/3N^2 \) |
| \( N\rho \)         | 0.050                               | 0.012                |                     |
| \( \Delta\rho \)    | -0.017                              | -0.003               |                     |
| \( N\rho\omega\omega_1 \)| -0.033                              | -0.010               |                     |
| **Total**            | 0.151                               | 0.147                |                     |

the OZI hierarchy [13]. In a similar fashion, we showed that the CQM results for the magnetic moments of the octet baryons also hold in the unquenched constituent quark model (UCQM) [8].

In this contribution, we use harmonic oscillator wave functions up to five oscillator shells for the intermediate baryons and mesons. All parameters were taken from the literature without attempting to optimize their values in order to improve the agreement with experimental data [8, 9].

3. Flavor content

The flavor asymmetry of the proton \( \mathcal{A}(p) \) is related to the Gottfried integral \( S_G \) for the difference of the proton and neutron electromagnetic structure functions as

\[
S_G = \int_0^1 \frac{F_2^p(x) - F_2^n(x)}{x} \, dx = \frac{1}{3} - \frac{2}{3} \int_0^1 [\bar{d}_p(x) - \bar{u}_p(x)] \, dx = \frac{1}{3}[1 - 2\mathcal{A}(p)] .
\]

Under the assumption of a flavor symmetric (or rather flavor independent) sea one obtains the Gottfried sum rule \( S_G = 1/3 \) [16, 1], whereas any deviation from this value is an indication of the \( \bar{d}/\bar{u} \) asymmetry of the nucleon sea, thus providing evidence of the existence of higher Fock components (such as \( qqq - \bar{q}\bar{q} \) configurations) in the proton wave function. The first clear evidence of a violation of the Gottfried sum rule came from the New Muon Collaboration (NMC) [17] which was later confirmed by Drell-Yan experiments [18, 19] and a measurement of semi-inclusive deep-inelastic scattering [20]. All experiments show evidence that there are more \( \bar{d} \) quarks in the proton than there are \( \bar{u} \) quarks [1]. The final NMC value is 0.2281 ± 0.0065 at \( Q^2 = 4 \text{ (GeV/c)}^2 \) for the Gottfried integral over the range 0.004 \( \leq x \leq 0.8 \) [17], which implies a flavor asymmetric sea. The observed flavor asymmetry is far too large to be accounted for by processes that can be described by QCD in perturbative regime and therefore has to attributed to non-perturbative QCD mechanisms. It was shown in the framework of the meson-cloud model, that the coupling of the nucleon to the pion cloud provides a mechanism that is able to produce a flavor asymmetry due to the dominance of \( n\pi^+ \) among the virtual configurations [21].

In the unquenched quark model, the flavor asymmetry of the proton can be calculated directly from the difference of the number of \( d \) and \( \bar{u} \) sea quarks in the proton, even in the absence of explicit information on the (anti)quark distribution functions. Table 1 shows that the flavor asymmetry for the proton in the UCQM is 0.151 which corresponds to a value of the Gottfried integral of 0.232, remarkably close to the experimental value. The main contribution to the flavor asymmetry of the proton is due to the pion loops, especially the \( n\pi^+ \) intermediate state, thus confirming in an explicit calculation the explanation given in Refs. [21] in the context of
the meson-cloud model. In addition, we find that there are important contributions from the
\( \Delta\pi \) channel and, especially, from the off-diagonal terms \( p\pi^0-\eta_8 \) and \( p\pi^0-\eta_1 \) which together are of the order of 15-20 \% of that of the \( N\pi \) channel, but with the opposite sign (see Table 1).

The contribution of the intermediate vector mesons is very small due to a cancelation between
the \( np^+ \) and the \( \Delta p \) channels and the cross terms \( pp^0-\rho_8 \) and \( pp^0-\rho_1 \). Kaon loops do not contribute to the proton flavor asymmetry. Table 1 shows that the full four-shell calculation
is dominated by the contribution of the ground state intermediate baryons and mesons (0 \( \hbar\omega \)). Both columns show the same qualitative behavior: dominance of the pion loops with a small
negative correction of the order of 10-15 \% due to the off-diagonal terms involving \( \pi \) and \( \eta \)
pseudoscalar mesons and an almost vanishing contribution from the vector mesons.

A similar result can be obtained in the meson-cloud model by considering a proton wave function including not only pion loops but also eta loops

\[
|\psi_p\rangle \rightarrow |p\rangle + a \left[ \frac{1}{\sqrt{3}} |p\pi^0\rangle - \sqrt{\frac{3}{2}} |n\pi^+\rangle \right] + c |N\eta_8\rangle + d |N\eta_1\rangle + b \left[ \frac{1}{\sqrt{2}} |\Delta^{++}\pi^-\rangle - \frac{1}{\sqrt{3}} |\Delta^{++}\pi^0\rangle + \frac{1}{\sqrt{6}} |\Delta^{++}\pi^+\rangle \right]. \tag{3}
\]

In the last column of Table 1 we show the contributions of the different terms of Eq. (3) to the
flavor asymmetry of the proton to obtain

\[
A(p) = \frac{2a^2 - b^2 - 2a(c + d\sqrt{2})}{3(1 + a^2 + b^2 + c^2 + d^2)}. \tag{4}
\]

Since the unquenched quark model is valid not only for the proton, but for all baryons
(ground state or resonance), it is straightforward to calculate the flavor asymmetries of the
other octet baryons. For the \( \Sigma^+ \) hyperon and the \( \Xi^0 \) cascade particle we find
\( A(\Sigma^+) = 0.126 \) and \( A(\Xi^0) = -0.001 \) [9], respectively. The flavor asymmetries of the remaining octet baryons can be obtained by using the isospin symmetry of the unquenched quark model [9]. For example, the excess of \( d \) over \( u \) in the proton is related to the excess of \( \bar{u} \) over \( \bar{d} \) in the neutron, \( A(p) = -A(n) \). Similar relations hold for the other octet baryons: \( A(\Sigma^+) = -A(\Sigma^-) \), \( A(\Xi^0) = -A(\Xi^-) \) and \( A(\Lambda) = A(\Xi^0) = 0 \). Just as for the proton, the flavor asymmetry of the other octet baryons is expected to be dominated by pion loops, whereas the other contributions are suppressed by the
energy denominator in Eq. (1). For the \( \Sigma \) hyperon this is indeed the case, but for the cascade
particles the pion loops are suppressed by the value of the \( SU(3) \) flavor coupling which is a
factor of 5 smaller than that for the proton. Hence for the \( \Xi \) hyperons there is no dominant
contribution. Since for the \( \Xi \) hyperon all contributions are roughly of the same order and small, and moreover some with a positive and others with a negative sign, the value of the flavor asymmetry of the cascade particles is calculated to be small [9].

In Table 2, we show a comparison of some predictions for the flavor asymmetry of the \( \Sigma^+ \)
and \( \Xi^0 \) hyperons relative to that of the proton. In the unquenched quark model, the flavor asymmetry of the proton is predicted to be of the same order as that of the \( \Sigma^+ \) hyperon and much larger than that of the cascade particle

\[
A(p) \sim A(\Sigma^+) \gg |A(\Xi^0)|. \tag{5}
\]

This behavior is very different from that obtained in the chiral quark model \( A(\Sigma^+) = 2A(p) = 2A(\Xi^0) \) [22], the balance model \( A(\Sigma^+) > A(\Xi^0) > A(p) \) [23], and the octet model \( A(p) > |A(\Xi^0)| > A(\Sigma^+) \) [24]. The values for the chiral quark model and the balance model were taken from [25].
Table 2. Relative flavor asymmetries of octet baryons.

| Model            | $A(\Sigma^+)/A(p)$ | $A(\Xi^0)/A(p)$ | Ref. |
|------------------|---------------------|------------------|------|
| Unquenched CQM   | 0.833               | −0.005           | [9]  |
| Chiral QM        |                     |                  | [22] |
| Balance Model    | 3.083               | 2.075            | [23] |
| Octet couplings  | 0.353               | −0.647           | [24] |

In order to distinguish between the predictions of the different models and to obtain a better understanding of the non-perturbative structure of QCD, new experiments are needed to measure the flavor asymmetry of hyperons. In particular, the flavor asymmetry of charged Σ hyperons can obtained from Drell-Yan experiments using charged hyperon beams on the proton [24] or by means of backward $K^\pm$ electroproduction [26].

4. Spin content

The contribution of the quark spins to the spin of the proton can be obtained from the proton spin structure function $g_1^p$ in combination with the neutron and hyperon semileptonic decays [4]. The observation by the European Muon Collaboration that the total quark spin constitutes only a small fraction of the spin of the nucleon [27] sparked an enormous interest in the spin structure of the proton [4]. Recent experiments show that approximately one third of the proton spin is carried by quarks [28, 29], and that the gluon contribution is rather small (either positive or negative) and compatible with zero [30]. This rules out the possibility that most of the missing spin be carried by the gluon and indicates that the origin of the missing spin of the proton has to be attributed to other mechanisms.

In the unquenched quark model, the effect of hadron loops on the fraction of the proton spin carried by the quark (antiquark) spins and orbital angular momentum can be studied in an explicit way [8]. As in other effective models [4], gluonic effects associated with the axial anomaly are not included, and therefore the contribution from the gluons is missing from the outset. The total spin of the proton can then be written as the sum of the contributions from the quark (and antiquark) spins and orbital angular momentum

$$1 = 2\Delta J = \Delta\Sigma + 2\Delta L .$$

Table 3 shows that the inclusion of the quark-antiquark pairs has a dramatic effect on the spin content of the proton. Whereas in the CQM the proton spin is carried entirely by the (valence) quarks, in the unquenched calculation the contributions of the valence quark spins, the sea quark spins and the orbital angular momentum to the proton spin are comparable in size and equal to approximately 38, 30 and 32 %, respectively. The importance of orbital angular momentum to the proton spin was discussed many years ago by Sehgal [31] and Ratcliffe [32] in the context of the quark-parton model and, more recently, by Myhrer and Thomas in framework of the bag model [33].

These results can be understood in a qualitative way by considering the proton wave function of Eq. (3), whose contribution to the orbital angular momentum can be derived as

$$\Delta L = \frac{2a^2 - b^2 + 2c^2 + 2d^2}{3(1 + a^2 + b^2 + c^2 + d^2)} .$$

The effects of pion loops for the proton flavor asymmetry and the contribution of orbital angular momentum to the proton spin are identical as a consequence of the spin and isospin.
Table 3. Contribution of quark spins $\Delta \Sigma$ and orbital angular momentum $\Delta L$ to the spin of the proton and the $\Lambda$ hyperon.

|        | CQM          | Unquenched QM |
|--------|--------------|---------------|
|        | Valence     | Sea | Total |
| $p$ $\Delta \Sigma$ | 1  | 0.378 | 0.298 | 0.676 |
| 2$\Delta L$ | 0  | 0.000 | 0.324 | 0.324 |
| 2$\Delta J$ | 1  | 0.378 | 0.622 | 1.000 |
| $\Lambda$ $\Delta \Sigma$ | 1  | 0.422 | 0.429 | 0.851 |
| 2$\Delta L$ | 0  | 0.000 | 0.149 | 0.149 |
| 2$\Delta J$ | 1  | 0.422 | 0.578 | 1.000 |

properties [34]. Since in the unquenched calculations both the flavor asymmetry and the orbital angular momentum are dominated by pion loops (see Tables 1 and 4), this relation is to a good approximation still valid in the UCQM, $A(p) = 0.151$ and $\Delta L = 0.162$, respectively. Table 4 shows that, just as for the flavor asymmetry, the orbital angular momentum is dominated by the contribution of the ground state intermediate baryons and mesons (0 $h\omega$) and in particular by the $N\pi$ channel. The contributions of the eta and kaon loops to the orbital angular momentum, as well as that of the vector mesons, are small with respect to that of the pions.

The situation for the quark spins is completely different. In the unquenched calculations, the contributions of valence and sea quarks are given by $\Delta \Sigma_{\text{val}} = 0.378$ and $\Delta \Sigma_{\text{sea}} = 0.298$, respectively. While the orbital angular momentum arises almost entirely from the $N\pi$ channel, the sea quark spins are dominated by the intermediate vector mesons with a very small contribution from the pseudoscalar mesons (see second column of Table 5). The third column of Table 5 shows that the contribution of the ground state intermediate baryons and mesons (0 $h\omega$) is small for both the pseudoscalar and vector mesons, whereas the full calculation is dominated by the contribution of the vector mesons. This shows that for the sea quark spins it is crucial to include the effects of the excited vector mesons which makes the convergence of the sum over intermediate states is much slower. Therefore, the sum was carried out over five complete oscillator shells for both the intermediate baryons and mesons [8].

In a simple meson-cloud model based on ground state baryons and mesons only, the contribution of the sea quark spins is very small. For example, for the proton wave function of Eq. (3) in which only pion and eta loops are taken into account, the contribution of the quark spins is given by $\Delta \Sigma = \Delta \Sigma_{\text{val}} + \Delta \Sigma_{\text{sea}} = 1 - 2\Delta L$ with

$$\Delta \Sigma_{\text{val}} = \frac{1}{1 + a^2 + b^2 + c^2 + d^2},$$

$$\Delta \Sigma_{\text{sea}} = \frac{-a^2 + 5b^2 - c^2 - d^2}{3(1 + a^2 + b^2 + c^2 + d^2)}.$$  

With the values of the coefficients $a$, $b$, $c$ and $d$, as determined by comparing the third and fourth columns of Tables 4 and 5, we find that for this case the contribution of the sea quark spins is very small $\Delta \Sigma_{\text{sea}} = -0.035$.

The experimental data on the spin structure of the proton have raised many questions about the contributions of valence and sea quarks, gluons and orbital angular momentum to the proton spin. In this respect it is of interest to investigate the spin structure of other octet baryons, in particular the $\Lambda$ hyperon. In most studies, additional assumptions had to be made about the sea quarks in order to get an estimate of its spin content. For example, the assumption that both
Table 4. Contribution of the orbital angular momentum $2\Delta L$ to the spin of the proton. $N^2 = 1 + a^2 + b^2 + c^2 + d^2$ is the normalization factor of the wave function of Eq. (3).

|             | Unquenched QM | Meson-Cloud |
|-------------|---------------|-------------|
|             | 0-5 $\hbar\omega$ | 0 $\hbar\omega$ | Eq. (7) |
| $N\pi$      | 0.370         | 0.336       | $4a^2/3N^2$ |
| $\Delta\pi$ | -0.027        | -0.020      | $-2b^2/3N^2$ |
| $N\eta_8, N\eta_1$ | 0.007         | 0.0012      | $4(c^2 + d^2)/3N^2$ |
| $\Sigma K, \Lambda K$ | 0.016         | 0.004       |         |
| Pseudoscalar | 0.367         | 0.321       |         |
| Vector      | -0.043        | -0.011      |         |
| **Total**   | **0.324**     | **0.310**   |         |

Table 5. Contribution of the sea quark spins $\Delta\Sigma_{\text{sea}}$ to the spin of the proton.

|             | Unquenched QM | Meson-Cloud |
|-------------|---------------|-------------|
|             | 0-5 $\hbar\omega$ | 0 $\hbar\omega$ | Eq. (8) |
| $N\pi$      | -0.089        | -0.084      | $-a^2/3N^2$ |
| $\Delta\pi$ | 0.074         | 0.049       | $5b^2/3N^2$ |
| $N\eta_8, N\eta_1$ | 0.006         | -0.0003     | $-(c^2 + d^2)/3N^2$ |
| $\Sigma K, \Lambda K$ | 0.013         | 0.002       |         |
| Pseudoscalar | 0.005         | -0.033      |         |
| Vector      | 0.293         | 0.052       |         |
| **Total**   | **0.298**     | **0.019**   |         |

Valence and sea quarks are related by $SU(3)$ flavor symmetry, allows to express the spin content of the $\Lambda$ hyperon in terms of that of the proton [35, 36, 37] and gives rise to equal contributions of the quark spins $(\Delta\Sigma)_\Lambda = (\Delta\Sigma)_p$. In the unquenched quark model there is no need to make additional assumptions about the nature of the sea. Table 3 shows that the contribution of quark spins for the $\Lambda$ is larger than that for the proton, $(\Delta\Sigma)_\Lambda > (\Delta\Sigma)_p$, which is a result of $SU(3)$ flavor breaking by the sea quarks.

5. Summary and conclusions

In this contribution, we presented some recent work on unquenching the quark model in which the effects of hadron loops are taken into account via a $^3P_0$ pair creation model. In particular, we studied the spin and flavor content of the proton and presented an analysis of the numerical results by means of a simple exactly solvable meson-cloud model including pion and eta loops.

The inclusion of the $q\bar{q}$ pairs leads automatically to an excess of $\bar{d}$ over $\bar{u}$ quarks, in agreement with the observed flavor asymmetry of the proton. The results for the flavor asymmetry of the proton are dominated by the $N\pi$ channel, but with important contributions from the $\Delta\pi$ channel and the off-diagonal $N\pi-N\eta$ terms. The contributions from orbitally excited intermediate baryons and mesons is small.

Similarly, the inclusion of hadron loops leads to a sizeable contribution of the orbital angular momentum to the spin of the proton ($\sim 32\%$). Just as in the case of the flavor asymmetry, the contribution of orbital angular momentum to the spin of the proton is dominated by pion loops with relatively small contributions from the other channels. However, the contribution of sea quark spins to the spin of the proton ($\sim 30\%$) is almost entirely due to excited vector mesons.
We note, that the latter contribution is absent in meson-cloud models. Even though different models of hadron structure may show similar results for the properties of the proton, often their predictions for the other octet baryons exhibit large variations. Therefore, in order to be able to distinguish between the predictions of different models of hadron structure and to obtain a better understanding of the non-perturbative structure of QCD new experiments are needed to measure the flavor asymmetry and spin content of other octet baryons.

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