Structure of the nucleon in the unquenched quark model

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Abstract. We discuss the flavor asymmetry of the nucleon sea and the spin 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 and the $\Lambda$ hyperon. Special attention is paid to the symmetries of the unquenched quark model.

1. Introduction

One of the challenges of hadronic physics is to understand the structure of the nucleon and its excited states in terms of effective degrees of freedom and, at a more fundamental level, the emergence of these effective degrees of freedom from QCD, the underlying theory of quarks and gluons [1]. The constituent quark model (CQM) is an effective model that has been very successful in explaining hadron properties in terms of system of constituent quarks and antiquarks, $qqq$ for baryons and $q\bar{q}$ for mesons. Nevertheless, there is compelling 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 pair creation. The importance of 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 [2], parity-violating electron scattering experiments [3, 4], the proton spin crisis [5], as well as analysis of helicity amplitudes [6] and strong couplings of baryon resonances [7, 8].

The aim of this contribution is to study the flavor asymmetry and the spin of the proton in an unquenched quark model in which the effects of quark-antiquark pair creation ($u\bar{u}$, $d\bar{d}$ and $s\bar{s}$) are taken into account in an explicit form via a $^3P_0$ coupling mechanism [9]. In addition, we show some predictions for the other octet baryons.

2. Unquenched quark model

The present work on the unquenched quark model for baryons is motivated by earlier studies on extensions of the quark model that employ a $^3P_0$ model for the $q\bar{q}$ pair creation [10, 11]. Our approach is based on a CQM to which the quark-antiquark pairs with vacuum quantum numbers are added as a perturbation [9, 11]. The pair-creation mechanism is inserted at the quark level and the one-loop diagrams are calculated by summing over all possible intermediate states. 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

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

where $B$ and $C$ represent the intermediate baryon and meson, respectively. The operator $T^\dagger$ creates a $^3P_0$ quark-antiquark pair in a flavor singlet state [9, 12]. 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 closure limit, the energy denominator reduces to a constant and the higher Fock components of the baryon wave function have the same flavor symmetry as the valence quark configuration.

In order to calculate the effects of quark-antiquark pairs on an observable, one has to evaluate the contribution of all possible intermediate states. We developed a combination of group theoretical and computational techniques which makes it possible to perform the sum over intermediate states up to saturation and not only for the first few shells as in previous studies [10, 11]. In addition, it allows the evaluation of the contributions of quark-antiquark pairs for any initial baryon (ground state or resonance) and for any flavor of the quark-antiquark pair (not only $s\bar{s}$ as in [11], 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 [9].

The results of the unquenched calculations presented in this contribution are obtained by using a harmonic oscillator quark model for both baryons and mesons. The sum over intermediate states is carried out over five oscillator shells for both the intermediate baryons and mesons. In the unquenched calculations all parameters are taken from the literature without attempting to optimize their values in order to improve the agreement with experimental data [9]. Obviously, 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 [13] and preserves the OZI hierarchy [14]. In a similar fashion, we showed that the CQM results for the magnetic moments of the octet baryons also hold in the unquenched quark model [9].

### 3. Flavor asymmetry

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 $S_G = 1/3$, whereas any deviation from this value is an indication of the $\vec{d}/\bar{u}$ asymmetry of the nucleon sea, thus providing evidence of the existence of higher Fock components (such as $qq\bar{q} - \bar{q}q$ 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) [15], which was later confirmed by Drell-Yan experiments [16, 17] and a measurement of semi-inclusive deep-inelastic scattering [18]. All experiments show evidence that there are more $\bar{d}$ quarks in the proton than there are $\bar{u}$ quarks [2].

The flavor asymmetry is related to the Gottfried integral for the difference of the proton and neutron electromagnetic structure functions

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

Under the assumption of a flavor symmetric sea one obtains the Gottfried sum rule $S_G = 1/3$. The final NMC value is $0.2281 \pm 0.0065$ at $Q^2 = 4 \text{ (GeV/c)}^2$ for the Gottfried integral over the range $0.004 \leq x \leq 0.8$ [15], 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
Figure 1. Flavor asymmetry of octet baryons

perturbative regime and therefore has to be 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 [19].

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

$$A(p) = N_{\bar{d}}(p) - N_{\bar{u}}(p) = \int_0^1 [\bar{d}_p(x) - \bar{u}_p(x)] \, dx .$$

(3)

Even in absence of explicit information on the (anti)quark distribution functions, the integrated value can be obtained directly from the left-hand side of Eq. (3). The corresponding value for the Gottfried integral of Eq. (2) is 0.21, in qualitative agreement with the experimental results. The flavor asymmetries of the octet baryons are related by isospin symmetry. Since the operator $\hat{N}_{\bar{d}} - \hat{N}_{\bar{u}}$ is an isovector in isospin space, the flavor asymmetries satisfy [20]

$$A(A) = \langle \psi_A(I,I_3) | \hat{N}_{\bar{d}} - \hat{N}_{\bar{u}} | \psi_A(I,I_3) \rangle = I_3 I \langle \bar{d}_p(I,I) - \bar{u}_p(I,I) \rangle ,$$

(4)

where $I$ and $I_3$ denote the isospin and its projection of baryon $A$. As a consequence, the excess of $\bar{d}$ over $\bar{u}$ 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 $A(\Lambda) = A(\Sigma^0) = 0$. These relations help to explain the regularities observed for the flavor asymmetry as shown in Figure 1.

Finally, 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, $A(p) \sim A(\Sigma^+)/(A(\Xi^0)$. This behavior is very different from that obtained in other models, such as the cloudy bag model, the chiral quark model and the balance model which all
predict that the asymmetry of the cascade particle is equal or larger than that of the proton $A(\Xi^0) \geq A(p)$ [21]. In order to distinguish between the predictions of the different models and to obtain a better understanding of non-perturbative structure of QCD new experiments are needed to measure the flavor asymmetry of hyperons. In particular, the flavor asymmetry of charged $\Sigma$ hyperons can obtained from Drell-Yan experiments using charged hyperon beams on the proton [22].

4. Proton and Lambda spin

The observation by European Muon Collaboration that the total quark spin constitutes a rather small fraction of the spin of the nucleon [23] sparked an enormous interest in the spin structure of the proton [5]. Recent experiments show that approximately one third of the proton spin is carried by the quarks and antiquarks [24, 25], and that the gluon contribution is rather small (either positive or negative) and compatible with zero [26]. 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 [27]. As in other effective models [5], 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

$$\frac{1}{2} = \frac{1}{2} \Delta \Sigma + \Delta L = \frac{1}{2} (\Delta u + \Delta d + \Delta s) + \Delta L.$$  (5)

Table 1 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. While the orbital angular momentum arises almost entirely from the $N\pi$ and $\Delta\pi$ channels, the contribution of the sea quark spins is dominated by the intermediate vector mesons, for which the convergence of the sum over intermediate states is much slower. Therefore, the sum was carried out over five oscillator shells for both the intermediate baryons and mesons [9].

The results of the HERMES analysis are presented in the column labeled DIS [24] and those of the naive quark model in the column labeled CQM. The importance of orbital angular momentum to the proton spin was discussed many years ago by Sehgal [28] and Ratcliff [29] in the context of the quark-parton model and, more recently, by Myhrer and Thomas in framework of the bag model [30].

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 that of the $\Lambda$ hyperon. In the naive CQM, the $\Lambda$ spin is carried entirely by the strange quark, which makes it a clean example to study the spin structure of baryons. Moreover, its polarization can be measured from the nonleptonic decay $\Lambda \rightarrow p\pi$ [31]. In summary, a study of the spin structure of the $\Lambda$ hyperon is not only interesting in its own right, but also may shed light on the origin of the spin crisis of the proton.

In most studies, additional assumptions had to be made about the sea quarks in order to get an estimate of the spin content of the $\Lambda$ hyperon. For example, the assumption that both valence and sea quarks are related by $SU(3)$ flavor symmetry, allows to express the spin content...
Table 1. Contribution of $\Delta u$, $\Delta d$, $\Delta s$, $\Delta \Sigma = \Delta u + \Delta d + \Delta s$ and $\Delta L$ to the spin of the proton and the $\Lambda$ hyperon in the unquenched constituent quark model (UCQM).

|       | CQM | DIS  | UCQM |
|-------|-----|------|------|
|       | Valence | Sea | Total |
| $p$   | $\Delta u$ | $4/3$ | 0.842 | 0.504 | 0.594 | 1.098 |
|       | $\Delta d$ | $-1/3$ | $-0.427$ | $-0.126$ | $-0.291$ | $-0.417$ |
|       | $\Delta s$ | 0 | $-0.085$ | 0.000 | $-0.005$ | $-0.005$ |
|       | $\Delta \Sigma$ | 1 | 0.330 | 0.378 | 0.298 | 0.676 |
|       | $2\Delta L$ | 0 | 0.000 | 0.324 | 0.324 |
|       | $2J$ | 1 | 0.378 | 0.622 | 1.000 |
| $\Lambda$ | $\Delta u$ | 0 | $-0.159$ | 0.000 | $-0.055$ | $-0.055$ |
|       | $\Delta d$ | 0 | $-0.159$ | 0.000 | $-0.055$ | $-0.055$ |
|       | $\Delta s$ | 1 | 0.647 | 0.422 | 0.539 | 0.961 |
|       | $\Delta \Sigma$ | 1 | 0.330 | 0.422 | 0.429 | 0.851 |
|       | $2\Delta L$ | 0 | 0.000 | 0.149 | 0.149 |
|       | $2J$ | 1 | 0.422 | 0.578 | 1.000 |

of the $\Lambda$ hyperon in terms of that of the proton [31]

$$(\Delta u)_\Lambda = (\Delta d)_\Lambda = (\Delta u + 4\Delta d + \Delta s)_p/6,$$

$$(\Delta s)_\Lambda = (2\Delta u - \Delta d + 2\Delta s)_p/3.$$  \hspace{1cm} (6)

An analysis of the experimental DIS data for the proton [24, 25] in combination with Eq. (6) shows that the strange quarks (and antiquarks) carry about 65 % of the $\Lambda$ spin, while the up and down quarks (and antiquarks) account for a negative polarization of $-32 \%$.

In the unquenched quark model there is no need to make additional assumptions about the nature of the sea. Since the $SU(3)$ flavor symmetry is broken by the sea quarks, Eq. (6) does not hold for the unquenched calculations. Table 1 shows that the unquenched quark model gives rise to a negatively polarized sea of up and down quarks and a large positively polarized sea of strange quarks. Other theoretical studies, such as the chiral quark-soliton model [32], lattice QCD [33] and QCD sum rules [34], also give a negative polarization of the up and down quarks. Finally, the contribution of quark spins for the $\Lambda$ is found to be 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 discussed the effects of hadron loops an unquenched quark model for baryons in which the quark loops are taken into account via a $^3P_0$ pair creation model. The ensuing unquenched quark model is valid for any baryon (or baryon resonance), includes all light flavors of the quark-antiquark pairs ($u\bar{u}$, $d\bar{d}$ and $s\bar{s}$), and can be used in combination with any CQM, as long as its wave functions are expressed in a harmonic oscillator basis.

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. In addition, it leads to a sizeable contribution of the orbital angular momentum to the spin of the proton ($\sim 32 \%$) and the $\Lambda$ hyperon ($\sim 15 \%$). In addition, there is a large contribution from the spins of the sea quarks due to intermediate vector mesons for the proton ($\sim 30 \%$) and the $\Lambda$ ($\sim 43 \%$). We note, that this contribution
is absent in meson-cloud models. In order to be able to distinguish between the predictions of different models of hadron structure and to obtain a better understanding of non-perturbative structure of QCD new experiments are needed to measure the flavor asymmetry and spin content of other octet baryons.

In conclusion, the formulation of an unquenched quark model in which the effects of quark-antiquark pairs are included explicitly in a general and consistent way, may provide an important step forward in CQM studies and increase considerably its range of applicability. Future work includes applications to radii, strong couplings, electromagnetic couplings and transition form factors of baryon resonances.

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