Electromagnetic and weak decays of baryons in the unquenched quark model

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Abstract. In this contribution, we discuss the electromagnetic and weak decays of baryons in the unquenched quark model and show that the observed discrepancies between the experimental data and the predictions of the constituent quark model can be accounted for in large part by the effects of sea quarks. Finally, the obtained results are discussed in terms of flavor-symmetry breaking.

1. Introduction
The constituent quark model (CQM) describes the nucleon as a system of three constituent, or valence, quarks. Despite the successes of the CQM (e.g. masses, electromagnetic couplings, and magnetic moments), there is compelling evidence for the presence of sea quarks from other observables such as the observed flavor asymmetry of the proton, the proton spin crisis, and the systematics of strong decays of baryons.

In the CQM, baryons are described in terms of a configuration of three constituent (or valence) quarks neglecting the effects of pair-creation (or continuum couplings). Above threshold these couplings lead to strong decays and below threshold to virtual higher-Fock components (such as $qqq-\bar{q}$) in the baryon wave function. The effects of these multiquark configurations (or sea quarks) is studied by unquenching the CQM.

In this contribution, we study the importance of sea quarks for the electromagnetic and weak couplings of baryons.

2. Unquenched quark model
In the unquenched quark model (UQM), the effects of sea quarks are included via a $^3P_0$ quark-antiquark pair-creation mechanism [1, 2, 3, 4, 5]. 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. As a result, the baryon wave function is given by a superposition of a valence contribution and higher-Fock components consisting of intermediate baryon-meson configurations

$$| \psi_A \rangle = \mathcal{N}_A \left\{ | A \rangle + \gamma \sum_{BCIJ} \int dK k^2 dk \ | BC,l,J; K,k \ | T^\dagger \ | A \rangle \right\}. \quad (1)$$
Here $\vec{k}$ and $l$ denote the relative radial momentum and relative orbital angular momentum of the baryon-meson system BC. The operator $T^\dagger$ creates a quark-antiquark pair in the $^3P_0$ state with the quantum numbers of the vacuum \[4, 5, 6\]

$$T^\dagger(3P_0) = \begin{align*} &-3\gamma \int d\vec{p}_4 d\vec{p}_5 \delta(\vec{p}_4 + \vec{p}_5) C_{45} F_{45} e^{-\alpha_2(\vec{p}_4-\vec{p}_5)^2/8} \times \frac{b_4^0(\vec{p}_4) d_1^1(\vec{p}_5)}{[\chi_{45} \times Y_1(\vec{p}_4 - \vec{p}_5)](0)} b_4^1(\vec{p}_4) d_1^0(\vec{p}_5) . \end{align*}$$

(2)

The quark-antiquark pair is characterized by a color singlet wave function $C_{45}$, a spin triplet wave function $\chi_{45}$ with spin $S = 1$ and a solid spherical harmonic $Y_1(\vec{p}_4 - \vec{p}_5)$ that indicates that the quark and antiquark are in a relative $P$ wave. $F_{45}$ denotes the flavor wave function of the created quark-antiquark pair \[7, 8\]

$$\frac{1}{\sqrt{2 + (m_n/m_s)^2}} \left[ |u\bar{u}\rangle + |d\bar{d}\rangle + \frac{m_n}{m_s} |s\bar{s}\rangle \right] ,$$

(3)

which, in the limit of equal quark masses, reduces to the usual expression for a flavor singlet. The ratio of nonstrange to strange quark masses is determined from the quark magnetic moments as

$$\frac{m_n}{m_s} = \frac{m_u + m_d}{2m_s} = \frac{\mu_s(\mu_u - 2\mu_d)}{2\mu_u \mu_d} .$$

(4)

For some observables like the magnetic moments, the effects of quark-antiquark pairs to a large extent can be taken into account by introducing effective (or renormalized) values of the model parameters \[4\]. As a result, the CQM results are not altered much by the introduction of higher Fock components in baryon (and meson) wave functions. There are other observables for which the explicit inclusion of sea quarks is crucial since the quark-antiquark pairs provide non-negligible contributions that cannot be accounted for by renormalization of model parameters. Examples of the latter are the orbital angular momentum in the spin of the proton \[4\], the flavor asymmetry of the proton \[5\], strangeness content of nucleon electromagnetic form factors \[3, 9\], strangeness suppression \[10\], and self-energy corrections to baryon and meson masses \[11, 12\].

In the next section, we discuss the importance of higher-Fock components in electromagnetic and weak decays of baryons.

3. Results

In this section, we discuss some recent results for electromagnetic and weak couplings. A more detailed account will be given in future publications \[13, 14\]. In the present calculation, the sum over intermediate states is limited to octet and decuplet baryons in combination with pseudoscalar octet and singlet mesons. The contributions of radially excited baryons and mesons are not taken into account.

3.1. Electromagnetic decays

The experimental data obtained by the CLAS Collaboration for the electromagnetic decays of $\Sigma$ hyperons of the baryon decuplet show a large deviation from the CQM predictions \[15, 16\]. Table 1 shows that the experimental widths are underpredicted by almost a factor of two. Here we study the effect of sea quarks for the electromagnetic decays of the decuplet baryons.

The radiative width for this process can be expressed in terms of the transition magnetic moment $\mu_{AB}$

$$\Gamma(A \to B\gamma) = \frac{\alpha E_B p_A^2}{2m_A m_N^2} \mu_{AB}^2 .$$

(5)
The results in Table 1 show that for the Δ resonance the coupling to the pseudoscalar meson cloud (mostly pions [18]) accounts in large part for the observed discrepancy between the quark model value 399 keV and the experimental value 704 ± 63 keV. However, for the Σ hyperons the calculated width is larger than the CQM value but still rather far from the experimental result.

### Table 1. Electromagnetic decay widths in keV.

| Decay | CQM | UQM | Exp [17] |
|-------|-----|-----|----------|
| \(\Gamma(\Delta \to N\gamma)\) | 399 | 606 | 704 ± 63 |
| \(\Gamma(\Sigma^0 \to \Lambda\gamma)\) | 260 | 318 | 451 ± 77 |
| \(\Gamma(\Sigma^{++} \to \Sigma^{+}\gamma)\) | 110 | 131 | 254 ± 59 |

### 3.2. Weak decays

Semi-leptonic decay processes of baryons are described by means of the axial couplings. In the case of octet baryons they can be expressed in terms of the couplings \(F\) and \(D\). In the quark model their values are given by \(F = 2/3\) and \(D = 1\). In the Cabibbo approach, \(F\) and \(D\) are determined from the experimental axial couplings, \(g_A(n \to p)\) and \(g_A(\Sigma^- \to n)\), leading to effective values, \(F = 0.465\) and \(D = 0.805\). With these values the semileptonic decay processes of baryons are described very well [19].

In Table 2 we show a comparison of the results for the axial couplings in the CQM and the Cabibbo approach with those of the unquenched quark model. The contribution of the pseudoscalar mesons (and especially that of the pions [18]) is responsible for a substantial lowering of the neutron axial coupling from the CQM value thus bringing it in much closer agreement with experiment without the need to introduce effective values of \(F\) and \(D\). On the other hand, the result for the \(\Sigma^-\) hyperon which is described very well in the CQM is hardly changed. This shows that the effective values of \(F\) and \(D\) used in the Cabibbo approach can be accounted for in large part by the coupling to the pseudoscalar mesons. A similar conclusion was reached in an earlier study of the meson-cloud model [20].

### Table 2. Axial couplings for \(\beta\) decays.

| Decay | \(g_A\) | CQM | UQM | Cabibbo | Exp [17] |
|-------|---------|-----|-----|---------|----------|
| \(n \to p\) | \(F + D\) | 1.67 | 1.35 | 1.27 | 1.2701 ± 0.0025 |
| \(\Sigma^- \to n\) | \(F - D\) | -0.33 | -0.31 | -0.34 | -0.340 ± 0.017 |
| \(\Xi^0 \to \Sigma^+\) | \(F + D\) | 1.67 | 1.33 | 1.27 | 1.21 ± 0.05 |
| \(\Lambda^0 \to p\) | \(\frac{1}{\sqrt{6}}(3F + D)\) | 1.22 | 0.93 | 0.90 | 0.879 ± 0.018 |
| \(\Sigma^- \to \Lambda^0\) | \(\frac{\sqrt{2}}{3}D\) | 0.82 | 0.71 | 0.66 | 0.60 ± 0.03 |
| \(\Xi^- \to \Lambda^0\) | \(\frac{1}{\sqrt{6}}(3F - D)\) | 0.41 | 0.30 | 0.24 | 0.31 ± 0.06 |

\(F = \frac{2}{3}\), \(D = \frac{2}{3}\).
Table 3. Flavor-symmetry breaking in transition magnetic moments (top) and axial couplings (bottom).

|                | UQM    | SU(3)  | Exp       | Exp                  |
|----------------|--------|--------|-----------|----------------------|
| $\mu_{\Delta N}$ | 3.29   | 3.29   | *         | 3.53 ± 0.16 $\mu_N$  |
| $\mu_{\Sigma^++\Sigma^+}$ | −2.52  | −3.07  | −3.50 ± 0.43 $\mu_N$ |
| $\mu_{\Sigma^0\Lambda^0}$ | 2.52   | 2.85   | 3.03 ± 0.27 $\mu_N$ |
| $g_A(n \to p)$   | 1.35   | 1.35   | *         | 1.2701 ± 0.0025       |
| $g_A(\Sigma^- \to n)$ | −0.31  | −0.31  | *         | −0.340 ± 0.017        |
| $g_A(\Sigma^0 \to \Sigma^+)$ | 1.33   | 1.35   |           | 1.21 ± 0.05           |
| $g_A(\Lambda^0 \to p)$   | 0.93   | 0.97   |           | 0.879 ± 0.018         |
| $g_A(\Sigma^- \to \Lambda^0)$ | 0.71   | 0.68   |           | 0.60 ± 0.03           |
| $g_A(\Xi^- \to \Lambda^0)$ | 0.30   | 0.29   |           | 0.31 ± 0.06           |

4. Flavor-symmetry breaking
Finally, we discuss the UQM results for electromagnetic and weak decays in terms of flavor-symmetry breaking effects. In the UQM, the flavor symmetry is broken by the use of the physical masses of baryons and mesons in the energy denominator in Eq. (1) and the ratio of nonstrange to strange quark masses in the created quark-antiquark pair of Eq. (3). The third column of Table 3 shows the results for the $SU(3)$ flavor symmetry limit. In this case, the transition magnetic moments depend on a single coupling which is normalized to $\mu_{\Delta N}$. For the $\beta$ decays there are two independent couplings. Table 3 shows that, whereas for the weak decays the flavor symmetry is broken by less than 5%, for the transition magnetic moments the breaking is much larger $\sim 15 - 25\%$.

5. Summary and conclusions
In this contribution, we studied the importance of higher-Fock components (or sea quarks) in electromagnetic and weak decays of baryons in the framework of the unquenched quark model. It was shown that the observed discrepancies between the experimental data and the predictions of the CQM can be accounted for in large part by the contributions of quark-antiquark pairs in the UQM. Moreover, it was found that the effects of flavor-symmetry breaking in the UQM are much larger for electromagnetic decays than they are for weak decays.

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