The baryon spectroscopy: strong decays and strange suppression

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Abstract. In this contribution, we present the open-flavor strong decays of light baryons computed within the framework of quark model. The transition amplitudes are computed using a modified $\frac{3}{2}^0$ operator, where a mechanism strange suppression is taken into account. Also we discuss the strange suppression within an extension of the quark model.

1. Introduction
At the moment, the number of known light-quark mesons is much larger than the number of known baryon resonances [1]. However, it is known that the baryon spectrum is much more complex than the meson one. For instance, it is difficult to identify those high-lying baryon resonances that are only weakly coupled to the $N\pi$ channel [2, 3], since they cannot be seen in elastic $N\pi$ scattering experiments. Regarding strong decays of baryons no satisfactory description has yet been achieved. We could list several problems, for instance, the QCD mechanism behind the OZI-allowed strong decays [4] is still not clear. Theoretical calculations of baryon strong, electromagnetic and weak decays can still help the experimentalists in their search of those resonances that are still unknown.

In this contribution, we first discuss a strange suppression mechanism in the open-flavor strong decays of light baryons within the quark model framework. The quark model (QM) [8, 9, 10, 11, 12, 13, 14, 15, 16, 17] can reproduce the behavior of observables such as the spectrum and the magnetic moments in the baryon and meson sector. The decay widths of baryon resonances into baryon-pseudoscalar meson pairs were recently reported in Ref. [5], within the $\frac{3}{2}P_0$ decay model framework [6, 7], using the mass spectrum of two different models: the $U(7)$ algebraic model [17], by Bijker, Iachello and Leviatan, and the hypercentral model (hQM) [12], developed by Giannini and Santopinto.

Finally, we discuss one of the latest applications of the Unquenched Quark Model (this approach is a generalization of the unitarized quark model [18, 19, 20, 21, 22]) to describe the strangeness suppression in the electro-production of resonances from proton [23] within the UQM framework. The unquenching of the quark model for hadrons is a way to take into account the continuum-coupling effects. Above threshold, these couplings lead to strong decays and below threshold, they lead to virtual $qq - q\bar{q}$ ($qqq - q\bar{q}$) components in the hadron wave function and shifts of the physical mass with respect to the bare mass.

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2. The $3P_0$ decay model with strangeness suppression

Here, we present the formalism to compute the two-body strong decay widths of baryons resonances in the $3P_0$ pair-creation model, when a strangeness suppression mechanism is included. The decay widths are computed as [5, 6, 7, 24, 25, 26]

$$\Gamma_{A\rightarrow BC} = \Phi_{A\rightarrow BC}(q_0) \sum_{\ell,J} |\langle BCq_0^0 \ell J| \Gamma^I| A \rangle|^2,$$  

(1)

where, $\Phi_{A\rightarrow BC}(q_0)$ is the relativistic phase space factor:

$$\Phi_{A\rightarrow BC}(q_0) = 2\pi q_0 E_b(q_0)E_c(q_0),$$  

(2)

depending on $q_0$ and on the energies of the two intermediate state hadrons, $E_b = \sqrt{M_b^2 + q_0^2}$ and $E_c = \sqrt{M_c^2 + q_0^2}$. We assumed harmonic oscillator wave functions, depending on a single oscillator parameter $\alpha_{1}$ for the baryons and $\alpha_{m}$ for the mesons. The coupling between the final state hadrons $|B\rangle$ and $|C\rangle$ is described in terms of a spherical basis [5]. Specifically, the final state $|BCq_0^0 \ell J\rangle$ can be written as

$$|BCq_0^0 \ell J\rangle = \sum_{m_{b}M_{b},m_{c}} \langle J_{b}M_{b}J_{c}M_{c}| J_{bc}M_{bc} \rangle \langle J_{bc}M_{bc}\ell m | JM \rangle \frac{Y_{\ell m}(\hat{q})}{q^{2}}\delta(q - q_{0})$$  

(3)

where the ket $|BCq_0^0 \ell J\rangle$ is characterized by a relative orbital angular momentum $\ell$ between $B$ and $C$ and a total angular momentum $\hat{J} = \hat{J}_{b} + \hat{J}_{c} + \ell$.

The transition operator of the $3P_0$ model is given by [5, 24, 25, 26]:

$$T^I = -3\gamma_{0}^{\text{eff}}^{2} \int d\vec{p}_{4} d\vec{p}_{5} \delta(\vec{p}_{4} + \vec{p}_{5}) C_{45} F_{45} e^{-r_{b}^{2}(\vec{p}_{4} - \vec{p}_{5})^{2}/6}$$  

$$[\chi_{45} \times \mathcal{Y}_{1}(\vec{p}_{4} - \vec{p}_{5})]^{(0)}_{0} b_{4}^I(\vec{p}_{4}) d_{5}^I(\vec{p}_{5}).$$  

(4)

Here, $b_{4}^I(\vec{p}_{4})$ and $d_{5}^I(\vec{p}_{5})$ are the creation operators for a quark and an antiquark with momenta $\vec{p}_{4}$ and $\vec{p}_{5}$, respectively. The $q\bar{q}$ pair is characterized by a color singlet wave function $C_{45}$, a flavor singlet wave function $F_{45}$, a spin triplet wave function $\chi_{45}$ with spin $S = 1$ and a solid spherical harmonic $\mathcal{Y}_{1}(\vec{p}_{4} - \vec{p}_{5})$, since the quark and antiquark are in a relative $P$ wave. The operator $\gamma_{0}^{\text{eff}}$ of Eq. (4) is the effective pair-creation strength $\gamma_{0}^{\text{eff}}$ [5, 24, 25, 26, 28], defined as

$$\gamma_{0}^{\text{eff}} = \frac{m_{n}}{m_{i}} \gamma_{0},$$  

(5)

is introduced, with $i = n$ (i.e. $u$ or $d$) or $s$. In our recent study [5], we performed the correct treatment of $\gamma_{0}^{\text{eff}}$ in the open flavor strong decays. We showed that $\gamma_{0}^{\text{eff}}$ can be absorbed in the flavor couplings, thus the flavor singlet wave function is change as follow

$$\gamma_{0}^{\text{eff}} \phi_{0} = \frac{\gamma_{0}^{\text{eff}}}{\sqrt{2}} \left[ |u\bar{u}| + |d\bar{d}| + |s\bar{s}| \right]$$  

$$\rightarrow \gamma_{0}^{\text{eff}} \phi_{0} = \gamma_{0} \frac{|u\bar{u}| + |d\bar{d}| + |s\bar{s}|}{\sqrt{2 + \left( \frac{m_{n}}{m_{i}} \right)^{2}}},$$  

(6)
3. UQM

In the unquenched quark model for baryons [30, 31, 32, 33] and mesons [25, 24, 26, 27], the hadron wave function is made up of a zeroth order $qqq$ ($q\bar{q}$) configuration plus a sum over the possible higher Fock components, due to the creation of $^3P_0$ $q\bar{q}$ pairs. Thus, we have

$$|\psi_A\rangle = N \left[ |A\rangle + \sum_{BC\ell J} \int d\vec{K}k^2dk \ |BC\ell J;\vec{K}k\rangle \frac{\langle BC\ell J;\vec{K}k | T^\dagger | A\rangle}{E_a - E_b - E_c} \right],$$  

(7)

where $T^\dagger$ stands for the $^3P_0$ quark-antiquark pair-creation operator [24, 25, 26, 27], $A$ is the baryon/meson, $B$ and $C$ represent the intermediate state hadrons, see Figures 1 and 2. $E_a$, $E_b$ and $E_c$ are the corresponding energies, $k$ and $\ell$ the relative radial momentum and orbital angular momentum between $B$ and $C$ and $\vec{J} = \vec{J}_b + \vec{J}_c + \vec{\ell}$ is the total angular momentum. It is worthwhile noting that in Refs. [24, 25, 26, 27, 28], the constant pair-creation strength in the operator (7) was substituted with an effective one, to suppress unphysical heavy quark pair-creation.

![Figure 1](image1.png)

**Figure 1.** Quark line diagrams for $A \rightarrow BC$ with $q\bar{q} = s\bar{s}$ and $q_1q_2q_3 = uud$

![Figure 2](image2.png)

**Figure 2.** Two diagrams can contribute to the process $A \rightarrow BC$. $q_i$ and $\bar{q}_i$ stand for the various initial ($i = 1 - 4$) and final ($i = 5 - 8$) quarks or antiquarks, respectively.

The introduction of coupling continuum effects in the QM has been essential to study observables that only depend on $q\bar{q}$ sea pairs, like the strangeness content of the nucleon electromagnetic form factors [29, 30] or the flavor asymmetry of the nucleon sea [31]. In other cases, continuum effects can provide important corrections to baryon/meson observables, like the self-energy corrections to meson masses [24, 25, 26, 27] or the importance of the orbital angular momentum in the spin of the proton [32].

4. Strengeness suppression in the electro-production

The UQM wave function can be tested in the production ratios of baryon-meson states [23]. In Ref. [23] was shown that the production rates can be expressed as the product of a spin-flavor-isospin factor and a radial integral

$$\frac{p \rightarrow \Lambda K^+}{p \rightarrow n\pi^+} = \frac{27 I_{N \rightarrow \Lambda K}}{50 I_{N \rightarrow N\pi}},$$

(8)
Table 1. Comparison of the strong decay widths with/without strangeness suppression mechanism.

| Decay mode         | Model | Without suppression | With suppression [5] | Exp [1] |
|--------------------|-------|---------------------|----------------------|---------|
| \( N(1710) \to \Lambda K \) | U(7)  | 8                   | 3                    | 3-63    |
|                    | hQM   | 39                  | 14                   |         |
| \( N(1720) \to \Lambda K \) | U(7)  | 39                  | 14                   | 2-60    |
|                    | hQM   | 33                  | 12                   |         |
| \( N(1900) \to \Lambda K \) | U(7)  | 36                  | 13                   | 0-37    |
|                    | hQM   | 36                  | 13                   |         |
| \( N(1900) \to \Sigma K \) | U(7)  | 3                   | 1                    | 6-26    |
|                    | hQM   | 3                   | 1                    |         |
| \( \Delta(1910) \to \Sigma K \) | U(7)  | 105                 | 38                   | 9-48    |
|                    | hQM   | 105                 | 38                   |         |
| \( \Delta(1920) \to \Sigma K \) | U(7)  | 64                  | 23                   | 3-7     |
|                    | hQM   | 61                  | 22                   |         |
| \( \Delta(1950) \to \Sigma K \) | U(7)  | 14                  | 4                    | 1-2     |
|                    | hQM   | 8                   | 3                    |         |
| \( \Sigma^*(2030) \to \Xi K \) | U(7)  | 208                 | 75                   | 26-46   |

Table 2. Ratios of electro-production cross sections.

| Ratio               | UQM [23]   | Exp. [34]  |
|---------------------|------------|------------|
| \( p \to \Lambda K^+ / p \to n \pi^+ \) | 0.227      | 0.19 ± 0.01 ± 0.03 |
| \( p \to \Lambda K^+ / p \to p \pi^0 \) | 0.454      | 0.50 ± 0.02 ± 0.12 |
| \( p \to p \pi^0 / p \to n \pi^+ \) | 0.500      | 0.43 ± 0.01 ± 0.09 |

with

\[
I_{A\to BC} = \int_0^\infty \frac{k^4 e^{-2F^2 k^2}}{\Delta E_{A\to BC}^2(k)} dk . \tag{9}
\]

Here, the energy denominator represents the energy difference between initial and final hadrons calculated in the rest frame of the initial baryon \( A \). The value of \( F^2 \) depends on the size of the harmonic oscillator wave functions for baryons and mesons, and the Gaussian smearing of the pair-creation vertex, and its value is taken from [30] to be \( F^2 = 2.275 \, \text{GeV}^{-2} \).

5. Results and discussion

The strong decay widths with/without strangeness suppression mechanism are present in Table 1. In the case of nucleon resonances, we can observe both calculations can be compatible with
Table 3. The pair creation rates and the strangeness suppression factor in the proton.

| Ratio               | UQM [23] | Exp.     | Ref.  |
|---------------------|----------|----------|-------|
| $s\bar{s}/d\bar{d}$ | 0.265    | 0.22 ± 0.07 | [34] |
| $u\bar{u}/d\bar{d}$ | 0.568    | 0.74 ± 0.18 | [34] |
| $2s\bar{s}/(u\bar{u} + d\bar{d})$ | 0.338    | 0.25 ± 0.08 | [34] |
|                     |          | 0.29 ± 0.02 | [35] |

the experimental data due to the experimental values do not have enough precision. For the case of $\Delta$ resonances the strangeness suppression mechanism is beneficial, but for the $\Sigma^*(2030) \rightarrow \Xi K$ process, the suppression mechanism is not enough to reproduce the experimental data. Thus in general the suppression mechanism seems to be beneficial, but more precision in the experimental data is needed, and other decay channels should be studied to make a definitive conclusion.

Regarding to electro-production, in the UQM the ratios for exclusive two-body production can be determined in a straightforward way, and Table 2 shows that the observed rates are reproduced very well by our calculation. Here, the isospin symmetry is still valid, thus the calculated ratio $p \rightarrow p\pi^0/p \rightarrow n\pi^+ = 1/2$ is a consequence of this symmetry.

The calculation of the strangeness suppression factor, $\lambda_s = \frac{2s\bar{s}}{(u\bar{u} + d\bar{d})}$, takes into account all channels involving pseudoscalar mesons ($\pi$, $K$, $\eta$ and $\eta'$) in combination with octet and decuplet baryons. The results are presented in Table 3. The value $\lambda_s$ is in good agreement with both the values determined in exclusive reactions [34] and in high-energy production [35].

In conclusion, the observed ratios for the production of baryon-meson channels in exclusive reactions can be understood in a simple and transparent way in the framework of the UQM. It is important to emphasize that the UQM results do not depend on the strength of the $^3P_0$ quark-antiquark pair creation vertex. The value of the remaining coefficient $(F^2)$ was taken from previous work, no attempt was made to optimize their values. Finally, the UQM value for the strangeness suppression factor in the proton is in good agreement with the value determined in exclusive reactions [34] as well as the result from high-energy production [35].

We point out the difference between the strangeness suppression mechanism in the strong decays and the strangeness suppression factor extracted in the production rates, in the first case the mechanism is incorporated to take into account the $SU(3)$ symmetry breaking due to the heavier $s$-mass quark in comparison with the mass of $u$ and $d$ quarks. In the other hand, the strangeness suppression factor obtained from production rates is a consequence of the extra components in the proton wave function treated in similar way as the asymmetry in the proton within the UQM framework[23].

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