Open-flavor strong decays of Baryons

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Introduction

Hadron physics, challenge at low energies

One of the main goals of hadron physics is to understand the structure of the baryons and mesons. However, at low energies, no solution of QCD is known. Then we can use the effective degrees of freedom theories that replace part of unknown interactions by physically approximations.

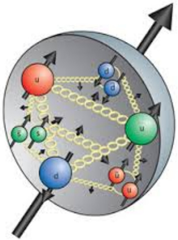
Open problems in hadrons

- Missing resonances
- Electromagnetic Decays of baryon.
- Strong decays
- Hadronization
- etc

Quark models

Effective degrees of freedom

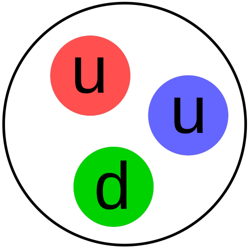
The developed effective models of hadrons, such as bag models, chiral quark models, soliton models, instanton liquid model and the constituent quark model. Each of these approaches are constructed in order to mimic some selected properties of the strong interaction, but obviously none of them are QCD.



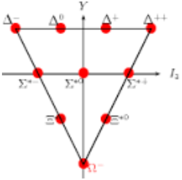
constituent quark models (CQM)

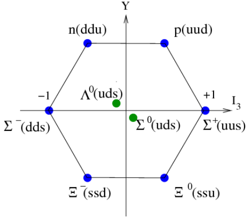
constituent quark models (CQM)

An important class is provided by CQM which are based on constituent (effective) quark degrees of freedoms. There exists a large variety of CQM's. The main features: the effective degrees of freedom of three constituent quarks (qqq configurations), the $SU(3) \otimes SU(2)$ flavor-spin symmetry and a long-range confining potential.

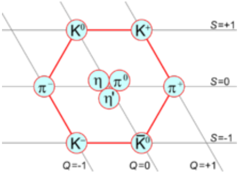


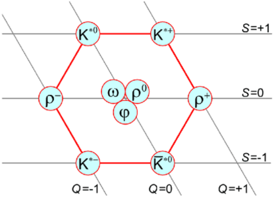
Baryons





Mesons





$U(7)$ Model Ann. Phys. **284**, 89 (2000)

- In the $U(7)$ algebraic model the baryon spectrum is computed through algebraic methods, introduced in the 60's by Gell-Mann, Ne'eman and Okubo (flavor and spin part). In the U(7) model, such methods are also used to describe the spatial part.
- The full algebraic structure is obtained by combining the symmetry of the spatial part, $U(7)$, with that of the internal spin-flavor-color part $SU_{\mathrm{sf}}(6) \otimes SU_{\mathrm{c}}(3)$

$$U(7) \otimes SU_{\mathrm{sf}}(6) \otimes SU_{\mathrm{c}}(3) \ .$$

- The baryon mass formula is written as the sum of three terms

$$\hat{M}^2 = M_0^2 + \hat{M}^2_{\mathrm{space}} + \hat{M}^2_{\mathrm{sf}} \ ,$$

where $\hat{M}^2_{\mathrm{space}}$ is a function of the spatial degrees of freedom and $\hat{M}^2_{\mathrm{sf}}$ depends on the internal ones. The energy spectrum, corresponding to the spatial degrees of freedom, is given by:

$$\hat{M}^2_{\mathrm{space}} = \hat{M}^2_{\mathrm{vib}} + \hat{M}^2_{\mathrm{rot}} \ .$$

Since the space-spin-flavor wave function is symmetric under permutation group S_3 of the three identical constituents, the permutation symmetry of the spatial wave function has to be the same as that of the spin-flavor part. Thus, the spatial part of the mass operator $\hat{M}^2_{\mathrm{space}}$ has to be invariant under the S_3 permutation symmetry.

- The mass formula

$$\hat{M}^2 = M_0^2 + \kappa_1 \, v_1 + \kappa_2 \, v_2 + \alpha L + M^2_{\mathrm{GR}} \ ,$$

N^* Spectra in $U(7)$ Model Ann. Phys. **284**, 89 (2000)

Mass spectrum of nonstrange baryon resonances in the oblate top model. The masses are given in MeV.

Baryon $L_{2I,2J}$	Status	Mass	State	(v_1, v_2)	M_{calc}
$N(939)P_{11}$	****	939	$^{2}8_{1/2}[56,0^+]$	(0,0)	939
$N(1440)P_{11}$	****	1430-1470	$^{2}8_{1/2}[56,0^+]$	(1,0)	1444
$N(1520)D_{13}$	****	1515-1530	$^{2}8_{3/2}[70,1^-]$	(0,0)	1563
$N(1535)S_{11}$	****	1520-1555	$^{2}8_{1/2}[70,1^-]$	(0,0)	1563
$N(1650)S_{11}$	****	1640-1680	$^{4}8_{1/2}[70,1^-]$	(0,0)	1683
$N(1675)D_{15}$	****	1670-1685	$^{4}8_{5/2}[70,1^-]$	(0,0)	1683
$N(1680)F_{15}$	****	1675-1690	$^{2}8_{5/2}[56,2^+]$	(0,0)	1737
$N(1700)D_{13}$	***	1650-1750	$^{4}8_{3/2}[70,1^-]$	(0,0)	1683
$N(1710)P_{11}$	***	1680-1740	$^{2}8_{1/2}[70,0^+]$	(0,1)	1683
missing			$^{2}8_{1/2}[20,1^+]$	(0,0)	1713
missing			$^{2}8_{3/2}[20,1^+]$	(0,0)	1713
$N(1720)P_{13}$	****	1650-1750	$^{2}8_{3/2}[56,2^+]$	(0,0)	1737
misssin			$^{2}8_{3/2}[70,2^-]$	(0,0)	1874
misssin			$^{2}8_{5/2}[70,2^-]$	(0,0)	1874
misssin			$^{2}8_{5/2}[70,2^+]$	(0,0)	1874
$N(1860)F_{15}$	**	1820-1960	$^{4}8_{5/2}[70,2^+]$	(0,0)	1975
$N(1875)D_{13}$	***	1820-1920	$^{4}8_{3/2}[70,2^-]$	(0,0)	1975
$N(1880)P_{13}$	**	1835-1905	$^{4}8_{3/2}[70,2^+]$	(0,0)	1975
$N(1895)S_{11}$	**	1880-1910	$^{4}8_{1/2}[70,2^-]$	(0,0)	1975
$N(1900)P_{13}$	***	1875-1935	$^{2}8_{3/2}[70,2^+]$	(0,0)	1874
misssin			$^{2}8_{1/2}[70,1^-]$	(1,0)	1909

The Hypercentral Model (hQM) PL. **B364**, 231 (1995)

In the hQM, the Jacobi coordinates $\vec{\rho} = \frac{1}{\sqrt{2}}(\vec{r}_1 - \vec{r}_2)$ and $\vec{\lambda} = \frac{1}{\sqrt{6}}(\vec{r}_1 + \vec{r}_2 - 2\vec{r}_3)$, which constitute the usual choice in QM calculations, are substituted with the hyperspherical coordinates. These are the angles $\Omega_\rho = (\theta_\rho, \phi_\rho)$ and $\Omega_\lambda = (\theta_\lambda, \phi_\lambda)$, the hyperradius, x, and the hyperangle, ξ, defined as

$$x = \sqrt{\vec{\rho}^2 + \vec{\lambda}^2} , \qquad \xi = \arctan \frac{\rho}{\lambda} .$$

the hQM has the assumption that the quark interaction only depends on the hyperradius :

$$V_{3q}(\vec{\rho}, \vec{\lambda}) = V(x)$$

With the form

$$V(x) = -\frac{\tau}{x} + \alpha x$$

where τ and α are free parameters. Thus, ψ_{space}, is factorized as

$$\psi_{space} = \psi_{3q}(\vec{\rho}, \vec{\lambda}) = \psi_{\gamma\nu}(x) Y_{[\gamma]l_\rho l_\lambda}(\Omega_\rho, \Omega_\lambda, \xi) ,$$

where the hyperradial wave function, $\psi_{\gamma\nu}(x)$, is labeled by the grand angular quantum number γ and the number of nodes ν. The dynamics is contained in $\psi_{\gamma\nu}(x)$, which is a solution of the hyperradial equation

$$[\frac{d^2}{dx^2} + \frac{5}{x}\frac{d}{dx} - \frac{\gamma(\gamma+4)}{x^2}]\psi_{\gamma\nu}(x) = -2m\,[E - V_{3q}(x)]\ \psi_{\gamma\nu}(x) .$$

The complete hCQM hamiltonian is then

$$H_{hCQM} = 3m + \frac{\vec{p}_\rho^{\,2}}{2m} + \frac{\vec{p}_\lambda^{\,2}}{2m} - \frac{\tau}{x} + \alpha x + H_{hyp} .$$

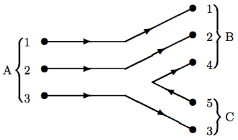
where $\vec{p}_\rho$ and $\vec{p}_\lambda$ are the momenta conjugated to the Jacobi coordinates $\vec{\rho}$ and $\vec{\lambda}$.

The baryon spectra in the hQM P. L. **B364**, 231 (1995)

Mass spectrum of N and Δ resonances within the hQM, compared with the existing experimental data.

Baryon $L_{2I,2J}$	Status	Mass (MeV)	State	M_{hQM} (MeV)
$N(939)P_{11}$	****	939	${}^2 8_{1/2}[56, 0_1^+]$	938
$N(1440)P_{11}$	****	1420-1470	${}^2 8_{1/2}[56, 0_2^+]$	1550
$N(1520)D_{13}$	****	1515-1525	${}^2 8_{3/2}[70, 1_1^-]$	1525
$N(1535)S_{11}$	****	1525-1545	${}^2 8_{1/2}[70, 1_1^-]$	1507
$N(1650)S_{11}$	****	1645-1670	${}^2 8_{1/2}[70, 1_2^-]$	1574
$N(1675)D_{15}$	****	1670-1680	${}^4 8_{5/2}[70, 1_1^-]$	1579
$N(1680)F_{15}$	****	1680-1690	${}^2 8_{5/2}[56, 2_1^+]$	1798
$N(1700)D_{13}$	***	1650-1750	${}^2 8_{3/2}[70, 1_2^-]$	1606
$N(1710)P_{11}$	***	1680-1740	${}^2 8_{1/2}[70, 0_1^+]$	1808
$N(1720)P_{13}$	****	1700-1750	${}^2 8_{3/2}[56, 2_1^+]$	1797
missing			${}^4 8_{3/2}[70, 2_1^+]$	1835
missing			${}^2 8_{1/2}[20, 1_1^+]$	1836
missing			${}^2 8_{3/2}[20, 1_1^+]$	1836
$N(1860)F_{15}$	**	1820-1960	${}^4 8_{5/2}[70, 2_1^+]$	1844
$N(1875)D_{13}$	***	1820-1920	${}^4 8_{3/2}[70, 1_1^-]$	1899
$N(1880)P_{11}$	**	1835-1905	${}^4 8_{1/2}[70, 2_1^+]$	1839
$N(1895)S_{11}$	**	1880-1910	${}^4 8_{1/2}[70, 1_1^-]$	1887
$N(1900)P_{13}$	***	1875-1935	${}^2 8_{3/2}[70, 2_1^+]$	1853
missing			${}^4 8_{1/2}[70, 1_2^-]$	1937
$N(1990)F_{17}$	**	1995-2125	${}^4 8_{7/2}[70, 2_1^+]$	1840

Strong Decays of baryons, $3P_0$ mechanism arXiv:1506.07469



The $^3P_0$ pair-creation model of hadron vertices; the $q\bar{q}$ pair (45) is created in a $^3P_0$ flavor-color singlet. A is the initial state baryon, B and C are the final baryon and meson states, respectively.

The $^3P_0$ operator

$$T^\dagger = -3\gamma \sum_{i,j} \int d\vec{p}_i d\vec{p}_j \delta(\vec{p}_i + \vec{p}_j) C_{ij} F_{ij} V(p_i - p_j)^2 \left[\chi_{ij} \times \mathcal{Y}_1(\vec{p}_i - \vec{p}_j)\right]_0^{(0)} b_i^\dagger(\vec{p}_i) d_j^\dagger(\vec{p}_j)$$

$SU(3)$ breaking symmetry arXiv:1506.07469

In the $SU(3)$ symmetry we have

$$\phi_0^{\text{eff}} = \frac{1}{\sqrt{3}}\left[|u\bar{u}\rangle + |d\bar{d}\rangle + |s\bar{s}\rangle\right] \quad \Longrightarrow \phi_0^{\text{eff}} = \frac{1}{\sqrt{2+\left(\frac{m_n}{m_s}\right)^2}}\left[|u\bar{u}\rangle + |d\bar{d}\rangle + \frac{m_n}{m_s}|s\bar{s}\rangle\right]$$

the production of the $s\bar{s}$ is suppressed in comparison with the quarks u and d
the flavor couplings:

$$\mathcal{F}^{\rho}_{A\rightarrow BC} = \langle \phi^{\rho}_{B}\phi_{C}|\phi^{\text{eff}}_{0}\phi^{\rho}_{a}\rangle$$

The widths were calculated

$$\Gamma_{A\rightarrow BC} = \Phi_{A\rightarrow BC}(q_0)\sum_{\ell}\left|\langle BCq_0\,\ell J|\,T^{\dagger}\,|A\rangle\right|^2 . \tag{1}$$

The final state is characterized by the relative orbital angular momentum ℓ between B and C and a total angular momentum $\vec{J} = \vec{J}_b + \vec{J}_c + \vec{\ell}$ and the phase space factors are:

The relativistic phase space factor

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

The effective phase space factor

$$\Phi_{A\rightarrow BC}(q_0) = 2\pi q_0\frac{\tilde{M}_b\tilde{M}_c}{M_a} ,$$

The $^3P_0$ vertex arXiv:1506.07469

The different forms depend on $p^2 = (\vec{p}_4 - \vec{p}_5)^2/4$ and they are given by

$$
\begin{aligned}
V_1(2p) &= \gamma_0\, e^{-\alpha_d^2 p^2/2} \\
V_2(2p) &= (\gamma_0 + \gamma_1 p^2)\, e^{-\alpha_d^2 p^2/2} \\
V_3(2p) &= \gamma_0 + \gamma_1\, e^{-\alpha_d^2 p^2/2} \\
V_4(2p) &= \gamma_0 + (\gamma_1 + \gamma_2 p^2)\, e^{-\alpha_d^2 p^2/2}
\end{aligned}
$$

Channel	V_1	V_2	V_3	V_4	Exp (MeV)
$\Delta(1232) \to N\pi$	115	118	116	120	114 − 120
$N(1520) \to N\pi$	102	98	101	98	55 − 81
$N(1535) \to N\pi$	106	108	102	107	44 − 96
$N(1650) \to N\pi$	71	72	68	72	60 − 162
$N(1680) \to N\pi$	63	55	60	50	78 − 98
$N(1720) \to N\pi$	123	114	114	118	12 − 56
$\Delta(1905) \to N\pi$	14	14	14	14	24 − 60
$\Delta(1910) \to N\pi$	39	42	38	43	33 − 102
$\Delta(1920) \to N\pi$	14	16	14	16	9 − 60

Comparison of the results obtained with different vertex functions, fitted to a selected number of experimental strong decays PDG. Columns 2 − 5 show the theoretical open-flavor decay widths, calculated with the vertices V_i of in combination with the effective phase space factor.

Parameters arXiv:1506.07469

$U(7)$ Parameter values used in the calculations The values of the constituent quark masses m_n $(n = u, d)$ and m_s are used in the vertex factor, where the pair-creation strength γ_0 is substituted with an effective one.

Parameter	Rel. PSF		Eff. PSF	
γ_0	14.3		13.2	
α_b	2.99	GeV^{-1}	2.69	GeV^{-1}
α_c	2.38	GeV^{-1}	2.02	GeV^{-1}
α_d	0.52	GeV^{-1}	0.82	GeV^{-1}
m_n	0.33	GeV		
m_s	0.55	GeV		

Parameter values used in the calculations, in combination with the relativistic phase space factor of Eq. (2) (column 2) and the effective phase space factor of Eq. The quantum number assignments for the decaying states are now taken from the hQM spectra.

Parameter	Value
γ_0	13.319
α_b	2.758
α_c	2.454
α_d	0
m_n	0.33
m_s	0.55

$U(7)$ Model Results, arXiv:1506.07469

Strong decay widths of three and four star nucleon resonances (in MeV), calculated with the relativistic phase space factor. The symbols (S) and (D) stand for S and D-wave decays, respectively.

Resonance	$N\pi$	$N\eta$	ΣK	ΛK	$\Delta\pi$	$N\rho$	$N\omega$
$N(1440)P_{11}$	85	–	–	–	13	–	–
	110 — 338	0 — 5			22 — 101		
$N(1520)D_{13}$	134	0	–	–	207	–	
	55 — 81	0			15 — 31		
$N(1535)S_{11}$	63	75	–	–	16	–	–
	44 — 96	40 — 91			< 2		
$N(1650)S_{11}$	41	72	–	0	18	–	–
	60 — 162	6 — 27		4 — 20	0 — 45		
$N(1675)D_{15}$	47	11	–	0	108	–	–
	46 — 74	0 — 2		< 2	65 — 99		
$N(1680)F_{15}$	121	1	–	0	100	–	–
	78 — 98	0 — 1			6 — 21		
$N(1700)D_{13}$	9	3	–	0	561	–	–
	7 — 43	0 — 3		< 8	10 — 225 (S)		
					< 50 (D)		
$N(1710)P_{11}$	5	9	0	3	56	–	–
	3 — 50	5 — 75		3 — 63	8 — 100	3 — 63	
$N(1720)P_{13}$	111	7	0	14	36	5	0
	12 — 56	5 — 20		2 — 60	90 — 360	105 — 340	
$N(1875)D_{13}$	0	0	0	0	0	0	0
	3 — 70	0 — 22	0 — 4		48 — 192 (S)		
					11 — 86 (D)	0 — 38	22 — 90
$N(1900)P_{13}$	11	12	1	13	63	64	24
	20 — 37	24 — 44	6 — 26	0 — 37			75 — 120

Results for Hypercentral Model

Strong decay widths of three and four star nucleon resonances (in MeV), calculated with the relativistic phase space factor. The symbols (S) and (D) stand for S and D-wave decays, respectively. hQM CASE

Resonance	$N\pi$	$N\eta$	ΣK	ΛK	$\Delta\pi$	$N\rho$	$N\omega$
$N(1440)P_{11}$	105	-	-	-	12	-	-
	$110 - 338$	$0 - 5$			$22 - 101$		
$N(1520)D_{13}$	111	0	-	-	206	-	-
	$55 - 81$	0			$15 - 31$		
$N(1535)S_{11}$	84	50	-	-	6	-	-
	$44 - 96$	$40 - 91$			< 2		
$N(1650)S_{11}$	51	29	-	0	4	-	-
	$60 - 162$	$6 - 27$		$4 - 20$	$0 - 45$		
$N(1675)D_{15}$	41	9	-	-	85	-	-
	$46 - 74$	$0 - 2$		< 2	$65 - 99$		
$N(1680)F_{15}$	91	0	0	0	92	-	-
	$78 - 98$	$0 - 1$			$6 - 21$		
$N(1700)D_{13}$	0	0	0	0	0	-	-
	$7 - 43$	$0 - 3$		< 8	$10 - 225$ (S)		
					< 50 (D)		
$N(1710)P_{11}$	18	12	0	14.1	70	-	-
	$3 - 50$	$5 - 75$		$3 - 63$	$8 - 100$	$3 - 63$	
$N(1720)P_{13}$	141	8	0	12	30	77	5
	$12 - 56$	$5 - 20$		$2 - 60$	$90 - 360$	$105 - 340$	
$N(1875)D_{13}$	14	8	2	0	560	80	82
	$3 - 70$	$0 - 22$	$0 - 4$		$48 - 192$ (S)		
					$11 - 86$ (D)	$0 - 38$	$22 - 90$
$N(1900)P_{13}$	15	12	1	13	70	53	23
	$20 - 37$	$24 - 44$	$6 - 26$	$0 - 37$			$75 - 120$

Conclusions

- We computed the open-flavor strong decays of light baryons (i.e. made up of u, d, s valence quarks) into baryon-pseudoscalar and baryon- vector mesons using a $^3P_0$ pair-creation model.
- We studied the strong decays in two different constituent quark Models. Some resonances have different assignments then we have different predictions.
- We to suppress heavier quark pair creation, like $s\bar{s}$ with respect to $u\bar{u}(d\bar{d})$
- A large number of decays were described with a few parameters.
- Maybe the deviations are due to the meson cloud effects or the contribution of the higher Fock components.

Thank you!