Extended schematic model for hadrons and what happens to the radius of an excited hadron

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- classification of hadrons: traditional quark model
  - mesons: $q\bar{q}$
  - baryons: qqq
- not everything fits $\Longrightarrow$ "exotic mesons"
  - light scalar nonet
  - some charmed mesons
- use diquarks $\mathcal{Q}$ as building blocks
- but diquarks were never used systematically as a classification tool for all known mesons...

Idea: construct a schematic model with quarks and diquarks as building blocks to reclassify mesons, and see what we might learn about QCD in the process.

arXiv:0910.2229

... ... I: Diquarks and Classification of Mesons

Which diquarks?

- interquark forces not known at low energies
- derive diquark building blocks from meson phenomenology:

$$\mathcal{Q}\bar{\mathcal{Q}} = \text{flavor nonets} \Longrightarrow Q \text{ is flavor-antisymmetric}$$

Table: Diquark configurations

	Flavor $SU(3)_f$	$SU(4)_f$	*Spin* $SU(2)_s$	*Color* $SU(3)_c$	$\mathcal{H}_{CM}$	$\mathcal{H}_{CE}$
$\mathcal{Q}_1$	$\bar{\mathbf{3}}_f(A)$	$\bar{\mathbf{6}}_f(A)$	$\mathbf{1}_s(A)$	$\bar{\mathbf{3}}_c(A)$	-8	$-8/3$
$\mathcal{Q}_2$	$\bar{\mathbf{3}}_f(A)$	$\bar{\mathbf{6}}_f(A)$	$\mathbf{3}_s(S)$	$\mathbf{6}_c(S)$	$-4/3$	$4/3$
$\mathcal{Q}_3$	$\mathbf{6}_f(S)$	$\mathbf{10}_f(S)$	$\mathbf{3}_s(S)$	$\bar{\mathbf{3}}_c(A)$	$8/3$	$-8/3$
$\mathcal{Q}_4$	$\mathbf{6}_f(S)$	$\mathbf{10}_f(S)$	$\mathbf{1}_s(A)$	$\mathbf{6}_c(S)$	4	$4/3$

Meson quantum numbers

- Color

$$q\bar{q} \;:\; \mathbf{3}_c \otimes \bar{\mathbf{3}}_c = \mathbf{8}_c \oplus \mathbf{1}_c \qquad SU(3)_c,$$

$$\mathcal{Q}_1\bar{\mathcal{Q}}_1 \;:\; \bar{\mathbf{3}}_c \otimes \mathbf{3}_c = \mathbf{8}_c \oplus \mathbf{1}_c \qquad SU(3)_c,$$

$$\mathcal{Q}_2\bar{\mathcal{Q}}_2 \;:\; \mathbf{6}_c \otimes \bar{\mathbf{6}}_c = \mathbf{27}_c \oplus \mathbf{8}_c \oplus \mathbf{1}_c \qquad SU(3)_c,$$

- Flavor

$$q\bar{q} \;:\; \mathbf{3}_f \otimes \bar{\mathbf{3}}_f = \mathbf{8}_f \oplus \mathbf{1}_f \qquad SU(3)_f,$$

$$\mathcal{Q}_i\bar{\mathcal{Q}}_i \;:\; \bar{\mathbf{3}}_f \otimes \mathbf{3}_f = \mathbf{8}_f \oplus \mathbf{1}_f \qquad SU(3)_f,$$

- J^{PC}

$$J = L \otimes S \;.$$

$$q\bar{q} \;:\; P = (-1)^{L+1}\,, \qquad C = (-1)^{L+S}$$

$$\mathcal{Q}_i\bar{\mathcal{Q}}_i \;:\; P = (-1)^{L}\,, \qquad C = (-1)^{L+S}\;.$$

Tables 2a, 2b, 2c: Meson quantum numbers for $q\bar{q}$, $\mathcal{Q}_1\bar{\mathcal{Q}}_1$, and $\mathcal{Q}_2\bar{\mathcal{Q}}_2$ up to $L = 3$.

Table 2a: $q\bar{q}$

L	S	J^{PC}	$^{2S+1}L_J$	
0	0	0^{-+}	$^1S_0$	$\surd\bullet$
0	1	1^{--}	$^3S_1$	$\surd\bullet$
1	0	1^{+-}	$^1P_1$	$\surd\bullet$
1	1	2^{++}	$^3P_2$	$\surd\bullet$
		1^{++}	$^3P_1$	$\surd\bullet$
		0^{++}	$^3P_0$	$\surd\bullet$
2	0	2^{-+}	$^1D_2$	$\surd\bullet$
2	1	3^{--}	$^3D_3$	$\surd\bullet$
		2^{--}	$^3D_2$	$\surd$
		1^{--}	$^3D_1$	$\surd\bullet$
3	0	3^{+-}	$^1F_3$	$\surd$
3	1	4^{++}	$^3F_4$	$\surd\bullet$
		3^{++}	$^3F_3$	
		2^{++}	$^3F_2$	$\surd\bullet$

Table 2b: $\mathcal{Q}_1\bar{\mathcal{Q}}_1$

L	S	J^{PC}	$^{2S+1}L_J$	
0	0	0^{++}	$^1S_0$	$\surd\bullet$
1	0	1^{--}	$^1P_1$	$\surd\bullet$
2	0	2^{++}	$^1D_2$	$\surd$
3	0	3^{--}	$^1F_3$	$\surd$

Table 2c: $\mathcal{Q}_2\bar{\mathcal{Q}}_2$

L	S	J^{PC}	$^{2S+1}L_J$	
0	0	0^{++}	$^1S_0$	
0	1	1^{+-}	$^3S_1$	
0	2	2^{++}	$^5S_2$	
1	0	1^{--}	$^1P_1$	
1	1	2^{-+}	$^3P_2$	$\surd\bullet$
		1^{-+}	$^3P_1$	$\surd$
		0^{-+}	$^3P_0$	$\surd\bullet$
1	2	3^{--}	$^5P_3$	
		2^{--}	$^5P_2$	$\surd\bullet$
		1^{--}	$^5P_1$	$\surd$
2	0	2^{++}	$^1D_2$	$\surd$
2	1	3^{+-}	$^3D_3$	
		2^{+-}	$^3D_2$	
		1^{+-}	$^3D_1$	$\surd$
2	2	4^{++}	$^5D_4$	
		3^{++}	$^5D_3$	
		2^{++}	$^5D_2$	$\surd$
		1^{++}	$^5D_1$	$\surd$
		0^{++}	$^5D_0$	$\surd$

Table 2c, cont'd

L	S	J^{PC}	$^{2S+1}L_J$	
3	0	3^{--}	$^1F_3$	$\surd$
3	1	4^{-+}	$^3F_4$	$\surd$
		3^{-+}	$^3F_3$	
		2^{-+}	$^3F_2$	$\surd$
3	2	5^{--}	$^5F_5$	
		4^{--}	$^5F_4$	
		3^{--}	$^5F_3$	
		2^{--}	$^5F_2$	
		1^{--}	$^5F_1$	

Classification of mesons:

- arrange mesons from PDG into flavor multiplets

- to each multiplet assign

  - meson type: $q\bar{q}$, $\mathcal{Q}_1\bar{\mathcal{Q}}_1$, or $\mathcal{Q}_2\bar{\mathcal{Q}}_2$

  - L and S numbers

Table 3a: Our suggested assignments for observed light mesons. Compare with Table 14.2 in the PDG.

J^{PC}	constituents	$^{2S+1}L_J$	$I=1$	$I=\frac{1}{2}$	$I=0$		$n^{2S+1}L_J(PDG)$
0^{-+}	$q\bar{q}$	$^1S_0$	$\bullet\pi$	$\bullet K$	$\bullet\,\eta$	$\bullet\,\eta'(958)$	1^1S_0
0^{-+}	$\mathcal{Q}_2\bar{\mathcal{Q}}_2$	$^3P_0$	$\bullet\pi(1300)$	$K(1460)$	$\bullet\,\eta(1475)$	$\bullet\,\eta(1295)$	2^1S_0
0^{++}	$\mathcal{Q}_1\bar{\mathcal{Q}}_1$	$^1S_0$	$\bullet a_0(980)$	$\kappa(800)$	$\bullet f_0(980)$	$\bullet\, f_0(600)$	—
0^{++}	$q\bar{q}$	$^3P_0$	$\bullet a_0(1450)$	$\bullet K_0^*(1430)$	$\bullet f_0(1710)$	$\bullet\, f_0(1370)$	1^3P_0
0^{++}	$\mathcal{Q}_2\bar{\mathcal{Q}}_2$	$^5D_0$		$K_0^*(1950)$	$f_0(2100)$	$\bullet\, f_0(2020)$	—
1^{--}	$q\bar{q}$	$^3S_1$	$\bullet\rho(770)$	$\bullet K^*(892)$	$\bullet\,\phi(1020)$	$\bullet\,\omega(782)$	1^3S_1
1^{--}	$\mathcal{Q}_1\bar{\mathcal{Q}}_1$	$^1P_1$	$\bullet\rho(1450)$	$\bullet K^*(1410)$	$\bullet\,\phi(1680)$	$\bullet\,\omega(1420)$	2^3S_1
1^{--}	$\mathcal{Q}_2\bar{\mathcal{Q}}_2$	$^5P_1$	$\rho(1570)$				—
1^{--}	$q\bar{q}$	$^3D_1$	$\bullet\rho(1700)$	$\bullet K^*(1680)$	$\bullet\,\omega(1650)$		1^3D_1
1^{--}	$\mathcal{Q}_2\bar{\mathcal{Q}}_2$	$^5F_1$	$\rho(2150)$				—
1^{-+}	$\mathcal{Q}_2\bar{\mathcal{Q}}_2$	$^3P_1$	$\bullet\pi_1(1600)$	$K(1630)$			—
1^{++}	$q\bar{q}$	$^3P_1$	$\bullet a_1(1260)$	$\bullet K_1(1400)$	$\bullet f_1(1420)$	$\bullet\, f_1(1285)$	1^3P_1
1^{++}	$\mathcal{Q}_2\bar{\mathcal{Q}}_2$	$^5D_1$	$a_1(1640)$	$K_1(1650)$	$f_1(1510)$		—
1^{+-}	$q\bar{q}$	$^1P_1$	$\bullet b_1(1235)$	$\bullet K_1(1270)$	$h_1(1380)$	$\bullet\, h_1(1170)$	1^1P_1
1^{+-}	$\mathcal{Q}_2\bar{\mathcal{Q}}_2$	$^3D_1$			$h_1(1595)$		—
2^{-+}	$\mathcal{Q}_2\bar{\mathcal{Q}}_2$	$^3P_2$	$\bullet\pi_2(1670)$	$K_2(1580)$	$\eta_2(1870)$	$\bullet\,\eta_2(1645)$	1^1D_2
2^{-+}	$q\bar{q}$	$^1D_2$	$\bullet\pi_2(1880)$				—
2^{-+}	$\mathcal{Q}_2\bar{\mathcal{Q}}_2$	$^3F_2$	$\pi_2(2100)$	$K_2(2250)$			—
2^{--}	$\mathcal{Q}_2\bar{\mathcal{Q}}_2$	$^5P_2$		$\bullet K_2(1770)$			—
2^{--}	$q\bar{q}$	$^3D_2$		$\bullet K_2(1820)$			1^3D_2

J^{PC}	constituents	$^{2S+1}L_J$	$I=1$	$I=\frac{1}{2}$	$I=0$		$n^{2S+1}L_J(PDG)$
2^{++}	$q\bar{q}$	$^3P_2$	$\bullet a_2(1320)$	$\bullet K_2^*(1430)$	$f_2(1430)$	$\bullet\ f_2(1270)$	1^3P_2
2^{++}	$\mathcal{Q}_2\bar{\mathcal{Q}}_2$	$^1D_2$			$\bullet f_2'(1525)$		—
2^{++}	$\mathcal{Q}_1\bar{\mathcal{Q}}_1$	$^1D_2$	$a_2(1700)$		$f_2(1640)$	$f_2(1565)$	—
2^{++}	$\mathcal{Q}_2\bar{\mathcal{Q}}_2$	$^5D_2$			$f_2(1810)$		—
2^{++}	$q\bar{q}$	$^3F_2$		$K_2^*(1980)$	$\bullet f_2(2010)$	$\bullet\ f_2(1950)$	—*
3^{--}	$q\bar{q}$	$^3D_3$	$\bullet\rho_3(1690)$	$\bullet K_3(1780)$	$\bullet\ \phi_3(1850)$	$\bullet\ \omega_3(1670)$	1^3D_3
3^{--}	$\mathcal{Q}_1\bar{\mathcal{Q}}_1$	$^1F_3$	$\rho_3(1990)$				—
3^{--}	$\mathcal{Q}_2\bar{\mathcal{Q}}_2$	$^1F_3$	$\rho_3(2250)$				—
3^{+-}	$q\bar{q}$	$^1F_3$		$K_3(2320)$			—
4^{-+}	$\mathcal{Q}_2\bar{\mathcal{Q}}_2$	$^3F_4$		$K_4(2500)$			—
4^{++}	$q\bar{q}$	$^3F_4$	$\bullet a_4(2040)$	$\bullet K_4^*(2045)$	$f_4(2220)$	$\bullet\ f_4(2050)$	1^3F_4
5^{--}	$\mathcal{Q}_2\bar{\mathcal{Q}}_2$	$^5F_5$	$\rho_5(2350)$	$K_5^*(2380)$			1^3G_5
6^{++}	$\mathcal{Q}_2\bar{\mathcal{Q}}_2$	$^5G_6$	$a_6(2450)$		$f_6(2510)$		1^3H_6

* This nonet was classified as 2^3P_2, a radial excitation, between 1992 and 2002.

Table 3b: Our suggested assignments for observed heavy (charm and bottom) mesons. Compare with Table 14.3 in the PDG.

J^{PC}	constituents	$^{2S+1}L_J$	**Charmed mesons** $I=1^\circ$	$I=\frac{1}{2}$	$I=0$	$I=0$	**Bottom mesons** $I=1^\circ$	$I=\frac{1}{2}$	$I=0$	$I=0$	$n^{2S+1}L_J$ (PDG)
0^{-+}	$q\bar{q}$	$^1S_0$		$\bullet D$	$\bullet D_s^\sharp$	$\bullet\eta_c(1S)$		$\bullet B^\dagger$	$\bullet B_s^\dagger, B_c^\dagger$	$\eta_b(1S)^\dagger$	1^3S_0
0^{-+}	$\mathcal{Q}_2\bar{\mathcal{Q}}_2$	$^3P_0$				$\bullet\eta_c(2S)^\dagger$					2^1S_0
0^{++}	$\mathcal{Q}_1\bar{\mathcal{Q}}_1$	$^1S_0$		$D_0^*(2400)^\sharp$	$\bullet D_{s0}^*(2317)$	$\bullet\chi_{c0}(1P)$				$\bullet\chi_{b0}(1P)$	1^3P_0
0^{++}	$q\bar{q}$	$^3P_0$								$\chi_{b0}(2P)^{\dagger\dagger}$	2^3P_0
1^{--}	$q\bar{q}$	$^3S_1$		$\bullet D^*$	$\bullet D_s^{*\sharp}$	$\bullet J/\psi(1S)$		$\bullet B^{*\dagger}$	$B_s^{*\dagger}$	$\bullet\Upsilon(1S)$	1^3S_1
1^{--}	$\mathcal{Q}_1\bar{\mathcal{Q}}_1$	$^1P_1$				$\bullet\psi(2S)$				$\bullet\Upsilon(2S)$	2^3S_1
1^{--}	$q\bar{q}$	$^3D_1$				$\bullet\psi(3770)$				$\bullet\Upsilon(3S)$	——*
1^{--}	$\mathcal{Q}_2\bar{\mathcal{Q}}_2$	$^5F_1$				$\bullet\psi(4040)$				$\bullet\Upsilon(4S)$	——*
1^{++}	$q\bar{q}$	$^3P_1$		$D_1(2420)$	$\bullet D_{s1}(2536)^\sharp$	$\bullet\chi_{c1}(1P)$		$\bullet B_1(5721)^{0\dagger}$	$\bullet B_{s1}(5830)^{0\dagger}$	$\bullet\chi_{b1}(1P)^{\dagger\dagger}$	——**
1^{++}	$\mathcal{Q}_2\bar{\mathcal{Q}}_2$	$^5D_1$			$\bullet D_{s1}(2460)$	$\bullet X(3872)^{\sharp\sharp}$				$\bullet\chi_{b1}(2P)^{\dagger\dagger}$	——**
2^{++}	$q\bar{q}$	$^3P_2$		$\bullet D_2^*(2460)$	$\bullet D_{s2}(2573)^\sharp$	$\bullet\chi_{c2}(1P)$		$\bullet B_2^*(5747)^{0\dagger}$	$\bullet B_{s2}^*(5840)^\dagger$	$\bullet\chi_{b2}(1P)^{\dagger\dagger}$	$1^3P_2^{**}$
2^{++}	$\mathcal{Q}_1\bar{\mathcal{Q}}_1$	$^1D_2$				$\chi_{c2}(2P)$				$\bullet\chi_{b2}(2P)^{\dagger\dagger}$	2^3P_2

Table 3c: Isorons and magic J^{PC}.

Isorons						
	0^{-+}	0^{++}	1^{--}	1^{-+}	2^{++}	4^{++}
Light	$\bullet\eta(1405)$ $\eta(1760)$ $\bullet\pi(1800)$ $K(1830)$ $\eta(2225)$	$\bullet f_0(1500)$ $f_0(2200)$ $f_0(2330)$	$\rho(1900)$	$\bullet\pi_1(1400)$	$f_2(1910)$ $f_2(2150)$ $\bullet f_2(2300)$ $\bullet f_2(2340)$	$f_4(2300)$
Heavy			$\bullet\psi(4160)$ $\bullet X(4260)$ $X(4360)$ $\bullet\psi(4415)$ $\Upsilon(10860)$ $\Upsilon(11020)$			

Glueballs						
	0^{-+}	0^{++}	1^{--}	1^{-+}	2^{++}	4^{++}
	X	X			X	

- isorons
- magic numbers and glueballs
- no "exotics"

former exotic mesons:

  - the "cryptoexotic" light scalar nonet with $J^{PC} = 0^{++}$ is a $\mathcal{Q}_1 \bar{\mathcal{Q}}_1$, ${}^1S_0$
  - a manifestly "exotic" meson with $J^{PC} = 1^{-+}$ is a $\mathcal{Q}_2 \bar{\mathcal{Q}}_2$, ${}^3P_1$
  - some newly discovered charmed mesons including:
    - the $D^*_{sJ}(2317)$ with $J^{PC} = 0^{++}$ is a $\mathcal{Q}_1 \bar{\mathcal{Q}}_1$, ${}^1S_0$;
    - the $D_{sJ}(2460)$ with $J^{PC} = 1^{++}$ is a $\mathcal{Q}_2 \bar{\mathcal{Q}}_2$, ${}^5D_1$;
    - the $X(3872)$ with $J^{PC} = 1^{++}$ is a $\mathcal{Q}_2 \bar{\mathcal{Q}}_2, {}^5D_1$.

former outcasts:

- some heavier scalar mesons with $J^{PC} = 0^{++}$ now form a nonet which is classified as $\mathcal{Q}_2\bar{\mathcal{Q}}_2$, ${}^5D_0$;
- some vector mesons with $J^{PC} = 1^{++}$ are now $\mathcal{Q}_2\bar{\mathcal{Q}}_2$, ${}^5D_1$;
- some 2^{++} mesons which are now $\mathcal{Q}_1\bar{\mathcal{Q}}_1$, ${}^1D_2$.

- no radials
  - the second 0^{-+} nonet, previously a radial excitation with $n^{2S+1}L_J = 2^1S_0$, is a $\mathcal{Q}_2\bar{\mathcal{Q}}_2$ with ${}^{2S+1}L_J = {}^3P_0$;
  - the second 1^{--} nonet, previously a radial excitation with $n^{2S+1}L_J = 2^3S_1$, is a $\mathcal{Q}_1\bar{\mathcal{Q}}_1$ with ${}^{2S+1}L_J = {}^1P_1$.

Baryon sector: which diquarks for baryons?

color singlets $\Longrightarrow$ color antisymmetric

Table: Diquark configurations

	Flavor		*Spin*	*Color*	$\mathcal{H}_{CM}$	$\mathcal{H}_{CE}$
	$SU(3)_f$	$SU(4)_f$	$SU(2)_s$	$SU(3)_c$		
$\mathcal{Q}_1$	$\bar{\mathbf{3}}_f(A)$	$\bar{\mathbf{6}}_f(A)$	$\mathbf{1}_s(A)$	$\bar{\mathbf{3}}_c(A)$	-8	$-8/3$
$\mathcal{Q}_2$	$\bar{\mathbf{3}}_f(A)$	$\bar{\mathbf{6}}_f(A)$	$\mathbf{3}_s(S)$	$\mathbf{6}_c(S)$	$-4/3$	$4/3$
$\mathcal{Q}_3$	$\mathbf{6}_f(S)$	$\mathbf{10}_f(S)$	$\mathbf{3}_s(S)$	$\bar{\mathbf{3}}_c(A)$	$8/3$	$-8/3$
$\mathcal{Q}_4$	$\mathbf{6}_f(S)$	$\mathbf{10}_f(S)$	$\mathbf{1}_s(A)$	$\mathbf{6}_c(S)$	4	$4/3$

– Ropers

$$1/2^+ : \; N(1440),\; \Lambda(1600),\; \Sigma(1660);$$
$$1/2^+ : \; N(1710),\; \Lambda(1810),\; \Sigma(1880);$$
$$3/2^+ : \; \Delta(1600).$$

Ropers as pentaquarks, $\mathcal{Q}_1\mathcal{Q}_1\bar{q}$ P-waves

$\Longrightarrow$ There are no radial excitations in the hadron spectrum

[The title of the paper was:

No Radial Excitations in Low-Energy QCD I: Diquarks and Classification of Mesons (arXiv: 0910.2229)]

- PDG - 1960's: $^{2S+1}L_J$

- PDG - 1980's: $n^{2S+1}L_J$

- PDG 2004

- experiment

What happens to the radius of hadrons when they are excited?

What happens to the radius of hadrons
when they are excited?

- The radius of a hadron is largest when the hadron is in its ground state.

Table: Measured sizes of ground state ($L = 0$) hadrons

Mesons				
	Mass (MeV)	Radius (fm)	Density (g/cm^3)	Source
$\pi^{\pm}$	140	.672	$.20 \times 10^{15}$	PDG
$K^{\pm}$	494	.560	1.2×10^{15}	PDG

Baryons				
	Mass (MeV)	Radius (fm)	Density (g/cm^3)	Source
p	938	.87	$.61 \times 10^{15}$	PDG
Σ^{-}	1197	.78	1.1×10^{15}	PDG
Δ	1382	.650	2.1×10^{15}	Lattice
	1425	.632	2.4×10^{15}	Lattice
	1470	.614	2.7×10^{15}	Lattice

What happens to the radius of hadrons
when they are excited?

- The radius of a hadron is largest when the hadron is in its ground state.

- The radius of a hadron decreases when the hadron's orbital excitation increases.

What happens to the radius of hadrons when they are excited?

- The radius of a hadron is largest when the hadron is in its ground state.

- The radius of a hadron decreases when the hadron's orbital excitation increases.

Opposite of atoms:

The radius of an atom is smallest in the ground state

The radius of an atom increases with L

- Corollary: the path from confinement to asymptotic freedom is a Regge trajectory

– simple testable prediction about a fundamental property of hadrons: their size

– Request to lattice QCD people: please compute more radii!

– Request to experimentalists: please measure more radii!

The title was:

No Radial Excitations in Low-Energy QCD II:

The Shrinking Radius of Hadrons (arXiv: 0910.2231)

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Physics Today on size of protons (August 2010):

"... the proton is a quark composite whose size and shape are quantum-chromodynamic manifestations beyond the purview of QED."

Summary:

Diquarks and quarks as building blocks

$\Longrightarrow$ reclassification of hadron spectrum

$\Longrightarrow$ no radial quantum number

$\Longrightarrow$ shrinking radius of hadrons