2012

A New QCD Effect: the Shrinking Radius of Hadrons

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(Received January 2, 2012)

We propose an extended schematic model for hadrons in which quarks as well as diquarks serve as building blocks. The outcome is a reclassification of the hadron spectrum in which there are no radially excited hadrons: all mesons and baryons previously believed to be radial excitations are orbitally excited states involving diquarks. Also, there are no exotic hadrons: all hadrons previously believed to be exotic are states involving diquarks and are an integral part of the model. We discuss the implications of this result for a new understanding of confinement and its relation to asymptotic freedom, as well as its implications for a novel relation between the size and energy of hadrons, whereby an excited hadron shrinks.

DOI:10.5506/APhysPolBSupp.5.695
PACS numbers: 12.38.–t, 12.39.–x, 12.28.Aw, 12.38.Mh

1. Introduction

It is well-known that making reliable predictions about low-energy QCD and hadrons is a great challenge, as perturbative methods of quantum field theory do not apply at low energies, where the coupling constant is strong. The common approach has been to propose various dynamical models which are inspired by assumptions, ideas, and intuition borrowed from physical systems, such as atomic physics and non-relativistic quantum mechanics, which are not QCD.

Here[1] we set out to study the hadron spectrum by employing purely QCD ingredients and invoking the role of diquarks in the mix.

One well-established pillar of QCD is the quark model [2], which has been the accepted framework for classifying the hadron spectrum. This is a schematic model for the mesons and baryons in which quarks are the

* Talk presented at HIC for FAIR Workshop and XXVIII Max Born Symposium "Three Days on Quarkyonic Island", Wrocław, Poland, May 19–21, 2011.

[1] This work is based on a more extensive manuscript, with many additional details and references [1].

building blocks for all the hadrons: mesons are bound states of a quark and an antiquark ($q\bar{q}$) and baryons are bound states of three quarks (qqq). In addition to quarks, bound configurations of two quarks, known as diquarks, may also be building blocks. The diquarks, explored already at the beginning of the quark model in the 1960s having been introduced by Gell-Mann in [3], were revisited following a surge of experimental and theoretical interest in pentaquarks ($qqqq\bar{q}$) [4][2]. In particular, diquarks have been used as building blocks in a systematic classification of all known baryons [6]. As to mesons, a few mesons have been viewed as having diquarks as constituents — to name just two examples, the light scalar mesons were interpreted as diquark–antidiquark states [7], as were several charmed mesons [8]. But diquarks have never been employed systematically as building blocks for the classification of *all* known mesons.

We undertake this task. Our purpose is to find out whether the entire meson spectrum can be re-classified with the aid of diquarks, and whether we can learn anything new about QCD in the process.

In this spirit, we construct a new extended schematic model for mesons in which certain diquark configurations, selected for us by the flavor structure of meson phenomenology, are building blocks for mesons in addition to, and on equal footing with, the quarks of the traditional quark model. These diquarks are the two flavor-antisymmetric ones. One of the two coincides with the most well-known "good" diquark which is antisymmetric in all quantum numbers; the other has been previously unfairly neglected.

What follows is a reclassification of the meson spectrum into quark–antiquark and diquark–antidiquark states and a reassignment of L and S quantum numbers to the mesons. Thus, diquark–antidiquark states are naturally integrated into the classification and no longer perceived as "exotic".

In the classification process, a new notion of *isorons* (iso-hadrons) emerges, along with their *magic* J^{PC} *quantum numbers*. The isorons are the natural analogs of isotopes or isotones in atomic or nuclear physics, and their magic J^{PC} quantum numbers are analogous to the magic numbers of the nuclear shell model. In the nuclear shell model, it was spin–orbit couplings which was the magic behind the magic numbers. Here, it remains an open problem to understand what is behind the magic J^{PC} of isorons. It is striking that the magic J^{PC} of isorons match the quantum numbers predicted for low-lying glueballs by lattice QCD.

Most significantly, we find that there are no radially excited mesons: no radial quantum number arises. In both the light and heavy quark sectors, mesons that have been believed to be radially excited quark–antiquark

[2] It was eventually found that the pentaquark Θ^+ does not exist [5]; as R.L. Jaffe said (Harvard seminar, 2004) "pentaquarks might come and go, but the diquarks are here to stay".

states are orbitally excited diquark–antidiquark states. The same is true for baryons: the baryons that have so far been considered to be radially excited are orbitally excited configurations of two diquarks and an antiquark. All in all, we are led to the conclusion that there are no radial excitations in the hadron spectrum. In turn, this leads to inescapable, surprising, and significant implications regarding the dynamics of the strong force, confinement, and asymptotic freedom. In particular, we uncover a new set of relations between two fundamental properties of hadrons: their size and their energy. These relations predict that hadrons shrink.

While our predictions may appear counterintuitive, they are completely consistent with the known properties of QCD, such as confinement and asymptotic freedom, and provide a novel explanation for the relation between them.

By now, our predictions have gotten experimental confirmation: two experiments which observe shrinkage of hadrons have surfaced several months after the papers [1] were posted to `arXiv`. In the first, a shrunk size of the proton was observed [9]. While it was initially believed that the reason for the unexpectedly small size came from QED, it was later realized [10] that the shrunk size of the proton manifests properties of QCD, as predicted in our papers [1]. The second experiment, carried out at HERMES, reported shrinkage of the size of the ρ meson [11]. Suggestions for further experiments appear in Sec. 5.

We emphasize that we have not imposed any form of interquark interaction on our model. Instead, we make extensive use only of experimental data together with the idea that quarks and diquarks serve as building blocks for hadrons. This approach is fundamentally different from the one behind non-relativistic QCD models which rely on an interquark potential. The results are also fundamentally different.

2. Extended schematic model for mesons: diquark building blocks and meson quantum numbers

Now we turn to meson phenomenology to determine what configurations of two quarks can be considered as the diquark building blocks for mesons. We note that all observed light meson multiplets are flavor nonets. No larger flavor multiplets appear. Therefore, the $\mathrm{SU}(3)_f$ flavor representation of the diquark building blocks may not be larger than an antitriplet or else flavor multiplets of mesons larger than nonets would be expected. Fortunately, an antitriplet indeed appears in the flavor representation of a diquark (the subcript f denotes flavor)

$$\mathcal{Q} = qq : \qquad \mathbf{3}_f \otimes \mathbf{3}_f = \mathbf{6}_f \oplus \bar{\mathbf{3}}_f \,. \tag{1}$$

So we require that a diquark be in $\bar{3}_f$ configuration, which is flavor antisymmetric. Since quarks are fermions, a totally antisymmetric configuration is needed, which leads to two possible diquark configurations: $\mathcal{Q}_1 = (\bar{\mathbf{3}}_f, \mathbf{1}_s, \bar{\mathbf{3}}_c)$ and $\mathcal{Q}_2 = (\bar{\mathbf{3}}_f, \mathbf{3}_s, \mathbf{6}_c)$ (the subscript s denotes spin and c denotes color). When we include heavy flavors, we continue to require antisymmetry in flavor; the spin and color representations remain unchanged.

So now we have three building blocks for mesons: ordinary quarks q and the diquarks $\mathcal{Q}_1$ and $\mathcal{Q}_2$. From these we construct meson states.

TABLE I

J^{PC} quantum numbers for the three types of mesons, up to $L = 2$ (see [1] for full table.

Table 1a: $q\bar{q}$

L	S	J^{PC}	${}^{2S+1}L_J$
0	0	0^{-+}	${}^1S_0$
0	1	1^{--}	${}^3S_1$
1	0	1^{+-}	${}^1P_1$
1	1	2^{++}	${}^3P_2$
		1^{++}	${}^3P_1$
		0^{++}	${}^3P_0$
2	0	2^{-+}	${}^1D_2$
2	1	3^{--}	${}^3D_3$
		2^{--}	${}^3D_2$
		1^{--}	${}^3D_1$

Table 1b: $\mathcal{Q}_1\bar{\mathcal{Q}}_1$

L	S	J^{PC}	${}^{2S+1}L_J$
0	0	0^{++}	${}^1S_0$
1	0	1^{--}	${}^1P_1$
2	0	2^{++}	${}^1D_2$

Table 1c: $\mathcal{Q}_2\bar{\mathcal{Q}}_2$

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^{-+}	${}^3P_2$
		1^{-+}	${}^3P_1$
		0^{-+}	${}^3P_0$
1	2	3^{--}	${}^5P_3$
		2^{--}	${}^5P_2$
		1^{--}	${}^5P_1$
2	0	2^{++}	${}^1D_2$
2	1	3^{+-}	${}^3D_3$
		2^{+-}	${}^3D_2$
		1^{+-}	${}^3D_1$
2	2	4^{++}	${}^5D_4$
		3^{++}	${}^5D_3$
		2^{++}	${}^5D_2$
		1^{++}	${}^5D_1$
		0^{++}	${}^5D_0$

As usual, mesons must be color singlet bosons. By computing the suitable tensor products of the representations of the color group $\mathrm{SU}(3)_c$, we find that the only color singlet combinations are $q\bar{q}$, $\mathcal{Q}_1\bar{\mathcal{Q}}_1$, and $\mathcal{Q}_2\bar{\mathcal{Q}}_2$. It remains to compute their J^{PC} quantum numbers. For $q\bar{q}$ these are well-known to be $J = L \otimes S$, $P = (-1)^{L+1}$, $C = (-1)^{L+S}$. For $\mathcal{Q}_1\bar{\mathcal{Q}}_1$ and $\mathcal{Q}_2\bar{\mathcal{Q}}_2$, J is as usual $L \otimes S$, and a calculation analogous to the derivation of P and C for $q\bar{q}$ mesons yields[3] $P = (-1)^L$ and $C = (-1)^{L+S}$. Now all J^{PC} quantum numbers for all three types of mesons in this model may be computed in terms of L and S. See Table I.

3. Reclassification of mesons

The next stage is to classify the known mesons based on this model. The PDG contains all mesons observed in experiments, with measurements of the meson's mass, J^{PC}, and decays[4]. We arrange the mesons in flavor nonets of common J^{PC} quantum numbers, and assign L and S quantum numbers from Table I. The result is a classification of all mesons, both light and heavy. See Table II.

We now discuss two central features of the classification[5].

(1) *Isorons and magic numbers.* In most cases, there is a unique assignment for each meson, but occasionally there are multiple mesons vying for one available space in the table. In analogy with the concept of "isotopes", which denote multiple atoms with the same atomic number and properties but different mass, we name the multiple mesons "isorons", short for iso-hadrons. They appear in Table II c.

One can see immediately that there are certain J^{PC} for which there is an abundance of isorons. Those J^{PC} are called "magic J^{PC}" in analogy with magic numbers of the nuclear shell model. Intriguingly, in the light meson sector, the magic J^{PC} exactly match the quantum numbers expected for low-lying glueballs from lattice QCD [12].

(2) *No radial excitation.* A distinct feature of the classification is that no radial quantum number arises: all mesons are reclassified as $q\bar{q}$, $\mathcal{Q}_1\bar{\mathcal{Q}}_1$, or $\mathcal{Q}_2\bar{\mathcal{Q}}_2$ with assigned L and S quantum numbers that are consistent with the measured J^{PC}. Mesons previously believed to be radially excited are one of the following: $\mathcal{Q}_1\bar{\mathcal{Q}}_1$ or $\mathcal{Q}_2\bar{\mathcal{Q}}_2$ mesons with one unit of orbital excitation, $L = 1$ (see the second light 0^{-+} nonet and the second light 1^{--} nonet, as well as their heavier charm and bottom partners); $q\bar{q}$ mesons with $L = 2$ (the $\psi(3770)$ and the $\Upsilon(3S)$); or $\mathcal{Q}_2\bar{\mathcal{Q}}_2$ mesons with $L = 3$ (the $\psi(4040)$ and the $\Upsilon(4S)$)[6].

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[3] Of course, the charge conjugation quantum number C is understood to apply only to charge conjugation eigenstates.

[4] Those mesons listed in the PDG under "further states" are not yet considered established and we leave them out of the discussion.

[5] Other features discussed in [1] involve expected new particles, mass hierarchies in light nonets, binding energies of diquarks, decays of $\mathcal{Q}_i\bar{\mathcal{Q}}_i$ mesons, interquark forces, and Regge trajectories, are omitted here due to space constraints.

[6] Note that the names $\Upsilon(nS)$ given to the bottomoniums are based on their previous classification as S-waves with n units of radial excitation.

TABLE II a

Classification of light mesons, up to $J = 2$ (see [1] for full table).

Light mesons						
J^{PC}	constituents	$^{2S+1}L_J$	$I = 1$	$I = \frac{1}{2}$	$I = 0$	
0^{-+}	$q\bar{q}$	$^1S_0$	$\bullet\pi$	$\bullet K$	$\bullet\,\eta$	$\bullet\,\eta'(958)$
0^{-+}	$\mathcal{Q}_2\bar{\mathcal{Q}}_2$	$^3P_0$	$\bullet\pi(1300)$	$K(1460)$	$\bullet\,\eta(1475)$	$\bullet\,\eta(1295)$
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^{++}	$q\bar{q}$	$^3P_0$	$\bullet a_0(1450)$	$\bullet K_0^*(1430)$	$\bullet f_0(1710)$	$\bullet\, f_0(1370)$
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^{--}	$\mathcal{Q}_1\bar{\mathcal{Q}}_1$	$^1P_1$	$\bullet\rho(1450)$	$\bullet K^*(1410)$	$\bullet\,\phi(1680)$	$\bullet\,\omega(1420)$
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^{--}	$\mathcal{Q}_2\bar{\mathcal{Q}}_2$	$^5F_1$	$\rho(2150)$		$\phi(2170)$	
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^{++}	$\mathcal{Q}_2\bar{\mathcal{Q}}_2$	$^5D_1$	$a_1(1640)$	$K_1(1650)$	$f_1(1510)$	
1^{+-}	$q\bar{q}$	$^1P_1$	$\bullet b_1(1235)$	$\bullet K_1(1270)$	$h_1(1380)$	$\bullet\, h_1(1170)$
1^{+-}	$\mathcal{Q}_2\bar{\mathcal{Q}}_2$	$^3D_1$			$h_1(1595)$	
2^{-+}	$\mathcal{Q}_2\bar{\mathcal{Q}}_2$	$^3P_2$	$\bullet\pi_2(1670)$	$K_2(1580)$	$\eta_2(1870)$	$\bullet\,\eta_2(1645)$
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^{--}	$q\bar{q}$	$^3D_2$		$\bullet K_2(1820)$		
2^{++}	$q\bar{q}$	$^3P_2$	$\bullet a_2(1320)$	$\bullet K_2^*(1430)$	$f_2(1430)$	$\bullet\, f_2(1270)$
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^{++}	$q\bar{q}$	$^3F_2$		$K_2^*(1980)$	$\bullet f_2(2010)$	$\bullet\, f_2(1950)$

For $J \geq 3$ see [1].

TABLE II b

Classification of heavy mesons.

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

TABLE II c

Isorons.

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

Although we have not discussed baryon reclassification in our extended quark model, one can show [1,4] that in the baryon sector it is also the case that there is no radial quantum number: all baryons previously believed to be radially excited are reclassified as states involving diquarks, such as $\mathcal{Q}_1\mathcal{Q}_1\bar{q}$, with orbital, but no radial, excitations. Hence, the result about no radial excitations in mesons extends to all hadrons.

One may now ask: can this result shed any new light on QCD? The answer is an emphatic "yes", and we discuss it in the following section.

Before we do so, we address the history that led to the current belief that radial excitations of hadrons do exist.

One of the main sources for the concept that hadrons may be radially excited goes back to potential models. According to these models, low-energy QCD is described by a quark–quark potential $V(r)$, where r is the distance between the quarks. The potential in these models has two terms: a short-distance term that is Coulomb-like (*i.e.*, proportional to $-1/r$) and analogous to the interaction between the proton and electron in the hydrogen atom, and a long-distance term $V_{\rm conf}(r)$ that increases with r and — according to the models — describes confinement.

In these models, the spectrum for quark–antiquark bound states, *i.e.* mesons, is obtained by solving the Schrödinger equation with the above potential $V(r)$. As with the hydrogen atom, or as with any central potential in non-relativistic quantum mechanics, the resulting quantum numbers that describe the spectrum include a principal or radial quantum number. Hence, potential models automatically allow for, and in fact require, radial quantum numbers and radial excitations. Another prominent set of models known as strong decay models also includes radials. Yet the theoretical predictions about radial excitations in hadrons have been known to encounter difficulties: data involving the masses of the candidates for radial excitations shows that they are often significantly lighter than predicted by the models, and data involving their decay modes often does not favor a radial assignment either [13].

If we turn back to the original quark model, we find that a radial quantum number was never part of this model, and the early versions of the PDG reported the quantum numbers of mesons with the notation ${}^{2S+1}L_J$, that is, spin and orbital quantum numbers only. It was only around 1980 that the PDG added a radial quantum number, ultimately modifying its notation to the atomic one, *i.e.* $n^{2S+1}L_J$. The reason was that additional mesons were detected that did not fit into the original quark model classification, and this extra quantum number was introduced as a classification tool. There was certainly no direct evidence that those additional mesons were radially excited. In fact, some years later the PDG removed the radial classification of two meson nonets because it was considered far fetched [14].

4. Implications

We now discuss the implications of our result, which we summarize as

> *The Law of the Hadronic Spectrum*: *There are no radial excitations in low-energy QCD.*

(1) *The laws of ground state and excited hadrons.* In order to understand the implications of the above Law of the Hadronic Spectrum, we first recall the properties of radial excitations in systems, where they do exist, such as atomic physics. Recall that in a radially excited hydrogen atom, the average distance between the proton and electron is larger than that distance in its ground state. As the radial excitation quantum number n_{r} increases, this distance — which defines the radius of the atom — grows, until finally when $n_{\mathrm{r}} \to \infty$, the electron and proton are completely separated and the atom has been ionized.

It is, therefore, clear that the absence of radial excitations in the hadron spectrum is directly related to the prohibition on separation of the constituents of a hadron, that is, it is directly related to quark confinement. Since radial excitations are prohibited for hadrons, but other excitations — such as orbital excitations — are allowed, it must follow that the distance between the quarks in excited states cannot be larger than their distance in the corresponding ground state, or else such excitations would have been prohibited just as radial excitations are. Therefore, unlike the case for atoms, we have:

> *The Law of Ground State Hadrons*: *The radius of a hadron is largest when the hadron is in its ground state.*

When a hadron is excited, does its radius stay the same or become smaller? While no radii of excited hadrons have ever been measured, four measurements of ground-state radii are available (proton: .87 fm, Σ^-: .78 fm, π: .67 fm, K: .56 fm; their masses are .94 GeV, 1.2 GeV, .14 GeV, and .49 GeV, respectively [5][7]). From these one can see that in both the meson and baryon sectors, a more massive hadron is smaller. Now, an orbitally excited hadron has higher mass than a ground state hadron — it follows roughly the Regge trajectory equation, where $m^2 \propto L$. Also, it is standard to associate higher energies or large momenta with smaller distances. So we have:

> *The Law of Shrinking Radii*: *The radius of a hadron decreases when the hadron's orbital excitation increases.*

We may express the Law of Shrinking Radii in the following way:

$$\frac{\Delta R}{\Delta L} < 0\,, \tag{2}$$

where R is the hadron's radius.

This result may appear counter-intuitive, since it is well-known in quantum physics, as well as in classical physics, that there is a centrifugal barrier associated with orbital angular momentum. That is, an object with orbital angular momentum tends to be larger. However, QCD and confinement have always proved counter-intuitive. We may re-state the result by saying that in hadrons, QCD overcomes the centrifugal barrier that would otherwise occur in an orbitally excited object.

(2) *Transition between confinement and asymptotic freedom.* It is one of the pillars of QCD that when quarks are at high energies and close to each other, their interaction is very weak — this is the concept of asymptotic freedom and antiscreening. Further, when quarks are at low energies and far apart (around 1 fm), their interaction is strong and confining.

We have shown that a hadron is largest at its lowest energy state, and its size decreases when it is orbitally excited. It follows that we can overcome confinement and reach asymptotic freedom by increasing a hadron's orbital excitation. Eventually, its quarks will be so close to each other that they become free and the hadron no longer exists.

Note that a set of hadrons, where each successive one has an additional unit of L, is called a Regge trajectory. Therefore, what we have shown is that *the path from confinement to asymptotic freedom is a Regge trajectory.*

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[7] Another ground state hadron, the ρ meson, arguably has a size similar to that of the pion [15]. Lattice QCD calculations [16] also provide a radius for the Δ.

So far, known Regge trajectories have at most 3 hadrons for baryons, and 6 hadrons for mesons [1, 6]. This means either that further hadrons of the trajectory have not yet been detected, or that they already do not exist as hadrons because the energy is already high enough that we have reached the regime of asymptotic freedom.

(3) *The top quark is free.* The top quark is the heaviest known quark and it is the only quark that has been observed on its own, not as a constituent of any hadron. It is standard to say that the top is so heavy that it decays before it hadronizes [5, 17]. We propose a different interpretation: the top quark is so heavy that its intrinsic energy is in the asymptotically free regime where there is no confinement, and no hadrons. It is a free quark.

5. Further experimental tests

In addition to the experiments [9, 11] mentioned in the introduction, a particularly direct test of the predictions proposed here about the size of hadrons would be a measurement of the size of excited hadrons as compared with a measurement of the size of their ground state. For example, one may take several mesons of a given Regge trajectory such as π, $b_1(1235)$, $\pi_2(1670)$ or a Regge trajectory of baryons such as $N(939)$, $N(1520)$, $N(1680)$ and measure their sizes. Such measurements have not yet been carried out and may prove challenging experimentally due to the short lifetime of the excited hadrons. However, extensive studies of N^*s have been carried out at JLAB and may contain promising data [18].

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