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Equal *u*, *d* Quark Mass and Diquark, Nucleon Structure

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ABSTRACT

The known masses of 6 mesons, $\pi^{\pm}$, $K^{\pm}$, D^0, $\phi(1020)$, J/ψ, and $Y(1S)$, chosen for their purity in their quark contents, have been inserted into the meson mass formula in SSI, scalar strong interaction hadron theory, to fix the masses of the five quarks, *u, d, s, c,* and *b* and a constant d_{m0} in that formula. The *u* and *d* quark masses were found to be nearly the same, $0.5891243\pm1.7\times10^{-5}$ GeV. This discovery revises our earlier conception that the *d* quark is about 2 MeV heavier than the *u* quark, obtained using 6 other mesons as input. Applied to nucleon, the strong interaction parts in the proton and neutron have also to be the same. But the proton charge is expected to contribute its Coulomb energy to its strong interaction mass to become heavier than the neutron mass. This result however contradicts data. This problem appears to be related to the diquark-quark structure of the nucleon. The diquark, considered as a point particle hitherto in SSI, has now a small extension, < 0.45 fm here, due to Coulomb repulsion. This force generates a "hidden" charge mass to be subtracted from the common strong interaction mass. Since this extra charge mass is greater for the *uu* diquark than for *dd*, the proton is lighter. A coarse estimate in SSI led to some qualitative values about 31 to 56 % smaller than the measured 1.293 MeV.

Keywords

scalar strong interaction hadron theory SSI, ground state mesons, meson mass formula, equality of predicted *u* and *d* mass, "arrow" model of nucleon, Coulomb repulsion in diquark, "rod" like diquark, virtual charge mass, nucleon mass difference.

1. INTRODUCTION

The ground state meson spectra [1] have largely been accounted for using the formula

$$E_J = \sqrt{\left(m_p + m_r\right)^2 - 4d_{m0} + 8d_h\left(J + \tfrac{3}{2}\right)} \qquad (1)$$

in the scalar strong interaction hadron theory SSI [2 (5.1.1)]. Here E_J is the strong interaction meson mass, m_p, m_r the quark masses with p, r =*1, 2, 3, 4,* and *5* referring to the *u*, *d*, *s*, *c*, and *b* quarks, respectively. The integration constants d_h is the confinement strength and d_{m0} a "zero-point strong potential" between the quark and antiquark. *J*=0 for pseudoscalar 0^- and *J*=1 for vector 1^- mesons. This formula is derived from the meson wave equations [2 (3.2.10b, 11a)] in the "hidden" relative space *x* between the quarks interacting via strong interaction. Mass contribution from the charges of the mesons does not enter this formula,

The 5 quark masses and the 2 constants d_h and d_{m0} have been obtained from [2 Sec. 5.2] using 7 meson masses. Practically, d_h has been fixed by an average of the differences between the squares of the masses of 0^- mesons and their 1^- meson partners and turns out to be 0.07 GeV^2 [2 (5.2.2)]. Thus, 6 input meson masses are needed to fix the 5 quark masses and d_{m0}.

From the 5 quarks and their antiquarks, we can form 25 0^- mesons and 25 1^- mesons. The isosinglet 0^- mesons $\bar{u}u$, $\bar{d}d$ $\bar{s}s$, $\bar{c}c$, and $\bar{b}b$ are forbidden (see the U(1) problem [2 p66-9]). The isosinglet 1^- meson ω(782) may contain $\bar{u}u$, $\bar{d}d$ and the sum of them divided by √2 but the proportions among them are uncertain. They are therefore excluded. Some of the remaining 44 mesons further drop out for various reasons. Putting together the + and – charged mesons into one with charge ± and using 6 meson masses to fix the 5 quark masses and d_{m0}, there are 16 meson masses available for test of (1).

2. PREVIOUS RESULTS

This program has been carried out in [3]. For the "nominal" combination there, the RMS valiue of all deviations from data is < 0.5 %, with a maximum deviation of 1.6 %. The invisible quark masses are not fixed natural constants like the electron mass. Each quark has some natural mean mass, around 0.64 GeV for the *u* and *d* quarks and 0.72 GeV for the s quark. These values can however vary ±10% dependent at least upon the flavor of its companion antiquark in the meson and its spin.

These results show that the quark masses and d_{m0} values are not natural constants with fixed values like the masses of leptons. Such values for each case can deviate from some "mean value" by up to ~±10% and still yield approximate meson masses. If such deviations become much larger, then the predicted masses will deviate more from their "mean values". However, the above "mean values" have not been specified. Also, the above ±10% deviation from such "mean values" also does not tell which case it refers to.

There are however a huge number of ways to choose these 6 input mesons; different choices yield different quark masses. Inasmuch as meson masses are known to an accuracy of 6 digits, one may hope to obtain the quark masses with the same accuracy. In a recent paper [4] aimed at such accuracy, however, it was found that the Coulomb contributions from the charged mesons will greatly affect such accuracy. Such contributions depend upon the charge radius of these mesons. But such radii have been measured only for pion and kaon.

To avoid such uncertainties, only neutral mesons were chosen [4]. Since the 1^- mesons have much larger width, the 0^- mesons were chosen firsthand. But there are only 5 neutral 0^- mesons; the η's were excluded because they contain more than 2 quarks. The 6th has to come from 1^- mesons. Most of them have large widths. The best ones are the 3 isoscalars $\phi(1020)$, J/ψ and $\Upsilon(1S)$. These have been chosen in 3 different cases. The input Case D**:** π^0, K^0, D^0, B^0, B_s^0, and $\phi(1020)$ and Case E**:** π^0, K^0, D^0, B^0, B_s^0, and J/ψ [4 Table 1, bold faced entries] led to the best results in [4 Tables 2-4]. The predicted masses of 16 mesons have an RMS accuracy of 0.9%. This 2 digit accuracy however far exceeds the measured 6 digit accuracy [1]. There has been no improvement of the earlier [3] accuracies.

3. PRESENT INPUT MESONS AND RESULTS

Both π^0 and K^0 enter Cases D and E in [4] above. π^0 may be criticized because it contains 4 quarks, different from all other 2 quark mesons. K^0 contains s and d quarks having the same charge and similar masses which may somehow mix with each other. The linear combinations $\bar{K}^0 \pm K^0$ to form K_S and K_L with different parities, decay modes and slightly different masses seem to indicate such a possibility.

Here, emphasis is on the purity and unambiguity of the input mesons. π^0 and K^0 above are replaced by $\pi^\pm$ and $K^\pm$ which do not have the above uncertainties. The effects of their charges can be subtracted because their charge radii have been measured. The remaining ones are chosen to be $\phi(1020)$, J/ψ and $\Upsilon(1S)$ for the s, c and b quarks respectively, to make up

$$\text{Case K: } \pi^\pm,\ K^\pm,\ D^0,\ \phi(1020),\ J/\psi,\ \Upsilon(1S) \tag{2}$$

Use the measured masses of these mesons shown in [1 or 4]. Lower the $\pi^\pm$ and $K^\pm$ values by 2.467 MeV and 2.904 MeV, respectively, from their charges [4 (2b)] using [5 (2.1b)]. (1) yields the quark masses

$m_1(u, \text{GeV})$	$m_2(d)$	$m_3(s)$	$m_4(c)$	$m_5(b)$	d_{m0} (GeV^2)
0.5891413	0.5891073	0.6798475	1.612472	4.751543	0.552368

$$m_2 - m_1 = -33.197 \text{ keV} \qquad \text{Case K} \qquad m_3 - m_2 = 90.74 \text{ MeV} \tag{3}$$

= 4943keV Case D

= 6805 keV Case E

The blue entries come from [4 Table 1, Cases D and E]. Application of (3) to (1) for the remaining 16 mesons leads to Tables 1 and 2 below.

Table 1.

Comparison of calculated 0^- meson masses, using (1) and (3), and data. * denotes that the charge radii of these mesons are unknown so that no correction due to these mesons′ charges have been included. E_0 denotes data [1]. Δ is the difference between prediction and data. Er=Δ/E_0.

	$\pi^\pm$	$K^0K^\pm$	$D^\pm$	$D_s^\pm$	$B^\pm$	$B_c^\pm$	B^0	B_s^0	η_c	η_b
E_0(GeV)		0.497611	1.86966	1.96835	5.27941	6.27447	5.27963	5.36691	2.9841	9.3983
(1)+(3)		0.4906877	1.8648	1.9711	5.2109	6.2555	5.21086	5.30382	3.005	9.4307
Δ(MeV)		−6.92	*−4.86	*2.75	*−68.5	*−19	−68.8	−63.1	20.9	32.5
Er %	0	−1.39	*−0.26	*0.14	*−1.3	*−0.3	−1.3	−1.2	0.7	0.35
(D)	−1.62	−1.31	+0.21	+0.26	−0.35	+0.48	0	0	-	-
(E)	−1.7	−2.3	+0.33	+0.34	−0.72	+0.67	0	0	-	-

Er(RMS value) for Cases K, D, E) = 0.92%, 0.895%, 1.25%, respectively.

Table 2.

Comparison of calculated 1^- meson masses, using (1) and (3), and data. Charge radii of these mesons are unknown, but their corrections are small relative to the masses and have been neglected.

	ρ^0	ρ^0	K^{*0}	D^{*0}	B^{*0}	$B_s{}^{*0}$	RMS
E_0(GeV)	0.77526	0.7692	0.89555	2.00685	5.32475	5.4154	
(1)+(3):	0.76079	0.76079	0.894911	2.0094	5.26432	5.35635	
Δ(MeV)	−14.6	−8.41	−0.64	−2.6	−60	−59	
Er %	−1.88	− 1.1	−0.07	−0.13	−1.13	−1.1	1.1%
(D)	−1.92	−1.16	−0.46	+0.13	+0.15	−0.9	1%
(E)	−1.92	−1.15	−0.75	+ 0.13	+0.15	−0.9	1%

	$\rho^{\pm}$	$\rho^{\pm}$	$K^{*\pm}$	$K^{*\pm}$	$D^{*\pm}$	$D_s^{*\pm}$	$B^{*\pm}$	RMS
E_0(GeV)	0.77511	0.7665	0.89167	0.8955	2.01026	2.1122	5.32475	
(1)+(3):	0.76079	0.7608	0.89491	0.89491	2.01	2.1084	5.2644	
Δ(MeV)	−14.3	−4.7	3.24	−0.6	−0.3	−3.8	−60	
Er %	−1.85	− 0.61	0.36	−0.07	−0.013	−0.18	−1.1	0.93%
(D)	−1.9	−0.8	−0.3	−0.46	+0.23	−0.16	+0.05	0.9**%**
(E)	−1.9	−0.8	−0.32	−0.74	+0.33	+0.2	+0.016	0.9**%**

4. EVALUATION OF THE RESULTS

4.1. Errors and Mixing of the *d, s, b* Quarks

The RMS values of the errors Er lie around 1% for all the 3 input Cases K, D and E. Most of the errors lie under 1%. There are no big error differences between Cases D, E and K for most of these 18 mesons. For Case K of interest here, errors ≈ and >1% holds for K^0, $B^{\pm}$, B^0, B_s^0, $\boldsymbol{B^{*0}}$, $\boldsymbol{B_s^{*0}}$, $\boldsymbol{B^{*\pm}}$. The ρ entries have been dropped due to their large widths.

These results indicate that the *s* quark in K^0 may mix with its *d* quark, as was mentioned at the beginning of Sec, 3. Similarly, the *b* quark in all *B* mesons may mix with the accompanying *d* or *s* quark. Note that the *c* quark does not mix with the *b* quark, as is indicated in the $B_c^{\pm}$ entry.

If and how such mixing works appears to be a different problem, beyond the scope of this paper.

4.2. Equality of *u* and *d* Quark Masses

Eq. (3) shows that the *d* quark is 32.1 keV heavier than the *u* quark. This difference is 5×10^{-5} the *u* quark mass and can be neglected here. The main new result here is that the *u and d quarks have the same (strong interaction) mass* 0.5891243±1.7×10^{-5} GeV. In all other combinations of input mesons in [2, 3, 4], π^0 or K^0 or both enter and the *d* quark turned out to be about 2 MeV heavier than the *u* quark. Replacing π^0 or K^0 by the basic mesons $\pi^{\pm}$ and $K^{\pm}$ and employing $\varphi(1020)$, J/ψ and $\Upsilon(1S)$ vector mesons with supposedly pure quark content made the difference. This result agrees with the saying: *Nature is economical and does not deal out natural constants close to each other.*

5. SOME MAIN NUCLEON RESULTS IN SSI

This equality in §4.2 has far-reaching consequences for nucleon properties. Before this discovery, meson data indicated that the *d* quark is slightly heavier than the *u* quark [2 Table 5.2], [4 Table 1].

This agrees with that neutron is slightly heavier than proton. The fact that the *u* and *d* quarks have the same mass tends to jeopardize this property, inasmuch as the proton´s charge will make the proton slightly heavier instead, contrary to data. This problem is considered in SSI here.

For this purpose, some main nucleon results in SSI are reproduced below.

In the quark–diquark model employed in SSI, the nucleon radial wave functions [2 Figure 11.1b], [5 Fig. A1] are plotted in Fig.1.

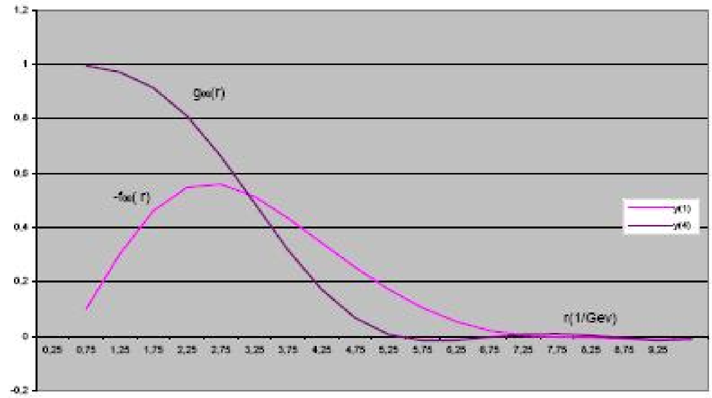

Fig. 1. Nucleon radial wave functions $f_{00}(r)$ and $g_{00}(r)$. *r* is the quark-diquark distance.

For this case, the average of the distance *r* between the diquark and quark is

$$r_a = \frac{\int drr^3\left(g_{00}^2(r)+f_{00}^2(r)\right)}{\int drr^2\left(g_{00}^2(r)+f_{00}^2(r)\right)} = 3.2 \text{ fm} \qquad (4)$$

This result is more precise than 3.05fm used earlier [2 (12.6.22)], [4 Fig. 1], [5 (A17)].

With Fig. 1, the scalar strong potential $V_S(r)$ between the *uu* diquark and the *d* quark in a proton has been found to be [2 (12.6.8), (10.1.6a)]

$$V_S(r) = \left|\frac{\Phi_b(r)}{2}\right|^{1/3} exp\left(\mp\left(1, \pm\frac{2/3}{1/3}\right)i\pi\right), \qquad r = |\underline{x}|, \qquad \underline{x} = \underline{x}_{II} - \underline{x}_I$$

(5a)

$$\Phi_b(\underline{x}) = \Phi_{bc}(\underline{x}) + \frac{d_b}{r} + d_{b0} + d_{b1}r + d_{b2}r^2 + d_{b4}r^4 \qquad (5b)$$

where the source term Φ_{bc} vanishes. $\underline{x}_{II}$ is the *d* quark and $\underline{x}_I$ the *uu* diquark coordinate. For the nucleon case in [2 Table 12.1] that led to Fig. 1, [2 Table 11.1] gives

d_b=1.024 GeV^2, d_{b0} = –4.922 GeV^3, d_{b1} =2.272 GeV^4, d_{b2} = –0.3202 GeV^5, d_{b4}=0 (6)

$V_S(r)$, dropping the phase factor, and $\Phi_b(r)$ in (5) have been plotted in [2 Fig. 12.1], [5 Fig. A2] and are reproduced Fig 2.

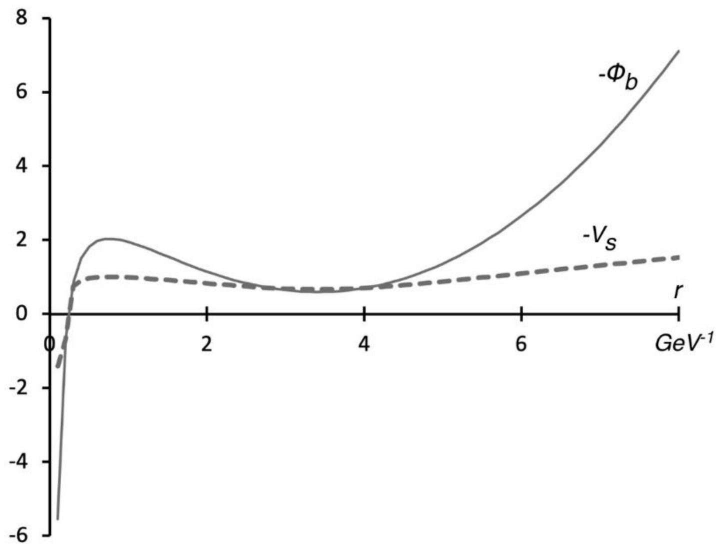

Fig. 2. Strong interaction potential $\Phi_b(r)$ in (5b) in unit of GeV^3 for the nucleon in [2 Table 12.1] and the corresponding *u-d* strong interaction potential $V_S(r)$ in unit of GeV in (5a).

These scalar potentials depend only upon the diquark-quark separation $|\underline{x}|=r$. By attaching a diquark and a quark at the ends of a 3.2 fm long (4), rigid rod, we have a "rod model" for the nucleon [5 Fig. 1]. This simplified model has been frequently applied to problems involving nucleons in laboratory as well as in cosmos. It bypasses the use of the more detailed but also cumbersome wave functions in Fig. 1.

$V_S(r)$ in (5a) originates in the scalar, strong potential $V_{SB}(x_I)$ in the quark wave equation [2 (2.1.1a)]. The latter represents the scalar potential felt by quark *A* at $\underline{x}_I$ generated by another quark *B* at x_{II}. Here, this potential has been taken over to apply to the *u* and *d* quarks in the nucleon in Fig. 2.

Unlike the observable Coulomb and gravitational potentials with a simple 1/distance dependence, the strong $V_S(r)$ is present in the "hidden" space $\underline{x}$ between a *u* and a *d* quark and depends upon their separation *r* in a more comeplicated manner. This is due to that the diquark-quark wave functions obey 3rd order equations, different from the two quark meson wave functions governed by 2nd order equations [2 Ch. 2, 9]. At large *r*, $V_S(r)$ is confining but leads to repulsion at very small *r*, preventing the *u* and *d* quarks from merging into each other.

The corresponding force both quarks act on each other

$$\underline{F}=-\partial V_S(r)/\partial\underline{x} \tag{7}$$

is largely attractive but is weakly repulsive around $r \sim$ 2-3 GeV^{-1}, as is seen in Fig. 2. There is no contradiction as *r* is a "hidden", invisible quantity.

6. DIQUARK AND NUCLEON STRUCTURE

Although a diquark [6] is a hypothetical subatomic particle, the quark-diquark model of baryon has been rather successful in accounting for nucleon properties [7]. Here, SSI is rather successfully based on this model.

However, the nature of such a diquark remains elusive. In the "rod model" above, the diquark is considered to a point particle. Assume that the forces between the two quarks in a diquark is attractive when both the colors and spins are antisymmetric. Then these quarks tend to form a low energy configuration considered to be a diquark [7]. This indicates that a diquark is not a single subatomic particle but consists of two quarks very close to each other so that they can be treated as one single particle with respect to strong interaction between this diquark and the third quark in a nucleon.

In SSI here, the above qualitative, attractive force is replaced by the strong, scalar attractive force between the *u* and *d* quarks in a nucleon. Let Fig. 2 represent the quark structure in a proton.

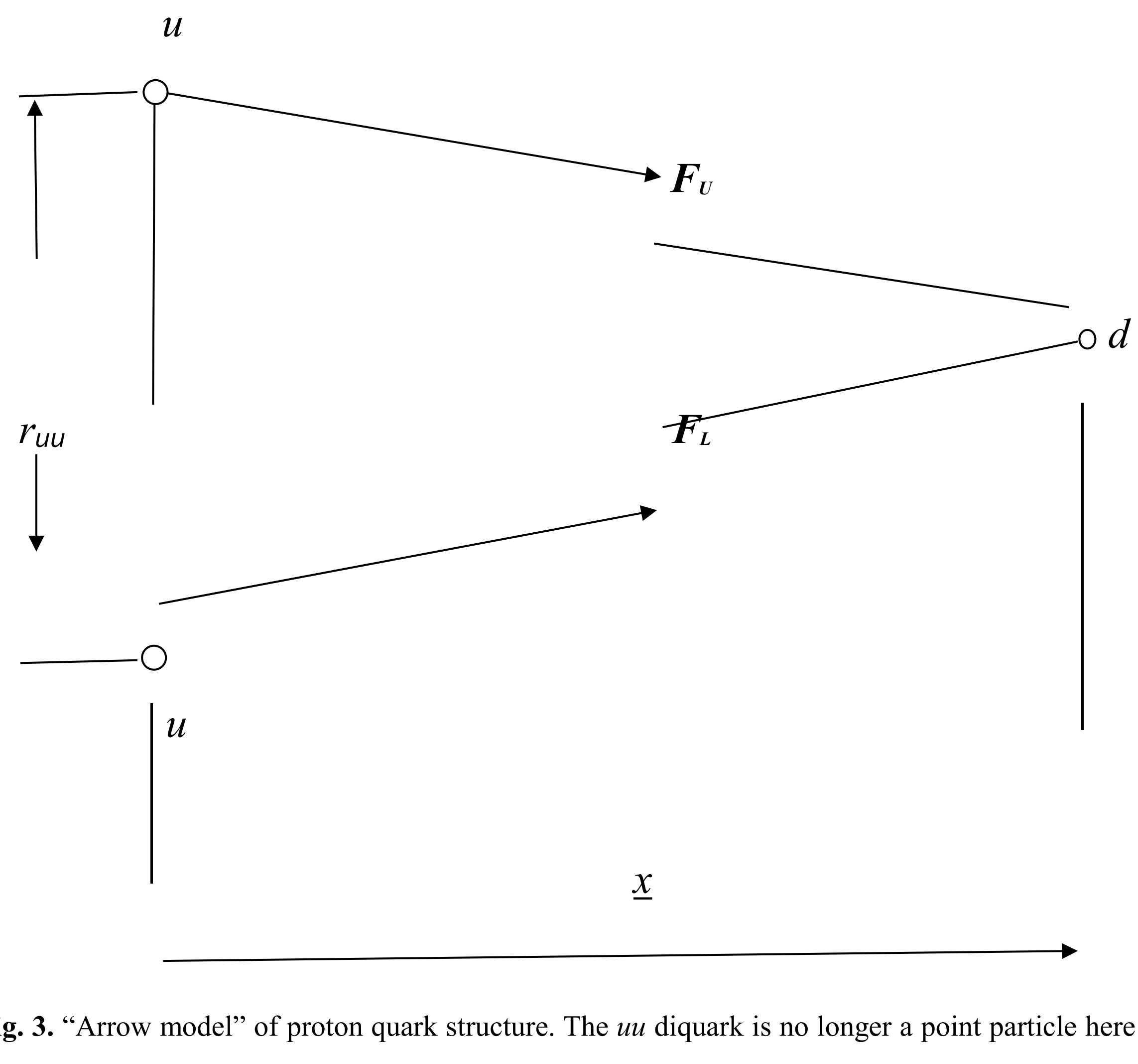

Fig. 3. "Arrow model" of proton quark structure. The *uu* diquark is no longer a point particle here but represented by a rod with length r_{uu} and a *u* quark at each end on the left side of the figure. Mutual repulsion of both *u* quarks tends to lengthen r_{uu}. This is countered by the vertical components of the

strong u-d attraction forces $\boldsymbol{F_U}$ and $\boldsymbol{F_L}$ that tend to push them together. These forces depend upon r_{uu} and the quark-diquark separation $r = |\underline{x}|$. r_{uu} is not a fixed quantity but varies with r. In Table 1 below, $r_{uu}\approx 0.44$ fm for $r\approx 3$ fm. By $u\leftrightarrow d$, this figure also holds for neutron.

The strong force (7) from (5a) is directed along the distance vector connecting the d quark and a u quark in the nucleon in Fig. 3. This is illustrated by the $\boldsymbol{F_U}$ and $\boldsymbol{F_L}$ in Fig. 3. It will be assumed that these 2 u quarks do not interact strongly. There is no evidence that they do. Then the vertical components of the strong $\boldsymbol{F_U}$ and $\boldsymbol{F_L}$ forces tend to push them to middle point of the vertical r_{uu} rod to form a point like uu diquark. However, these 2 u quarks have the same charge and tend to repel each other by Coulomb force. So, there can be a small separation r_{uu} between them. This takes place when these two opposing forces are equal in amplitude.

$u\leftrightarrow d$ leads to the neutron case. The Coulomb repulsion force of two d quarks is weaker because the d charge magnitude is smaller. Also, r_{uu} is replaced by r_{dd}, the separation between the two d quarks. As the u and d quarks have the same mass according to §4.2, they differ only in their charges.

7. ON PROTON AND NEUTRON MASS DIFFERENCE IN SSI

If u and d quarks have no charge. Proton uud and neutron ddu have the same strong interaction mass m_{Nu}, denoted by E_0 in [2 (10.1.1, 2)]. Both are indistinguishable. If a charge $2e/3$ is given to u quark, then the Coulomb energy $4e^2/9r_{uu}$ is created in uud. It depends upon the "hidden" variable r_{uu}, is therefore invisible and corresponds to dark matter [2 §15.3.1]. It has to be subtracted from m_{Nu}. Now the proton mass $m_p=m_{Nu}-4e^2/9r_{uu}$. Give now the charge $-e/3$ to d quark, the neutron mass $m_n=m_{Nu}-e^2/9r_{dd}$. The mass difference between neutron and proton becomes

$$m_n - m_p = 4e^2/9r_{uu} - e^2/9r_{dd} = (e^2/9)(4/r_{uu}, -/r_{dd}) \quad (8)$$

In Fig. 3, $\boldsymbol{F_U}$ and $\boldsymbol{F_L}$ depend upon the u-d distance, which will be approximated by r because $r_{uu} \ll r$. This is so as the main contributions come from $r \sim 3$ fm according to Table 1 below. The magnitude of $\boldsymbol{F_U}$ and $\boldsymbol{F_L}$ has been given by $F(r)$ in (7), specified by (5) and (6).

$$F(r)=\left(\frac{1}{2}\right)^{1/3}\frac{1}{3}\left(\frac{d_b}{r}+d_{b0}+d_{b1}r+d_{b2}r^2+d_{b4}r^4\right)^{-2/3}\left(-\frac{d_b}{r}+d_{b1}+2d_{b2}rd_{b4}r^4\right) \quad (9)$$

The vertical component of this force has to balance the Coulomb repulsion force

$$F(r)\,\frac{r_{uu}}{2r}=\frac{4e^2}{9(r_{uu})^2} \quad (10a)$$

For the neutron case, the corresponding expression is

$$F(r)\,\frac{r_{dd}}{2r}=\frac{e^2}{9(r_{dd})^2} \quad (10b)$$

Equations (6), (8), (9), and (10) yield the following results in Table 1.

Table 1. Results from solution of (8)-(10) using (6). The last line comes from the denominator in (4) using Fig. 1 and is proportional to the probability for diquark-quark separation r on the top row.

r(GeV^{-1})	1	2	2.5	3	4	5
F(GeV), (9)	0.104	0.178	0.151	0.003	–0.119	–0.209
r_{uu}(fm)	0.264	0.281	0.443	0.414	–0.417	–0.361
r_{uu}(GeV^{-1})	0.215	0.227	0.258	0.334	–0.326	–0.291
r_{dd}(GeV^{-1})	0.136	0.143	0.162	0.21	–0.205	–0.183
$m_n - m_p$(MeV). (8)	**0.888**	**0.842**	**0.741**	**0.571**	–0.586	–0.656
$r^2(f_{00}^2+g_{00}^2)$	1.03	3.88	5.03	3.08	1.24	0.258

The bold faced $m_n - m_p$ values are all less than the measured 1.293 MeV [1] by > 31%. These take place for the large $r^2(f_{00}^2+g_{00}^2)$ probability values.

At greater *u*-*d* separations r>3 GeV^{-1}, the *u*-*d* force $F(r)$ (10) turns negative and becomes repulsive instead of attractive, as was mentioned beneath (7) above. This is seen in Fig. 2 in which the *u*-*d* strong potential $|-V_S(r)|$ decreases with increasing r, implying repulsive force.

Thus, the above phenomenological, classical model (8) with Fig. 3 may be insufficient. Perhaps a quantum mechanical model is required. The "hidden" space strong potential $V_S(r)$ in (5a) and Fig. 2 appears to be complicated and are not well understood. But the calculated $m_n - m_p$ values are in order of magnitude agreement with data, indicating that the origin of $m_n - m_p$ is of the nature described above.

8. CONCLUDING REMARKS

The main result of this SSI paper is that the *u* and *d* quarks have the same strong interaction mass of 0.5891243±1.7×10^{-5} GeV (3) obtained from meson spectra. This eliminates one fundamental constant in nature. A brief summary of SSI is given in [8].

In the "arrow" model in Fig. 3, the *uu* diquark in a proton is no longer a point particle but consists of two *u* quarks < 0.44 fm apart and held together by a small component of the strong *u*-*d* force. The neutron-proton mass difference is estimated using this "arrow" model. The strong, largely attractive force between the quark and diquark in a nucleon is treated quantum-mechanically. A small component of it is balanced off by mutual Coulomb repulsive force between the two quarks in the diquark classically. The estimated mass difference is 31-56 % lower than data for the most probable *u*-*d* distances of 1.24-

3.72 fm in Table 1. This indicates that the origin of this mass difference is of Coulomb nature. This large discrepancy may indicate that the phenomenological, approximative treatments here are insufficient.

From the above interactions, we see the following unique property of quark. Quark is the only elementary particle that interacts via all three basic forces, strong, electromagnetic and gravitational, strongly and electrostatically with another quark and gravitationally with all matter in the universe [2 (15.1.1, 2)].

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