QCD based EMC Effect Model: Diquark Structures in Nuclear Matter

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EMC effect: Distortion of nucleon structure functions in nuclei

$$F_2(x_B) \equiv \sum_f x_B\, Q_f^2 \left(q_f(x) + \bar{q}_{\bar{f}}(x) \right)$$

- Predicted $F_2(x_B)$ in complete disagreement with theory
- Why should quark behavior - confined in nucleons at QCD energy scales ~200 MeV - be so affected when nucleons embedded in nuclei?
- Diquark formation gives a mechanism by which structure functions become distorted

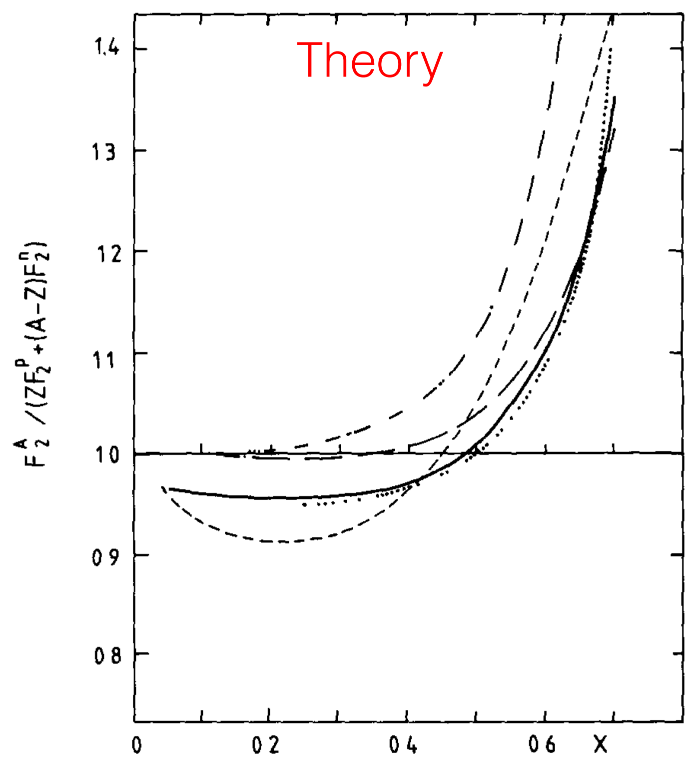


Fig. 1. Theoretical predictions for the Fermi motion correction of the nucleon structure function F_2^N for iron. Dotted line Few-nucleon-correlation-model of Frankfurt and Strikman [9]. Dashed line. Collective-tube-model of Berlad et al. [10] Solid line Correction according to Bodek and Ritchie [8]. Dot–dashed line. Same authors, but no high momentum tail included. Triple-dot–dashed line Same authors, momentum balance always by a $A-1$ nucleus. The last two curves should not be understood as predictions but as an indication of the sensitivity of the calculations to several assumptions which are only poorly known.

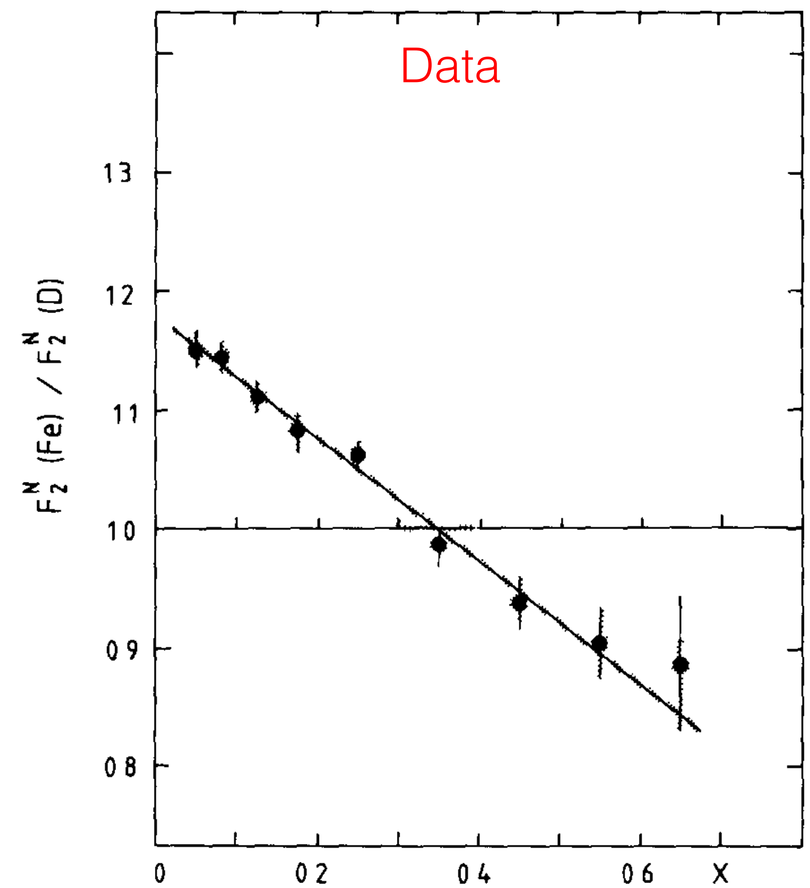


Fig. 2. The ratio of the nucleon structure functions F_2^N measured on iron and deuterium as a function of $x = Q^2/2M_p\nu$. The iron data are corrected for the non-isoscalarity of $^{56}_{26}$Fe, both data sets are not corrected for Fermi motion. The full curve is a linear fit $F_2^N(\mathrm{Fe})/F_2^N(\mathrm{D}) = a + bx$ which results in a slope $b = -0\ 52 \pm 0.04$ (stat.) $\pm$ 0.21 (syst) The shaded area indicates the effect of systematic errors on this slope.

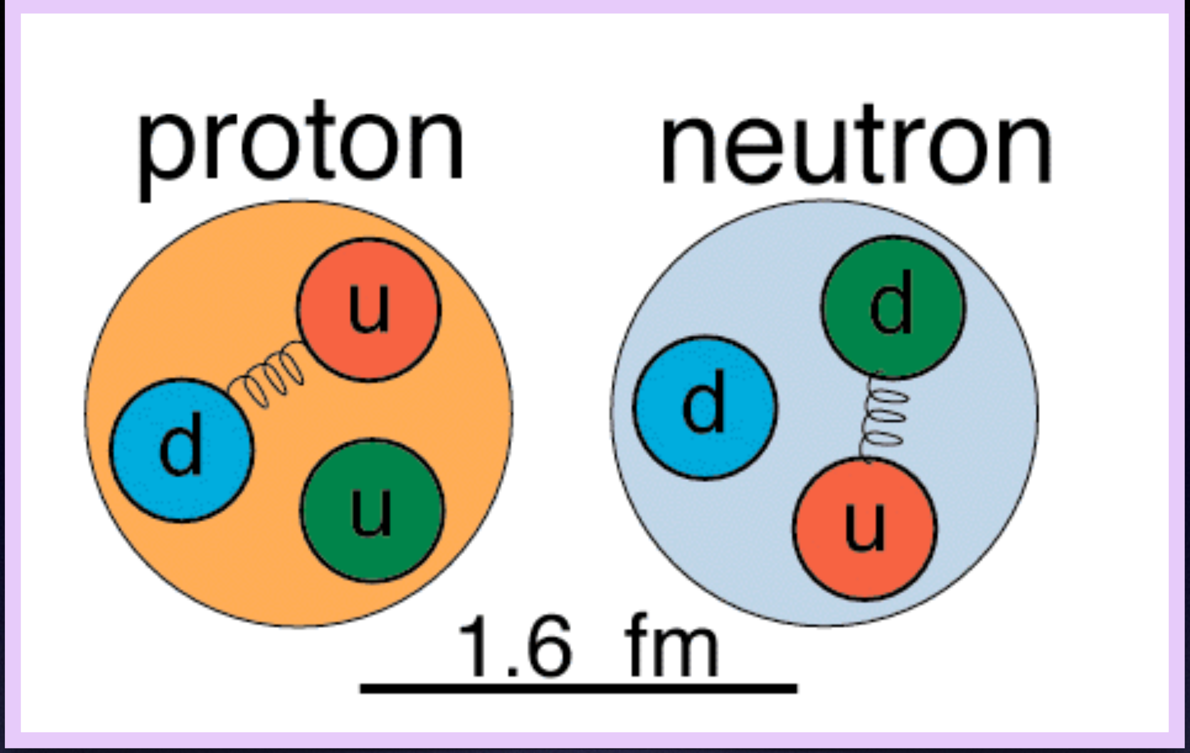
"THE RATIO OF THE NUCLEON STRUCTURE FUNCTIONS F_2^N FOR IRON AND DEUTERIUM "
The European Muon Collaboration, J.J. AUBERT et al. 1983

Proposed QCD model:
Diquark formation across nucleon pairs

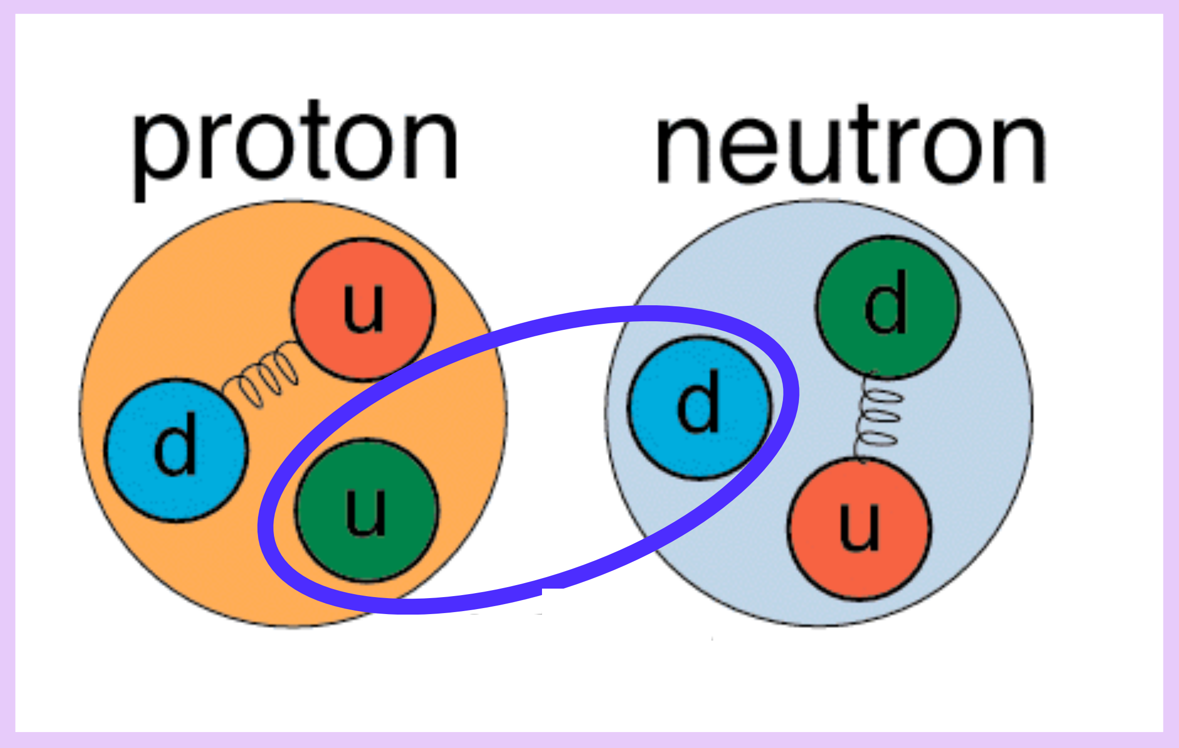
Diquark formation across N-N pairs in nuclei

Valence quarks in neighboring nucleons can bind together:
N_1 donates up quark + N_2 donates down quark with spins anti-aligned:

$$\psi_a^{[ud]} = \frac{1}{\sqrt{2}}\epsilon_{abc}\left(u^b \uparrow d^c \downarrow - d^b \uparrow u^c \downarrow\right)$$



adapted from http://fafnir.phyast.pitt.edu/particles/



1. Binding energy ~148 MeV - energetically favorable

2. The QCD color factor - a measure of strength of strong force potential $V(r)$ - it is attractive - diquark is bound

Diquark formation sticks pairs of nucleons together - it creates short-range correlations!

Diquark binding energy: Hadronic hyperfine structure

Spin-spin interaction affects hadron mass:

1. $M_{(\text{baryon})} = \sum_{i=1}^{3} m_i + a' \sum_{i<j} \left(\sigma_i \cdot \sigma_j\right) / m_i m_j$

2. $M_{(\text{meson})} = m_1 + m_2 + a\left(\sigma_1 \cdot \sigma_2\right) / m_1 m_2$

(de Rujula, Georgi & Glashow 1975, Gasiorowicz & Rosner 1981, Karliner & Rosner 2014)

Effective masses of light quarks are found using Eq.1 and fitting to measured baryon masses:

$$m_u^b = m_d^b \equiv m_q^b = 363 \text{ MeV}, \quad \mathrm{m_s^b} = 538 \text{ MeV}$$

Binding energy of $[ud]$:

$$\text{B.E.}_{[ud]} = m_u^b + m_d^b + m_s^b - M_\Lambda = 148 \ \pm \ 9\text{MeV}$$

TABLE I: Diquark properties

Diquark	Binding Energy (MeV)	Mass (MeV)	Isospin I	Spin S
$[ud]$	148 ± 9	578 ± 11	0	0
(ud)	0	776 ± 11	1	1
(uu)	0	776 ± 11	1	1
(dd)	0	776 ± 11	1	1

Uncertainties calculated using average light quark mass errors $\Delta m_q = 5\ MeV$ [37]

TABLE II: Relevant $\mathrm{SU}(3)_\mathrm{C}$ hyperfine structure baryons [28]

Baryon	Diquark-Quark content	Mass (MeV)	$I\left(J^P\right)$
Λ	$[ud]s$	1115.683 ± 0.006	$0\left(\frac{1}{2}^+\right)$
Σ^+	$(uu)s$	1189.37 ± 0.07	$1\left(\frac{1}{2}^+\right)$
Σ^0	$(ud)s$	1192.642 ± 0.024	$1\left(\frac{1}{2}^+\right)$
Σ^-	$(dd)s$	1197.449 ± 0.030	$1\left(\frac{1}{2}^+\right)$

$I\left(J^P\right)$ denotes the usual isospin I, total spin J and parity P quantum numbers, all have $L=0$ therefore $J = S$

"Diquark Formation from Nucleon-Nucleon Interactions I: Nuclear Matter," JRW, arXiv:2009.06968

Quark-quark potential in QCD: $V(r)$ calculation

- The $\mathrm{SU}(3)_C$ invariant QCD Lagragian:

$$\mathscr{L} = -\frac{1}{4}F^{\mu\nu a}F^{a}_{\mu\nu} + \bar{\Psi}_f\left(i\gamma^\mu D_\mu - m\right)\Psi_f$$

where covariant derivative $D_\mu = \partial_\mu - ig_s A^a_\mu t^a$ acts on quark fields, t^a are the 3x3 traceless Hermitian matrices (e.g. the 8 Gell-Mann matrices), g_s the strong interaction coupling, $\alpha_s \equiv \frac{g_s^2}{4\pi}$.

- The QCD potential for states in representations R and R' is given by:

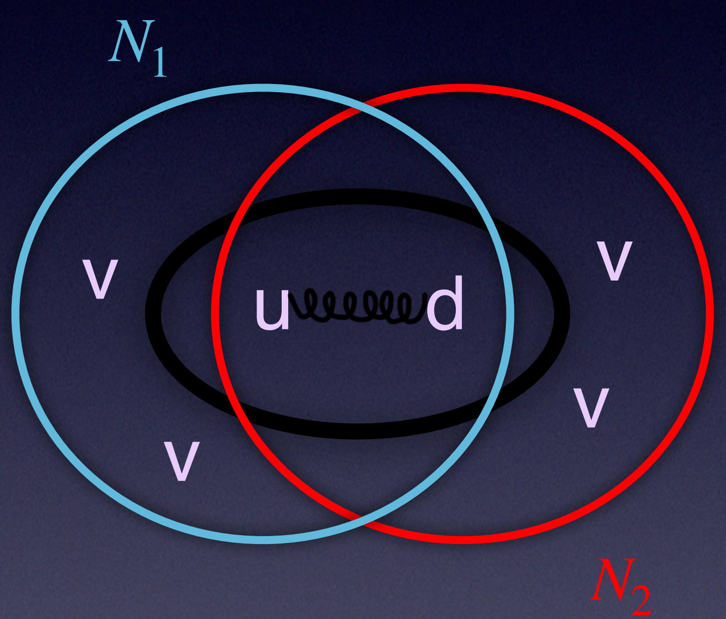
$$V(r) = \frac{g_s^2}{4\pi r} t^a_R \otimes t^a_{R'}$$

- To calculate $V(r)$ for a $3_c \times 3_c$, use the definition of the scalar $C_2(R)$, $t^a_R\, t^a_R = C_2(R)\,\mathbf{1}$, the *quadratic Casimir operator,* to find:

$$V(r) = \frac{g_s^2}{4\pi r}\cdot\frac{1}{2}\cdot\left(C_2\left(R_i\right) - C_2(R) - C_2\left(R'\right)\right)$$

- Diquarks combine 2 fundamental representation quarks into an anti-fundamental, $3_C \otimes 3_c \rightarrow \bar{3}_C$:

$$V(r) = -\frac{2}{3}\frac{g_s^2}{4\pi r} \Longrightarrow \text{Diquark is bound!}$$



Complementary Model: Novel color-singlet HEXADIQUARK in the core of A>3 nuclei

Hexadiquark (HdQ) color-singlet in A≥4 nuclei

Ref: JRW, S.J.Brodsky, G. de Teramond, I.Schmidt, F.Goldhaber, arXiv:2004.14659 Nuclear Physics A

- $^4\mathrm{He}$ nucleus proposed to contain a novel color singlet state
- 6 scalar diquarks strongly bound together to form a color singlet
- Fermi statistics upon quark exchange, Bose statistics upon diquark exchange

$$\left|\psi_{\mathrm{HdQ}}\right\rangle = |\,[ud][ud][ud][ud][ud][ud]\rangle$$

$$\psi_a^{[ud]} = \frac{1}{\sqrt{2}}\epsilon_{abc}\left(u^b \uparrow d^c \downarrow - d^b \uparrow u^c \downarrow\right)$$

Quark indices a, b, c = 1, 2, 3 are color indices in the fundamental $\mathrm{SU}(3)_{\mathrm{C}}$ *representation.*

Diquarks are in the anti-fundamental representation:

$$3_{\mathrm{C}} \otimes 3_{\mathrm{c}} \rightarrow \overline{3}_{\mathrm{C}}$$

Hexadiquark wavefunction

The HdQ is a $\mathrm{J^P} = 0^+, \ \ \mathrm{I} = 0$ object which is a component of the $^4\mathrm{He}$ nuclear wavefunction:

$$|\alpha\rangle = C_{pnpn} \left| (u[ud])_{1_C}(d[ud])_{1_C}(u[ud])_{1_C}(d[ud])_{1_C} \right\rangle + C_{\mathrm{HdQ}} \left| ([ud][ud])_{\overline{\mathbf{6}}_C}([ud][ud])_{\overline{\mathbf{6}}_C}([ud][ud])_{\overline{\mathbf{6}}_C} \right\rangle$$

All quantum numbers of the HdQ and the $^4\mathrm{He}$ ground state are identical: Q=2, B=4, I=0, J=0

Important: HdQ requires 2 correlated neutron-proton pairs. The effect of the HdQ is "isophobic" because $[ud]$ diquarks form only across n-p pairs in the quark-diquark nucleon structure approach.

NB: The HdQ does not act in $^3\mathrm{He}$, $^3\mathrm{H}$ -

To construct the HdQ wave function we follow the three-step procedure described above. The scalar diquark $\psi_a^{[ud]}$ is given by the spin-isospin singlet product

$$\begin{aligned} \psi_a^{[ud]} &= [ud]_a \\ &= \frac{1}{\sqrt{2}}\epsilon_{abc}(u^b{\uparrow}d^c{\downarrow} - d^b{\uparrow}u^c{\downarrow}), \end{aligned} \tag{6}$$

where the indices $a, b, c = 1, 2, 3$ are color indices in the fundamental $\mathrm{SU(3)_C}$ representation. The scalar diquark is a $\mathrm{J^P} = 0^+, \mathrm{I} = 0$ object which transforms as color $\overline{\mathbf{3}}$.

In the second step we construct the DdQ, $\psi^{[udud]}$, the product $\overline{\mathbf{3}}_C \otimes \overline{\mathbf{3}}_C$ from two scalar diquarks. It is the sum of a $\mathbf{3}_C$ and a $\overline{\mathbf{6}}_C$ represented by the symmetric tensor (A.3). The DdQ, $\psi^{[udud]}$, is thus given by the symmetric tensor operator

$$\psi_{ab}^{[udud]} = \psi_a^{[ud]}\psi_b^{[ud]}, \tag{7}$$

an isospin singlet state which transforms in the symmetric $\overline{\mathbf{6}}$ color representation under $\mathrm{SU(3)_C}$ transformations. The DdQ itself is also an effective scalar boson since it is the product of two scalar bosons: It transforms as a $\mathrm{J^P} = 0^+$ state under SO(3) rotations.

Lastly, we construct the HdQ which is the color singlet product of three DdQ in the $\overline{\mathbf{6}}_C$. To this end, we first construct the symmetric $\mathbf{6}_C$ out of the product of two $\overline{\mathbf{6}}_C$ in the complex conjugate representation: $\overline{\mathbf{6}}_C \otimes \overline{\mathbf{6}}_C \to \mathbf{6}_C$. It is given by the symmetric tensor (A.11). The HdQ wave function, ψ_{HdQ}, is thus the color singlet

$$\psi_{HdQ} = \epsilon^{acf}\epsilon^{bdg}\,\psi_{ab}^{[udud]}\psi_{cd}^{[udud]}\psi_{fg}^{[udud]}, \tag{8}$$

which, as required, is fully symmetric with respect to the interchange of any two bosonic duo-diquarks. The HdQ spatial wave function must also be totally symmetric with respect to the exchange of any two DdQs in order for the total wavefunction to obey the correct statistics. The HdQ is a $\mathrm{J^P} = 0^+$, I=0 color singlet state, matching the quantum numbers of the $^4\mathrm{He}$ nucleus ground state.

"QCD hidden-color hexadiquark in the core of nuclei," JRW, Brodsky, de Teramond, Goldhaber, Schmidt, *Nucl.Phys.A* 1007 (2021), arXiv:2004.14659

Diquark formation across N-N pairs: ^{3}He and ^{3}H

SRC prediction for MARATHON experiment:

Scalar [ud] diquark formation in A=3 nuclei
for 3-valence quark internal structure:

$$\begin{aligned} {}^3H: \quad & n-p \Longrightarrow [ud][ud][ud]\times 2 \\ & n-n \Longrightarrow [ud][ud] + \text{valence} \end{aligned} \Longrightarrow 75\,\%\ n-p,\ 25\,\%\, n-n$$

$$\begin{aligned} {}^3He: \quad & n-p \Longrightarrow [ud][ud][ud]\times 2 \\ & p-p \Longrightarrow [ud][ud] + \text{valence} \end{aligned} \Longrightarrow 75\,\%\ n-p,\ 25\,\%\, p-p$$

For nucleons in quark-diquark internal structure:

$$^3H: \quad u\,[ud] \; + \; u\,[ud] \; + \; d\,[ud] \Longrightarrow 100\,\%\ n-p$$

$$^3He: \quad d\,[ud] \; + \; d\,[ud] \; + \; u\,[ud] \Longrightarrow 100\,\%\ n-p$$

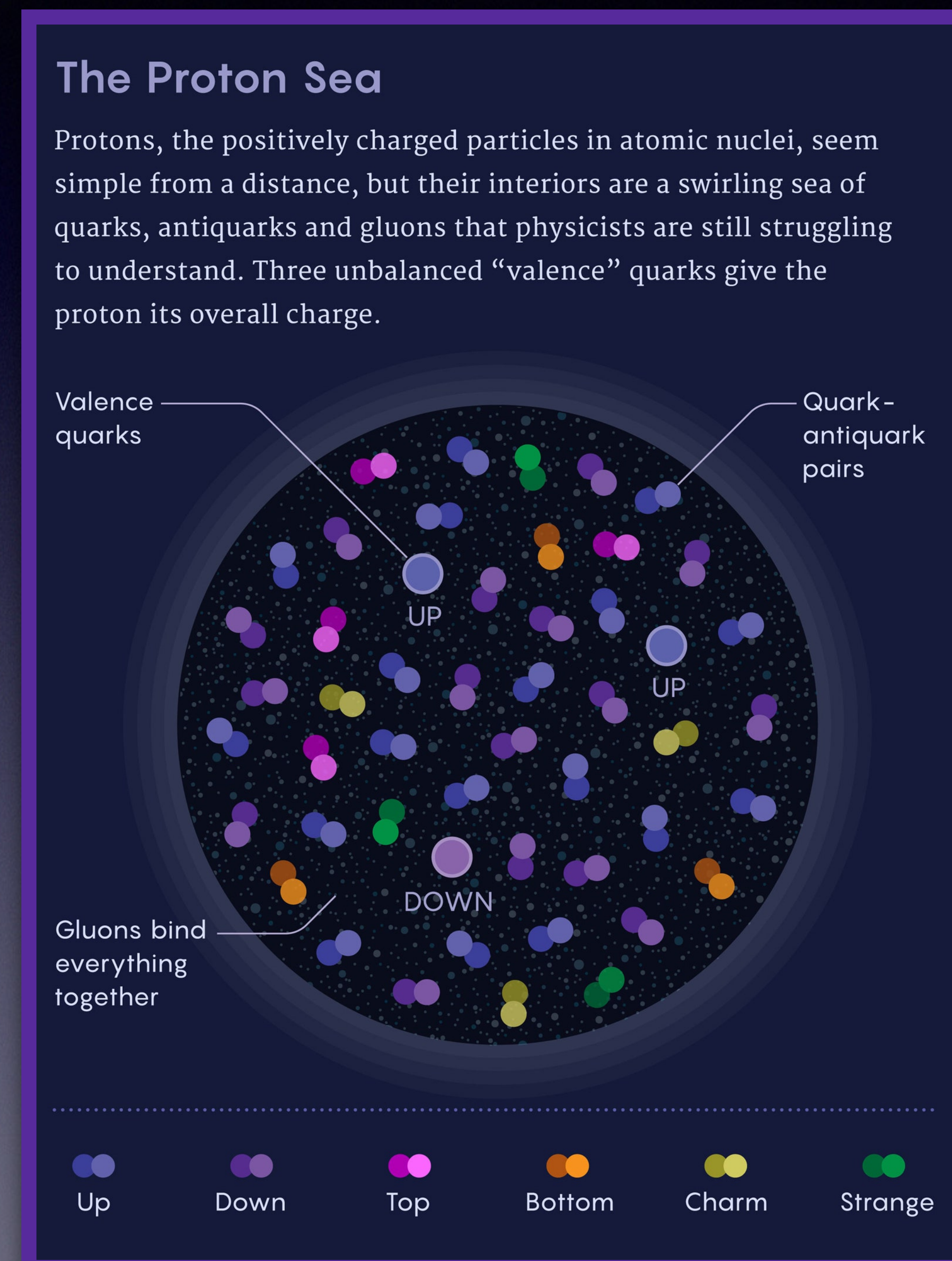
Diquark formation implications: SeaQuest Antimatter Asymmetry

Antimatter asymmetry in the quark sea of protons

Excess of $\bar{d}$ quarks over $\bar{u}$!

- Gluons produce quark-antiquark pairs in nucleons.
- $u\bar{u}$ and $d\bar{d}$ pairs form in equal amounts
- Binding energy of spin-0 $[ud]$ diquarks is ~148 MeV
- For protons with valence u (assuming the proton has quark-diquark structure) the d from gluon-to-$d\bar{d}$ can be captured into a $[ud]$ diquark
- Leaves a $\bar{d}$ quark behind - excess $\bar{d}$ in proton
- Predicts excess of $\bar{u}$ in the neutron sea
- SpinQuest prediction: $\bar{d}$ carries all the spin of the proton for the 5-quark Fock state:

$$[ud][ud][ud]\ \bar{d}$$



from Wired magazine, 28 February 2021

Fin!

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