Spin questions: Diquark effects and Hidden Color States in $^2\mathrm{H}$ and $^4\mathrm{He}$

EIC^2
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BERKELEY LAB

Talk Outline: Diquarks & Hidden Color States, $^2\mathrm{H}$ aim

- QCD definition of diquarks and hidden color states
- Diquark entry into nuclear physics - the EMC effect
- Diquarks as the creators of Short-Range Correlations (SRC)
- Hidden color Hexadiquark in $^4\mathrm{He}$
- Hidden color in $^2\mathrm{H}$ - Questions looking for answers at ECT*
- Relationship to spin observables - Questions looking for answers (& collaborators) at ECT*

Leading order structure function b_1 for DIS with a spin-1 target:

$$b_1 = \sum_q e_q^2 \left[q_\uparrow^0 - \frac{1}{2}\left(q_\uparrow^1 + q_\uparrow^{-1} \right) \right] \equiv \sum_i e_q^2 \delta q_i$$

where \$$\mathrm{q}_\uparrow^\mathrm{m}\left(\mathrm{q}_\downarrow^\mathrm{m}\right)$\$ is the number density of quarks with spin up(down) along the \$z\$ axis in a target hadron with helicity m . . .

Hoodbhoy, Jaffe & Manohar 1989, Frankfurt & Strikman 1983, Miller 2013

Diquarks & Hidden Color: Background QCD

Building blocks: Quantum chromodynamics, spin-statistics

- Begin with group theory mathematics of the strong interaction: $\mathrm{SU}(3)_\mathrm{C}$
- Next, degrees of freedom (particles carrying strong force charge) - indices run over 3 color charges:

$$q_a \text{ (triplet, } 3_\mathrm{C}), \quad q^a \text{ (antitriplet, } \overline{3}_\mathrm{C}), \quad g_c^b \text{ (octet, } 8_\mathrm{C})$$

- All combinations of D.o.F. predicted, color charged & color singlet. Examples (use δ^a_b, ϵ^{abc}, ϵ_{abc} to combine):

$$(\bar{q}^a q_a)_{1_\mathrm{C}} \quad (\epsilon^{abc}\; q_a q_b q_c)_{1_\mathrm{C}} \quad (\epsilon_{abc}\; \bar{q}^a \bar{q}^b \bar{q}^c)_{1_\mathrm{C}}, \quad (q_a q_b \epsilon^{abc})_{\bar{3}_\mathrm{C}} \quad \leftarrow (qq)^c$$

- Higher Fock states (baryon with 3 valence quarks is lowest order Fock states), e.g., the 5-quark Fock state for baryons:

$$(\epsilon^{abc} q_a q_b q_c\; \bar{q}^e q_e)_{1_\mathrm{C}} \;\subset \mathrm{N}$$

- Hidden color states are also predicted. Let's first build a nucleus out of nucleons, e.g., heavy hydrogen $^2\mathrm{H}$:

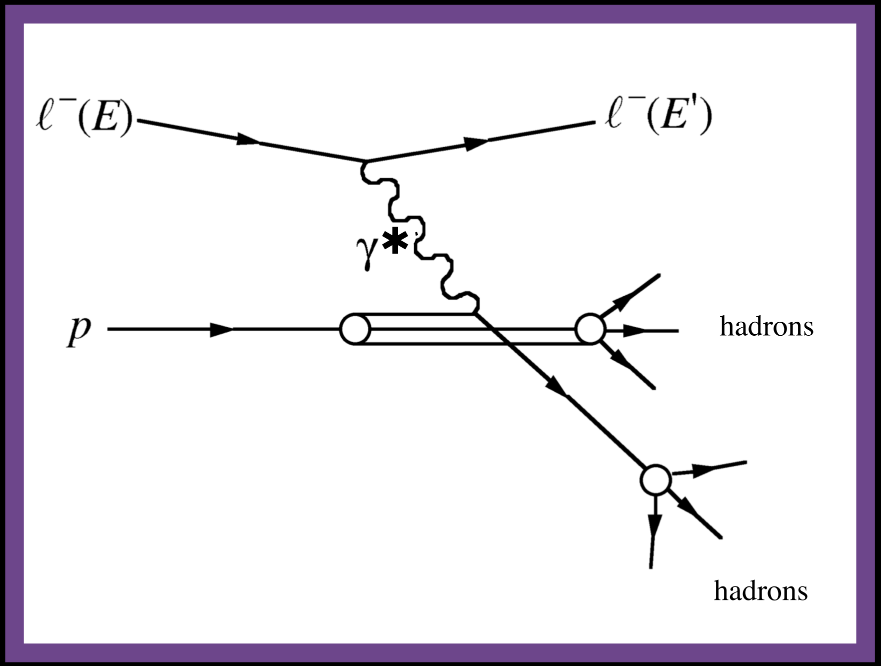
$$(\epsilon^{abc} q_a q_b q_c)_{1_\mathrm{C}}\, (\epsilon^{def} q_d q_e q_f)_{1_\mathrm{C}}$$

- Hidden color singlets carry same quantum numbers as a nucleus. They are subdominant states in the wavefunction and can be built with diquarks but need not be. A hidden color state using baryon octets in the deuteron:

$$q_a\; q_b\; q_c\; q_d\; q_e\; q_f \implies \Big((\epsilon^{abf} q_a q_b q_c)_{8_\mathrm{C}}\, (\epsilon^{dec} q_d q_e q_f)_{8_\mathrm{C}} \Big)_{1_\mathrm{C}} = (p_c^f\; n_f^c)_{1_\mathrm{C}} \subset\; ^2\mathrm{H}$$

Nuclear gateway to QCD: EMC effect

- Deep inelastic scattering (DIS) experiments
- Lepton scatters from target, exchanging virtual photon with 4-momentum q^2 given by: $Q^2 \equiv -q^2 = 2EE'(1-\cos\theta)$
- γ^* strikes quark: The fraction of nucleon momentum carried by the struck quark is known via the Bjorken scaling variable $x_B = \dfrac{Q^2}{2M_p\nu}$ where $\nu = E - E'$, M_p=mass of proton, lepton mass neglected



Adapted from Nuclear & Particle Physics by B.R. Martin, 2003

Differential cross section for DIS:

$$\frac{d\sigma}{dxdy}\left(e^-p \to e^-X\right) = \sum_f x\, e_f^2 \left[\, q_f(x) + \bar{q}_{\bar{f}}(x)\right] \cdot \frac{2\pi\alpha^2 s}{Q^4}\left(1 + (1-y)^2\right)$$

where $y = \dfrac{\nu}{E}$ is the fraction of ℓ^- energy transferred to the target. $F_2(x)$ is the **nucleon structure function**, defined as:

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

in terms of quark distribution functions $q_f(x)$: probability to find a quark with momentum $x_i \in [x, x+dx]$.

EMC effect: Distortion of nuclear structure functions

$$\text{Plotting ratio of } F_2(x_B) \equiv \sum_f x_B\, e_f^2 \left(q_f(x_B) + \bar{q}_{\bar{f}}(x_B) \right) \text{ vs. } x_B$$

- Predicted $F_2(x_B)$ ratio 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, BE $\gtrsim$ 2.2 MeV?
- Mystery has not been solved to this day.

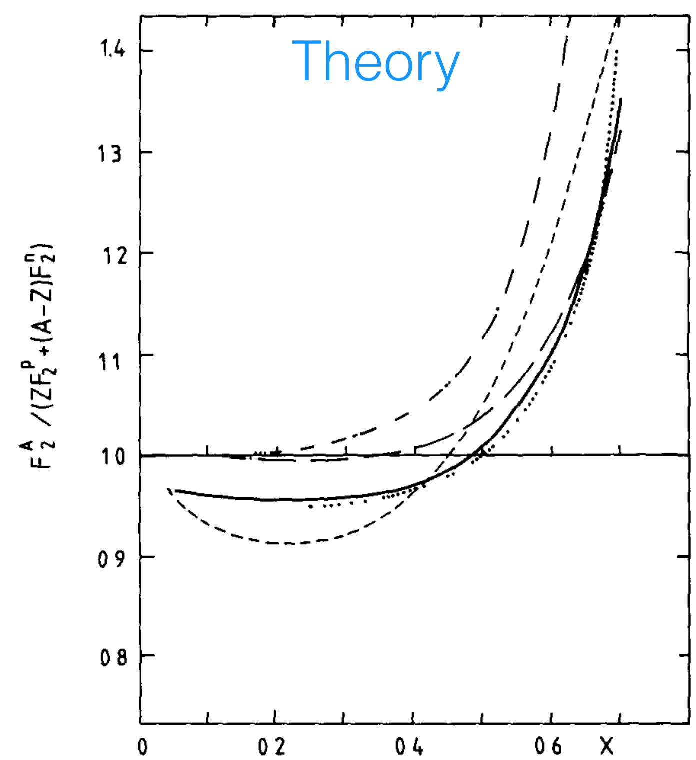


Fig. 1. Theoretical predictions for the Fermi motion correction of the nucleon structure function F_2^N for iron. Dotted line Few-nucleon-correlation-model of Frankfurt and Strikman [9]. Dashed line. Collective-tube-model of Berlad et al. [10] Solid line Correction according to Bodek and Ritchie [8]. 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.

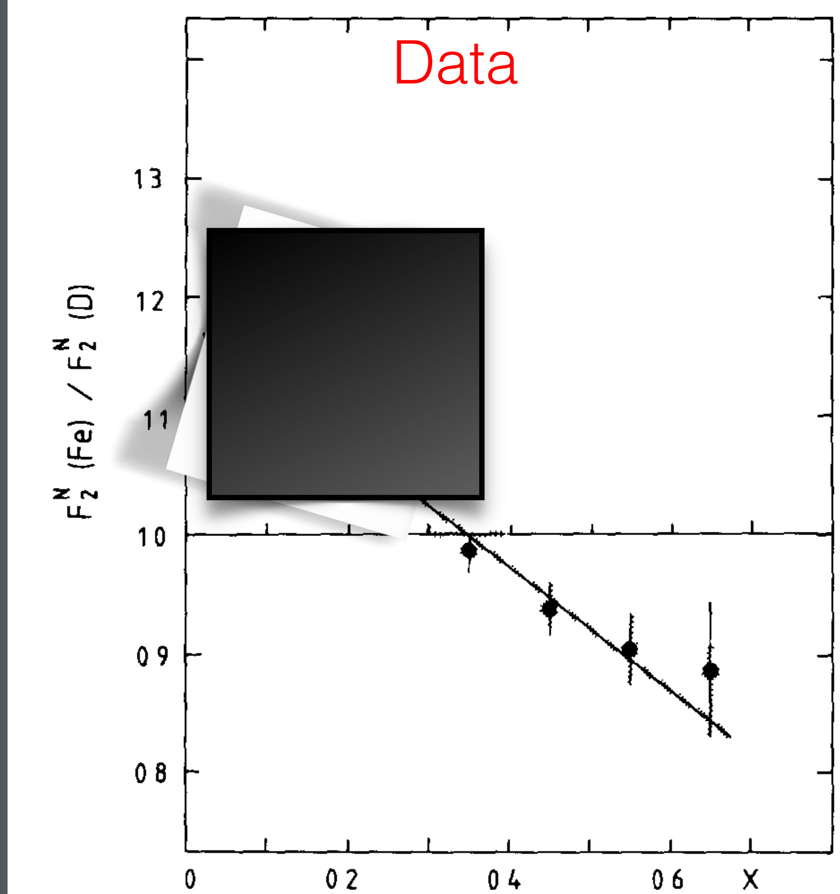


Fig. 2. The ratio of the nucleon structure functions F_2^N measured on iron and deuterium as a function of $x = Q^2/2M_p\nu$. The iron data are corrected for the non-isoscalarity of ${}^{56}_{26}$Fe, both data sets are not corrected for Fermi motion. The full curve is a linear fit $F_2^N(\mathrm{Fe})/F_2^N(\mathrm{D}) = a + bx$ 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

EMC effect experiments & explanations

POSSIBLE EXPLANATIONS

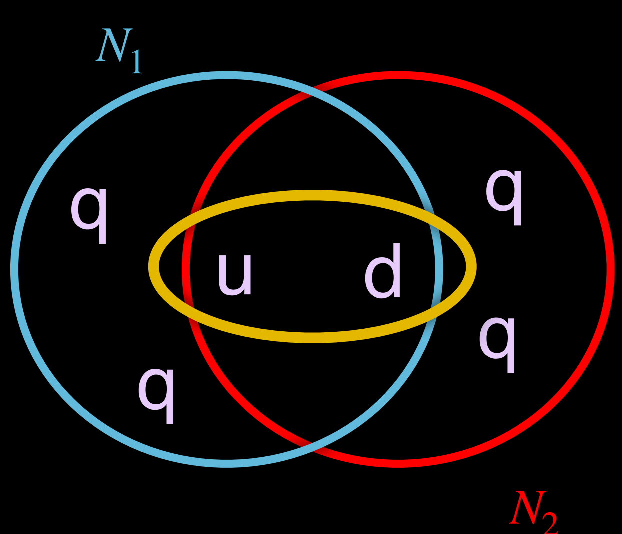
- Mean field effects involving the whole nucleus
- Local effects, *e.g.*, 2-nucleon correlations

Simple mean field effects inconsistent with the EMC effect in light nuclei - MC of $^9\mathrm{Be} \Longrightarrow$clustering
Seely *et al.*, 2009.

"This one new bit of information has reinvigorated the experimental and theoretical efforts to pin down the underlying cause of the EMC effect." *Malace et al., 2014*

Short-range NN correlated pairs (SRC) may cause EMC effect (*Ciofi & Liuti 1990, 1991 and many more afterward*).
Neutron-proton pairs found to dominate SRC (CLAS collaboration, EP & others)

New model: **Diquark formation** proposed to create correlations at high nucleon overlap, modifying quark behavior in the NN pair



"Diquark induced short-range nucleon-nucleon correlations & the EMC effect"
JRW, Nuc.Phys.A 2023

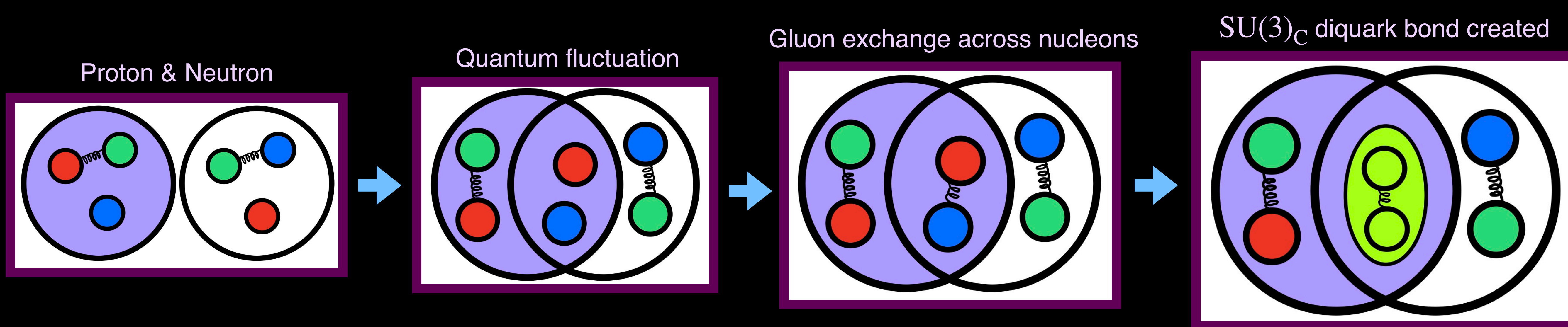
DOZENS OF EXPERIMENTS CONFIRM EMC EFFECT

Target	Collaboration/ Laboratory
^{3}He	JLab HERMES
^{4}He	JLab SLAC NMC
^{6}Li	NMC
^{9}Be	JLab SLAC NMC
^{12}C	JLab SLAC NMC EMC
^{14}N	HERMES BCDMS
^{27}Al	Rochester-SLAC-MIT SLAC NMC
^{40}Ca	SLAC NMC EMC
^{56}Fe	Rochester-SLAC-MIT SLAC NMC BCDMS
^{64}Cu	EMC
^{108}Ag	SLAC
^{119}Sn	NMC EMC
^{197}Au	SLAC
^{207}Pb	NMC

Malace, Gaskell, Higinbotham & Cloet, Int.J.Mod.Phys.E 23 (2014)

Overview: Fundamental QCD dynamics in NN pairs

New model: **Diquark formation** proposed to create short-range correlations (SRC), modifying quark behavior in the NN pair



Color scheme: The 3 SU(3) color charges are the usual red, green, blue - anticolor charge of antigreen represented by lime green

3N SRC a work in progress, diquark-based SRC makes predictions. 4N is published, the hidden color hexadiquark state.

JRW, S.J.Brodsky, G. de Teramond, I.Schmidt, A.Goldhaber, arXiv:2004.14659, Nuc. Phys A 2020

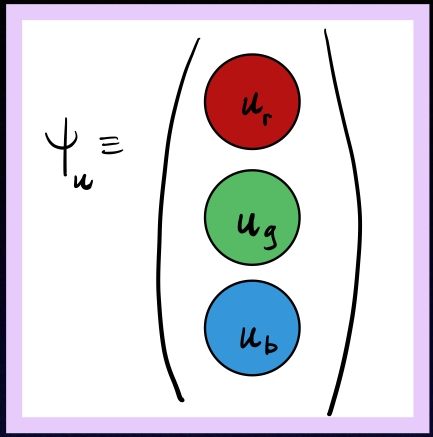
Quantum Chromodynamics prediction: Diquarks

- Strong force described by special unitary group $SU(3)_C$, a local gauge symmetry $\equiv$ QCD

- QCD $\Longrightarrow$ Diquark creation: Quark-quark bond with single gluon exchange **&** group theory transformation into a fundamentally different object:

$$3_C \otimes 3_C \rightarrow \bar{3}_C$$

Quark in the fundamental rep of $SU(3)_C$:



Diquark wavefunction :

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

Like quarks and gluons, diquarks carry color charge. They cannot be seen directly due to color confinement. Only 1_C (red+green+blue or red-antired etc.) directly detected.

Therefore there is no direct evidence for diquarks. Work in progress for diquark detection experimental proposals (*e.g.*, diquark jets from DIS increase Λ production)

Strong indirect evidence exists (baryon mass splittings, Regge slopes).

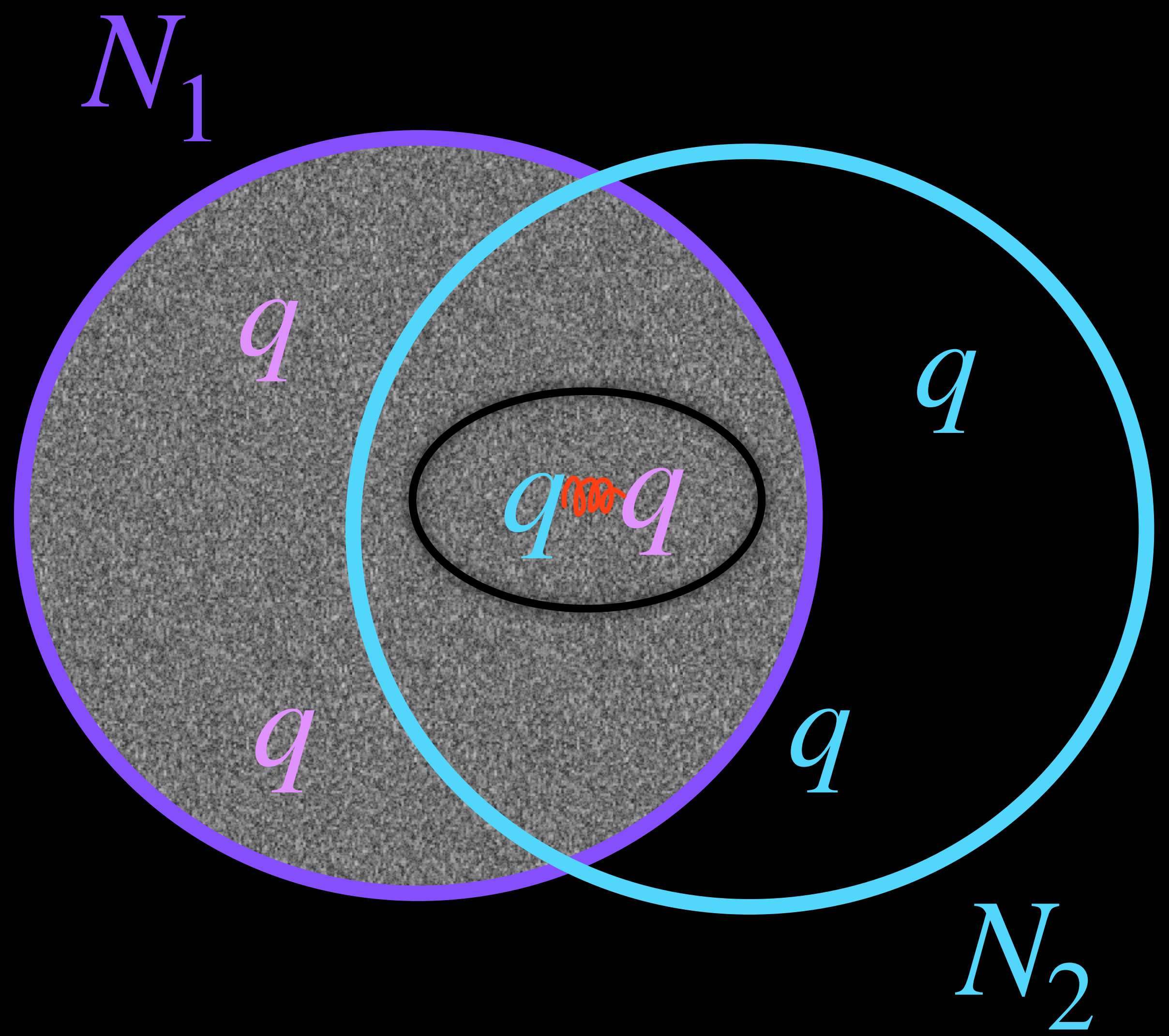
Diquark formation across N-N pairs

Requirements for diquark induced SRC:

1. Nucleon-Nucleon wavefunctions must strongly overlap

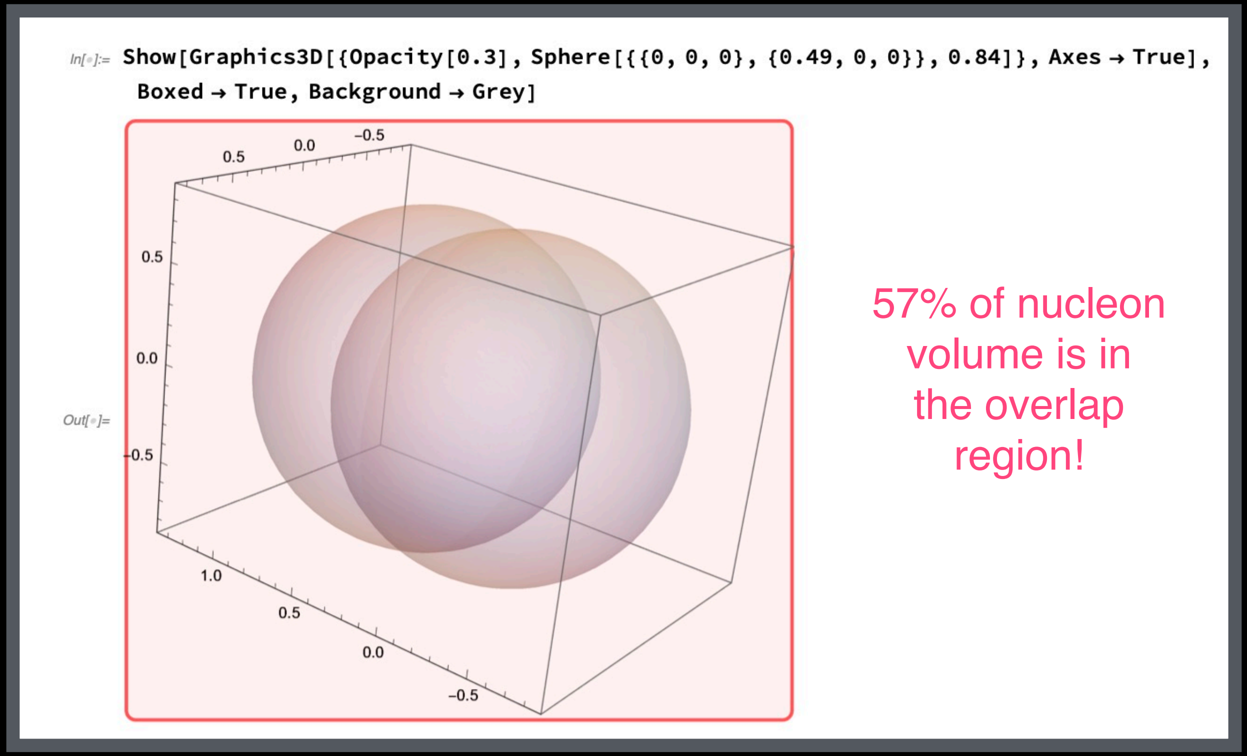
2. Attractive short-range QCD potential between valence quarks

3. Significant binding energy for diquark to form. Much stronger than nuclear binding energies - comparable to QCD confinement scale *for spin-0 up-down diquark*

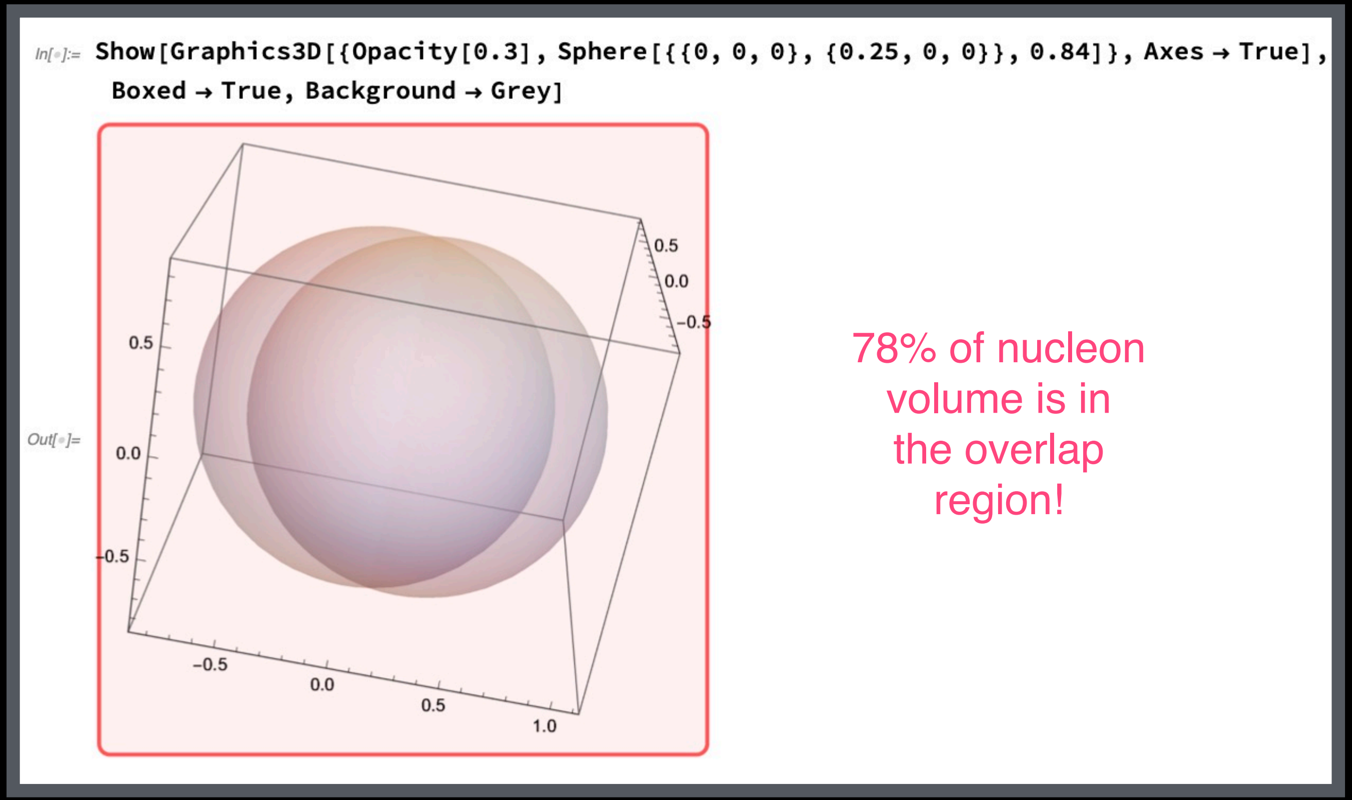


1. SRC 3D-overlap for relative momenta 400 MeV/c & 800 MeV/c

- *SRC Plot 1*: According to the ^{12}C measurements from 2021 CLAS, NN tensor force dominates at 400 MeV/c relative momenta. Natural unit conversion gives 0.49 fm = 400 MeV/c.



- *SRC Plot 2*: Tensor-scalar transition momenta - according to the ^{12}C measurements from 2021 CLAS, NN scalar force is in effect at 800 MeV/c relative momenta. Natural unit conversion gives 0.25 fm = 800 MeV/c .



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

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

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

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, $\alpha_s \equiv \dfrac{g_s^2}{4\pi}$

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

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

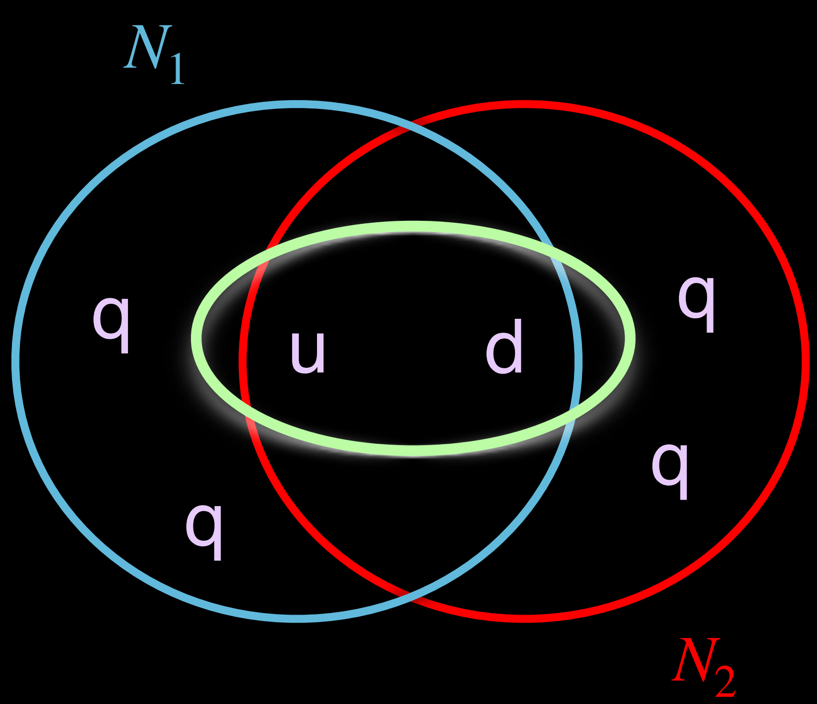
- To compute $V(r)$ for a $3_c \otimes 3_c \to \bar{3}_{c'}$, we use the definition of the scalar $C_2(R)$, $t^a_R\, t^a_R \equiv C_2(R)\ \mathbf{1}$, the *quadratic Casimir operator* (NB: R_f is the final state representation):

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

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

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

Diquark induced N-N correlation:



Compare to color singlet attractive potential:

$$q\bar{q}:\quad V(r) = -\frac{4}{3}\frac{g_s^2}{4\pi r}$$

3. Diquark binding energy: Color hyperfine structure

Use Λ^0 baryon to find binding energy of $[ud]$:

$$\text{B.E.}_{[ud]} = m_u^b + m_d^b + m_s^b - M_{\Lambda^0}$$

Spin-spin interaction contributes to hadron mass;
QCD hyperfine interactions:

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:

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

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

Relevant diquark-carrying baryons: $\Lambda, \Sigma^+, \Sigma^0, \Sigma^-$

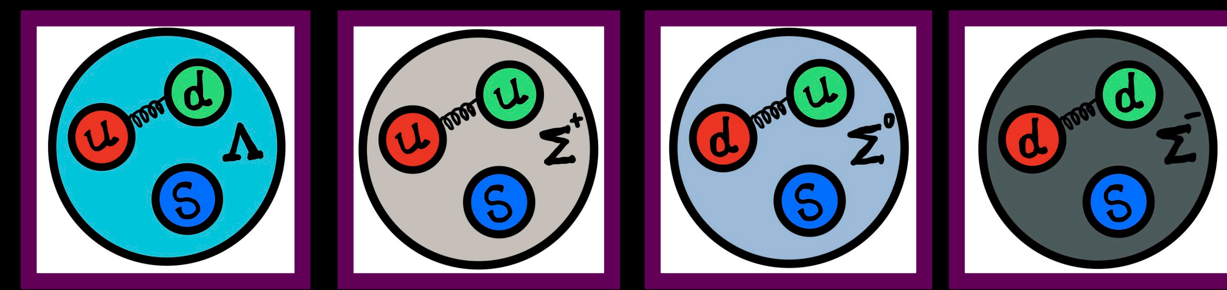


TABLE I: Diquark properties

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)	$I\,(J^P)$
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 Induced Short-Range Correlations & the EMC Effect," JRW, Nucl.Phys.A 2023

Diquark formation across N-N pairs

Requirements for diquark induced SRC:

1. Nucleon-Nucleon wavefunctions must STRONGLY overlap

2. Attractive short-range QCD potential between valence quarks

3. Significant binding energy for diquark to form. Much stronger than nuclear binding energies - comparable to confinement scale *for spin-0 up-down diquark*

Diquark formation Isospin prediction for A=3 SRC

Nucleon wavefunction : $|\mathrm{N}\rangle = \alpha\,|\mathrm{qqq}\rangle + \beta\,|\mathrm{q[qq]}\rangle$

Scalar [ud] diquark formation for nucleons with 3-valence quark internal structure $|\mathrm{N}\rangle \propto |\mathrm{qqq}\rangle$:

$$^{3}\mathrm{H}: \quad 2n + p \rightarrow 4u,\, 5d \implies np \supset [ud]\ \mathrm{x10} \quad \implies nn \supset [ud]\ \mathrm{x4} \implies 60\,\%\ \mathrm{np},\ 40\,\%\ \mathrm{nn}$$

$$^{3}\mathrm{He}: \quad 2p + n \rightarrow 5u,\, 4d \implies np \supset [ud]\ \mathrm{x10} \quad \implies pp \supset [ud]\ \mathrm{x4} \implies 60\,\%\ \mathrm{np},\ 40\,\%\ \mathrm{pp}$$

Scalar [ud] diquark formation for nucleons in quark-diquark internal configuration $|\mathrm{N}\rangle \propto |\mathrm{q[qq]}\rangle$:

$$^{3}\mathrm{H}: \quad u\,[ud] \ +\ d\,[ud] \ +\ d\,[ud] \implies 100\,\%\ \mathrm{np}$$

$$^{3}\mathrm{He}: \quad u\,[ud] \ +\ u\,[ud] \ +\ d\,[ud] \implies 100\,\%\ \mathrm{np}$$

The number of possible diquark combinations in A = 3 nuclei with nucleons in the 3-valence quark configuration is found by simple counting arguments. First, the 9 quarks of ^{3}He with nucleon location indices are written as:

$$\begin{aligned} \mathrm{N}_1 &: p \supset u_{11}\ u_{12}\ d_{13} \\ \mathrm{N}_2 &: p \supset u_{21}\ u_{22}\ d_{23} \\ \mathrm{N}_3 &: n \supset u_{31}\ d_{32}\ d_{33} \end{aligned} \tag{21}$$

where the first index of q_{ij} labels which of the 3 nucleons the quark belongs to, and the second index indicates which of the 3 valence quarks it is. Diquark induced SRC requires the first index of the quarks in the diquark to differ, $[u_{ij}d_{kl}]$ with $i \neq k$. The 4 possible combinations from $p-p$ SRC are listed below.

$$u_{11}d_{23} \quad u_{12}d_{23} \tag{22}$$

$$u_{21}d_{13} \quad u_{22}d_{13} \tag{23}$$

Short-range correlations from $n-p$ pairs have 10 possible combinations,

$$\begin{matrix} u_{11}d_{32} & u_{12}d_{32} \\ u_{11}d_{33} & u_{12}d_{33} \\ u_{21}d_{32} & u_{22}d_{32} \\ u_{21}d_{33} & u_{22}d_{33} \\ u_{31}d_{13} & u_{31}d_{23} \end{matrix} \tag{24}$$

which gives the number of $p-p$ combinations to $n-p$ combinations in this case as $\frac{2}{5}$.

Combining these results yields the following inequality for the isospin dependence of N-N SRC:

$$^{3}\mathrm{He}: \quad 0 \leq \frac{\mathcal{N}_{pp}}{\mathcal{N}_{np}} \leq \frac{2}{5} \tag{25}$$

where $\mathcal{N}_{NN}$ is the number of SRC between the nucleon flavors in the subscript.

The same argument may be made for ^{3}H due to the quark-level isospin-0 interaction, to find

$$^{3}\mathrm{H}: \quad 0 \leq \frac{\mathcal{N}_{nn}}{\mathcal{N}_{np}} \leq \frac{2}{5}. \tag{26}$$

JRW, Nuc.Phys.A 2023

Combine into isospin dependent SRC ratio predictions :

$$^{3}\mathrm{He}: \quad 0 \leq \frac{\mathcal{N}_{pp\ \mathrm{SRC}}}{\mathcal{N}_{np\ \mathrm{SRC}}} \leq \frac{2}{5}, \quad ^{3}\mathrm{H}: \quad 0 \leq \frac{\mathcal{N}_{nn\ \mathrm{SRC}}}{\mathcal{N}_{np\ \mathrm{SRC}}} \leq \frac{2}{5}, \quad \mathit{Maximum}\ 40\,\%$$

Diquark formation induced SRC inequality comparison to data: JLab experiment E12-11-112 A=3 mirror nuclei results

Results from JLab: $\dfrac{\mathcal{N}_{\rm pp}}{\mathcal{N}_{\rm np}} = \dfrac{1}{4.23} \sim 0.24$

Li et al., Nature September 2022

Individual nucleon wavefunctions at lowest order are dominated by two Fock states with unknown coefficients; the 3 valence quark configuration and the quark-diquark configuration,

$$|\mathrm{N}\rangle = \alpha|\mathrm{qqq}\rangle + \beta|\mathrm{q[qq]}\rangle, \tag{27}$$

where square brackets indicate the spin-0 $[ud]$ diquark. The full A = 3 nuclear wavefunction is given by

$$|\Psi_{\mathrm{A}=3}\rangle \propto (\alpha|qqq\rangle + \beta|q[qq]\rangle)(\alpha|qqq\rangle + \beta|q[qq]\rangle) (\gamma|qqq\rangle + \delta|q[qq]\rangle) \tag{28}$$

where the proton and the neutron are allowed to have different weights for each valence quark configuration. This expands out to

$$|\Psi_{\mathrm{A}=3}\rangle \propto \alpha^2\gamma|qqq\rangle^3 + 2\alpha\beta\gamma|qqq\rangle^2|q[qq]\rangle \; \alpha^2\delta|qqq\rangle^2|q[qq]\rangle + \beta^2\gamma|qqq\rangle|q[qq]\rangle^2 + 2\alpha\beta\delta|qqq\rangle|q[qq]\rangle^2 + \beta^2\delta|q[qq]\rangle^3, \tag{29}$$

with mixed terms demonstrating that it is not straightforward to map the $\frac{\mathcal{N}_{pp}}{\mathcal{N}_{np}}$ ratio to precise coefficients for each nucleon's Fock states. A perhaps reasonable simplification is to assume that the proton and the neutron have the same coefficients for their 2-body and 3-body valence states, i.e. to set $\gamma = \alpha$ and $\delta = \beta$ in Eq. 28. In this case, the nuclear wavefunction reduces to

$$|\Psi_{\mathrm{A}=3}\rangle \propto \alpha^3|qqq\rangle^3 + 3\alpha^2\beta|qqq\rangle^2|q[qq]\rangle + 3\beta^2\alpha|qqq\rangle|q[qq]\rangle^2 + \beta^3|q[qq]\rangle^3. \tag{30}$$

JRW, Nuc.Phys.A 2023

Isospin dependent SRC ratio inequalities from diquark induced SRC :

$$^3\mathrm{He}: \quad 0 \le \frac{\mathcal{N}_{pp\ \mathrm{SRC}}}{\mathcal{N}_{np\ \mathrm{SRC}}} \le 0.4$$

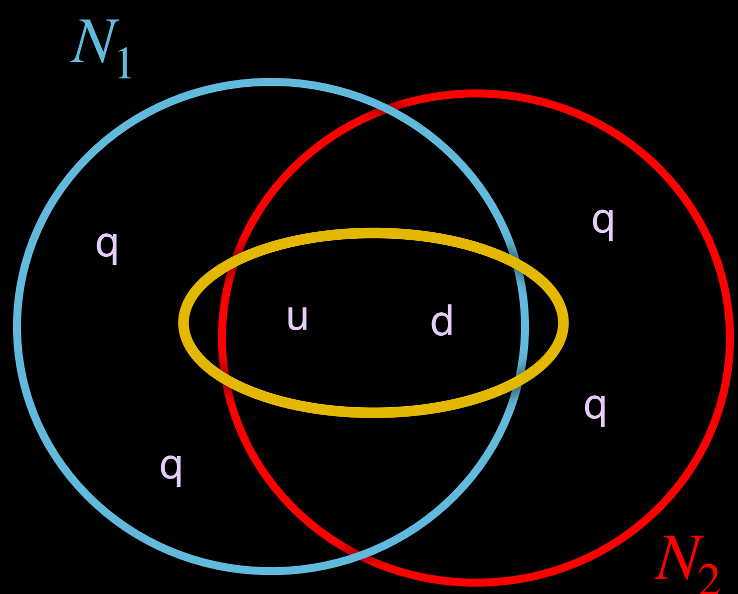
$$^3\mathrm{H}: \quad 0 \le \frac{\mathcal{N}_{nn\ \mathrm{SRC}}}{\mathcal{N}_{np\ \mathrm{SRC}}} \le 0.4$$

$\Longrightarrow$ Nucleon wavefunction : $\alpha|\mathrm{qqq}\rangle + \beta|\mathrm{q[ud]}\rangle$ combination may have approximately equal coefficients, $\alpha \approx \beta$

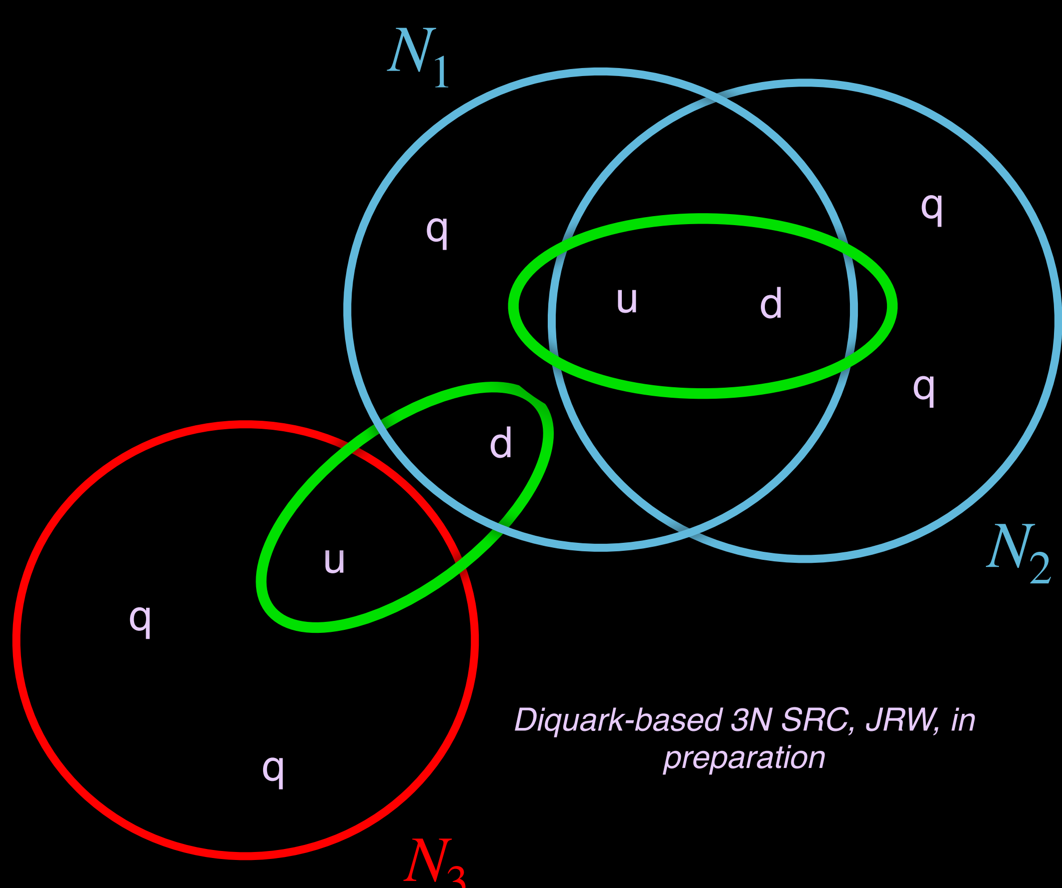
At least 2 Caveats:

1. Non-zero probability that existing diquarks may be broken up if overlap sufficient
2. Nucleon wavefunction written to lowest order - corrections in the form of spin-1 diquarks - proposed to be negligible

3N SRC builds on diquark-based 2N SRC



Diquark-based 2N SRC, JRW, Nuc.Phys.A 2023



Diquark-based 3N SRC, JRW, in preparation

- Fraction of 3N SRC in nuclei follows 2N (true of most (all?) models, not just diquark-based SRC)
- ∴ 3N Nucleus specific, because % SRC per nucleus not universal
- Assume independent events: Probability to form 2N SRC, eg 20%, multiplied by probability to form another SRC (where the model gives the second probability)
- For diquark model this means probability to undergo another quantum fluctuation into high spatial overlap and temporarily "stick" - i.e., 20%, with caveats
- Diquark formation depends on the number of available u and d quarks in the 2N system in order to form the low mass $[ud]$ diquark between the 3rd nucleon and the 2N system
- Immediately this implies that 3N SRC cannot form for nucleons in the quark-diquark configuration

$$\mathscr{P}_{3N}^{\mathrm{q-dq}} = 0.2 * 0 = 0$$

- If coefficients of nucleon wavefunction are roughly equal, $\alpha \approx \beta$, this reduces the 3N probability by

$$\mathscr{P}_{3N} = 0.2 * (\frac{1}{2} * 0.2) = 0.02 \implies 2\,\%\ 3\mathrm{N}$$

SRC separation energy of interest to 2N, 3N and 4N SRC: 150-400 MeV

Hidden color overview with example in $^4\mathrm{He}$

- Rigorous prediction of $\mathrm{SU(3)}_C$ based QCD
- Color-singlets with quantum numbers that match nuclei
- Nucleus = bag of color singlets
- Hidden-color = 1 color singlet
- Example: Hexadiquark hidden-color state in $^4\mathrm{He}$

QCD states within the nuclear wavefunction:

JRW, S.J.Brodsky, G. de Teramond, I.Schmidt, A.Goldhaber, Nuc. Phys. A 2021

$$|^4\mathrm{He}\rangle = C_{nnpp}\left|(u[ud])_{1_C}(d[ud])_{1_C}(u[ud])_{1_C}(d[ud])_{1_C}\right\rangle + C_{\mathrm{HdQ}}\left|\left(([ud][ud])_{\bar{\mathbf{6}}_C}([ud][ud])_{\bar{\mathbf{6}}_C}([ud][ud])_{\bar{\mathbf{6}}_C}\right)_{1_C}\right\rangle + \ldots$$

- *Building hidden-color states requires Fermi statistics upon quark exchange, Bose statistics upon diquark exchange.*
- *Spin-statistics constrains the other components of the wavefunction, often requires nonzero L & higher spin states $\Longrightarrow$ higher mass, less contribution to wavefunction (small coefficient C)*

Hidden-color research spans four+ decades:

Brodsky, Ji & Lepage, PRL 1983

Brodsky & Chertok, "The Asymptotic Form-Factors of Hadrons and Nuclei and the Continuity of Particle and Nuclear Dynamics" PRD 1976

M. Harvey, "Effective nuclear forces in the quark model with Delta and hidden color channel coupling" Nuc. Phys. A 1981

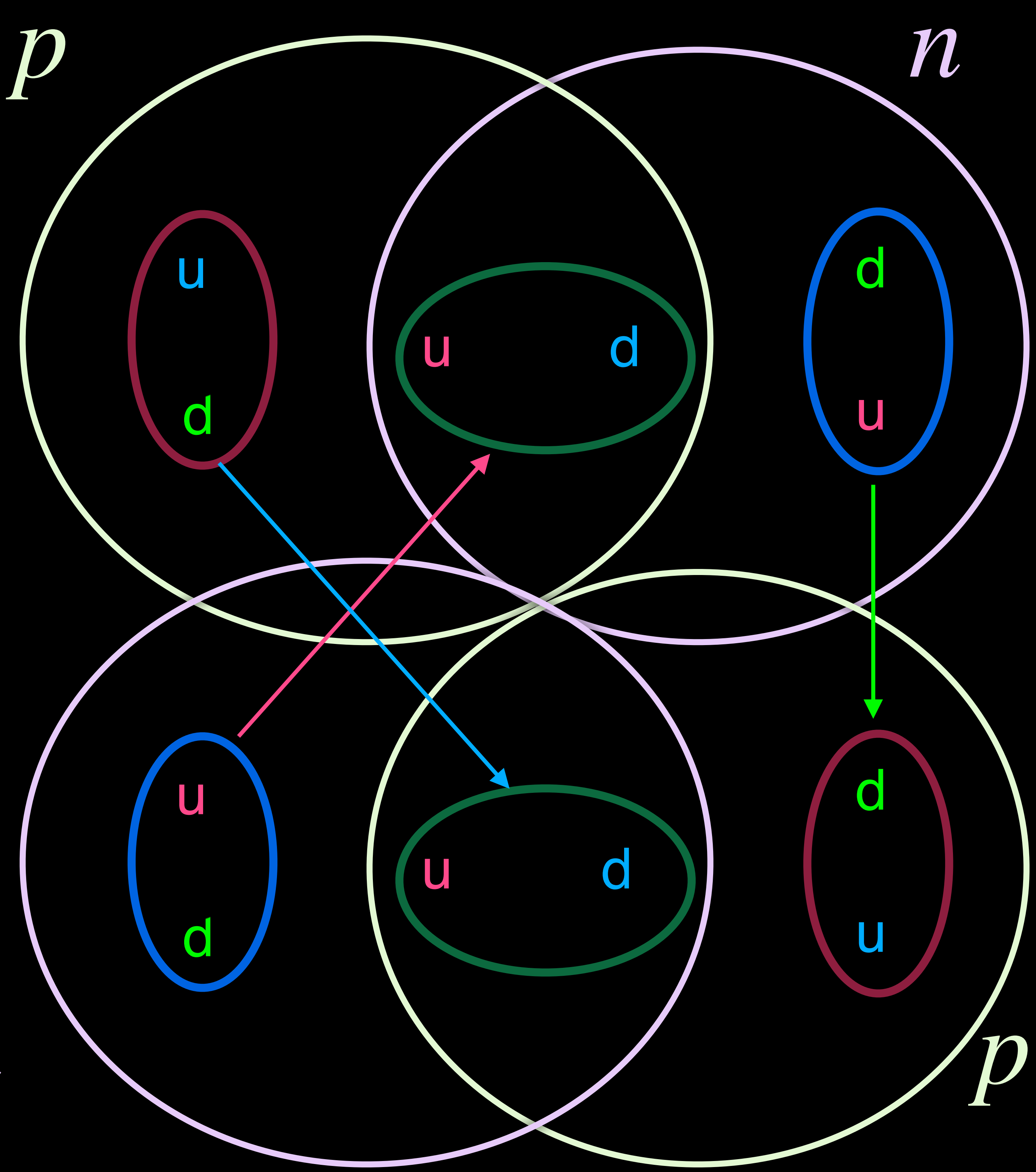
G.A.Miller "Pionic and Hidden-Color, Six-Quark Contributions to the Deuteron b1 Structure Function" Phys. Rev. C 2014

Hexadiquark (HdQ) hidden color state in A≥4 nuclei

- ^4He nuclear wavefunction a linear combination of nnpp and HdQ with unknown coefficients

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

- n-p dominance of SRC required by the HdQ model - PDF calculation work in progress
- New hadronic excitations predicted due to 6_C bonds between diquarks
- X17 solution proposed



New hadronic excitations predicted due to 6_C bonds between diquarks, a proposed X17 solution

- *First signal in* ^8Be: proton capture on ^7Li creates excited state of ^8Be. Decays to virtual photon which decays to e^+e^- pair. ∃ an anomaly in the angular correlation which may be translated to the creation and decay of an intermediate ~16.9 MeV particle, dubbed the X17.

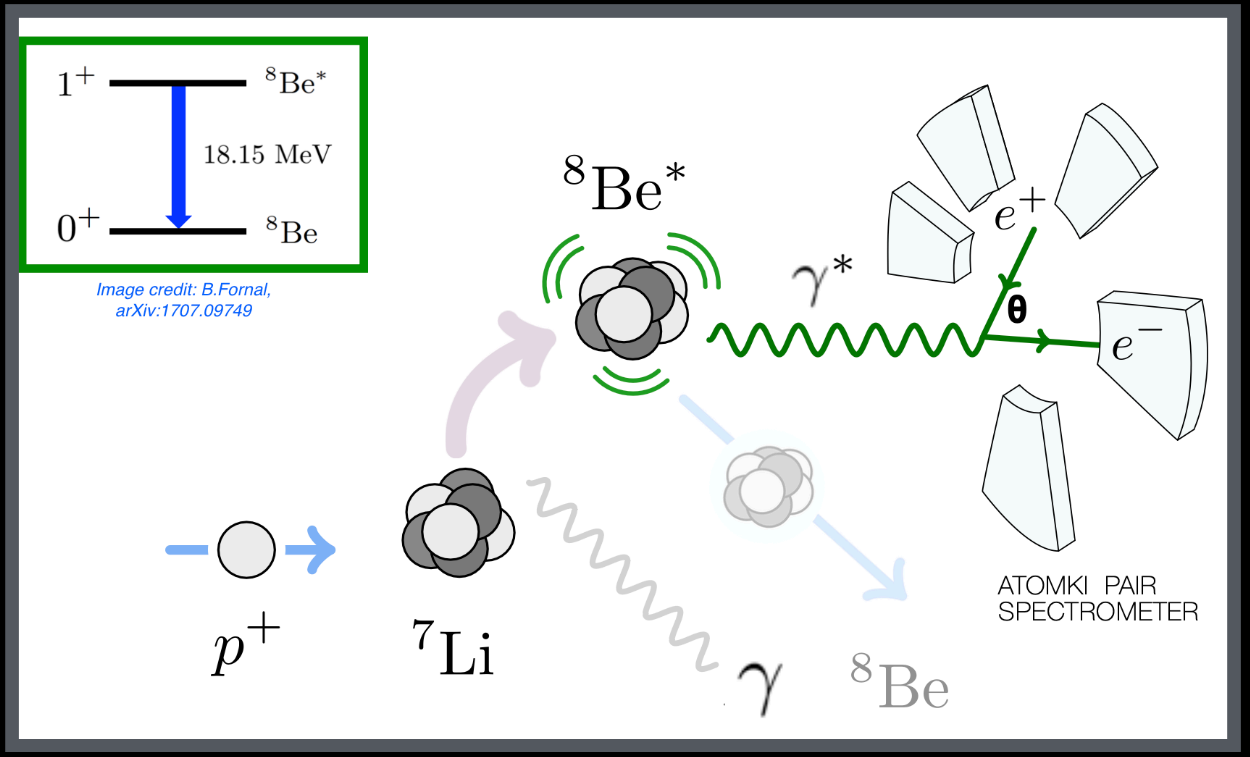


Image credit: B.Fornal, arXiv:1707.09749

- *Also seen in* ^4He: proton capture on ^3H, same process.
- We can fit their data with a decay from a new subdominant excited state of ^4He:

$$E^* = 17.9 \pm 1\text{MeV}$$

achieved with a hidden color excitation - radial or orbital - between 2 diquarks in the hexadiquark.

$$\Gamma_{^4\text{He}} = \int_{2m_e}^{m-m_0} dm_{e^+e^-} \left|\mathcal{M}_q\left(q^2\right)\right|^2 \left|p_e^*\right| \left|p_{He}\right|$$

"Quantum Chromodynamics Resolution of the ATOMKI Anomaly in 4He Nuclear Transitions"
V.Kubarovsky, JRW, S.J.Brodsky, 2206.14441

Tetraneutrons & Hidden Color

- $^4\mathrm{He}$ Hexadiquark wavefunction build can be duplicated in 4n and 4p systems
- Different spin & isospin structure: 2 of 6 diquarks change from $[ud]$ to (uu), (dd), adding ~400 MeV
- Tetraneutron ∴ gives an upper limit on mass/virtuality of the HdQ
- Work in progress: relating mass of QCD Hamiltonian eigenstate (hidden color state) to limit on HdQ coefficient in nuclear wavefunction
- Goal: Discovery of $^4\mathrm{He}$ composition, nuclear & QCD

$$|\alpha\rangle = C_{pnpn}\left|(u[ud])_{1_C}(d[ud])_{1_C}(u[ud])_{1_C}(d[ud])_{1_C}\right\rangle$$

$$+\ C_{\mathrm{HdQ}}\left|(([ud][ud])_{\bar{6}_C}([ud][ud])_{\bar{6}_C}([ud][ud])_{\bar{6}_C})_{1_C}\right\rangle + \dots$$

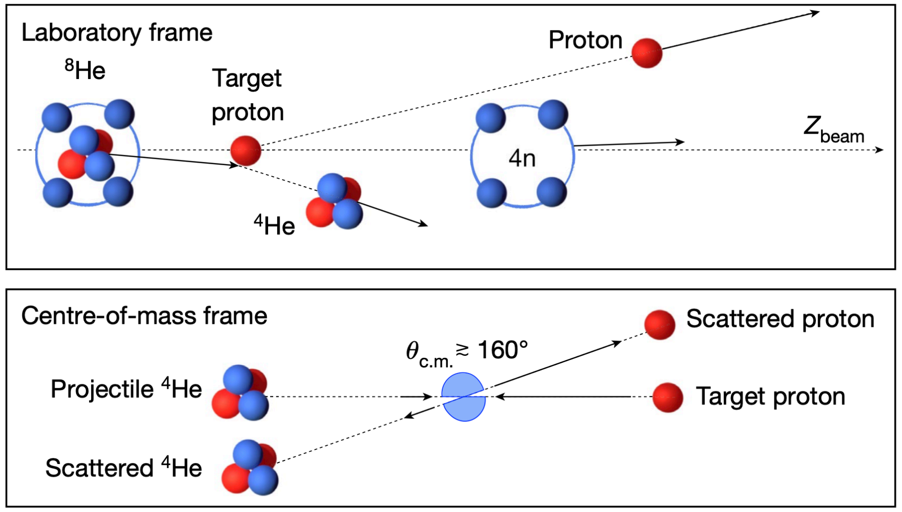


Fig. 1 | Schematic illustration of the quasi-elastic reaction investigated in this work. Top: quasi-elastic scattering of the ^{4}He core from a ^{8}He projectile off a proton target in the laboratory frame. The length of the arrows represents the momentum per nucleon (the velocity) of the incoming and outgoing particles. Z_{beam} is the beam axis. Bottom: the equivalent p−^{4}He elastic scattering in their centre-of-mass frame, where we consider reactions at backward angles close to 180°, $\theta_{\mathrm{c.m.}} \gtrsim 160°$. In this frame, the momentum of the proton balances that of the ^{4}He, $\mathbf{P}_\mathrm{p} = -\mathbf{P}_{^4\mathrm{He}}$, that is, the proton is four times faster than the ^{4}He.

"Observation of a Correlated Free Four-Nucleon System"
*M.Deur et al., Nature **606**, 678–682 (2022)*

Nuclear physics

Four neutrons might form a transient isolated entity

Lee G. Sobotka & Maria Piarulli

An experiment firing helium-8 nuclei at a proton target has generated evidence that four neutrons can exist transiently without any other matter. But doubts remain, because the existence of such systems is at odds with theory. **See p.678**

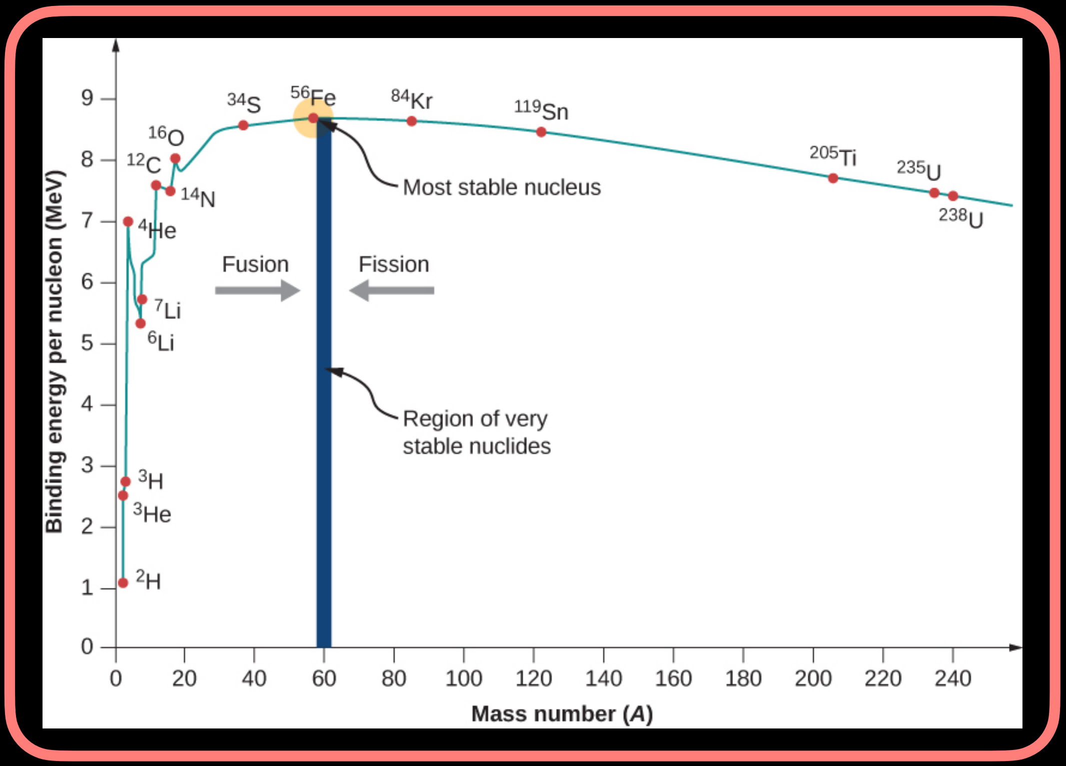
To understand the nature of cohesion in any system, you have to push the system until it breaks. In the case of atomic nuclei, this means knowing when the short-range attractive nuclear force that acts between nucleons (protons and neutrons) surrenders to the repulsive long-range Coulomb force between protons, and the extent to which extreme

tetraneutron) has an energy spectrum with a 'resonance-like' feature.

The authors undertook an experiment in which helium-8 nuclei (comprising two protons and six neutrons) were fired in a fast beam towards a stationary target of protons (Fig. 1a). The collision resulted in each helium-8 nucleus ejecting an α-particle, which contains

Diquark-based SRC Separation Energy implications

- 2N SRC $E_{\text{sep}} \sim 150\ \text{MeV}$, single $[ud]$ diquark BE
- 3N SRC $E_{\text{sep}} \sim 300\ \text{MeV}$, two $[ud]$ diquarks BE
- 4N SRC also has $E_{\text{sep}} \sim 300\ \text{MeV}$ but likely more because it is a strongly bound color singlet, 2N and 3N are not
- Assume $E_{\text{sep}} \sim 400\ \text{MeV}$ is from a 4N breakup
- Assume excess ^4He binding energy from HdQ, $\sim 12\ \text{MeV}$



phys.libretexts.org

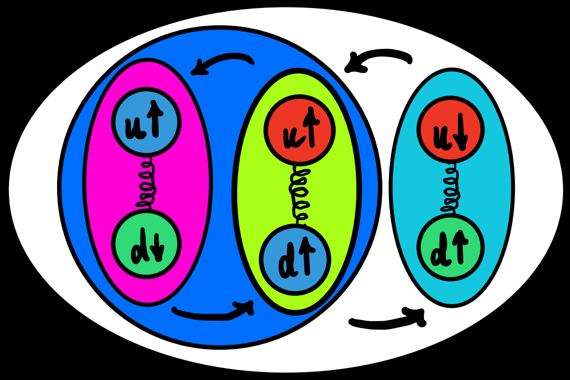
- Let x_1=fraction of hidden color $|\text{HdQ}\rangle$ contribution to ^4He nuclear wavefunction, x_2=fraction of $|\text{nnpp}\rangle$

Hidden color in ^{2}H, Take I

Work in progress:

- Brodsky, Ji & Lepage 1983 stated ∃ 5 QCD states in the deuteron - one of which is the nuclear state:

$$|np\rangle = |(\epsilon^{abc}u_a d_b d_c)_{1_C}\ (\epsilon^{lmn}u_l u_m d_n)_{1_C}\rangle$$



6 quark hidden color possibilites with quantum numbers of ^2H

- Typically the literature has color octets as the hidden-color state:

$$\Big((\epsilon^{abn}u_a d_b d_c)_{8_C}\ (\epsilon^{lmc}u_l u_m d_n)_{8_C}\Big)_{1_C}$$

A proposal for 3 others:

1. 3 antitriplet diquarks: $\Big(\epsilon_{prs}\ (qq)^p\ (qq)^r (qq)^s\Big)_{1_C}$ where $(qq)^s = \epsilon^{abs}q_a q_b$ - requires 2 L=1!
2. 3 sextet (symmetric - also slightly repulsive!) diquarks: $6_C \otimes 6_C \otimes 6_C \rightarrow 1_C$
3. 2 Triplet-1 sextet combo: $\bar{3}_C \otimes \bar{3}_C \otimes 6_C \rightarrow 1_C$

- No longer believe this is lowest order ^{2}H wavefunction (with $\alpha \gg \beta$):

$$|np\rangle = \alpha|(\epsilon^{abc}u_a d_b d_c)_{1_C}\ (\epsilon^{lmn}u_l u_m d_n)_{1_C}\rangle\ +\ \beta|(\epsilon^{abn}u_a d_b d_c)_{8_C}\ (\epsilon^{lmc}u_l u_m d_n)_{8_C}\rangle + \dots$$

Hidden color in ^{2}H, Take II

- Redux: Brodsky, Ji & Lepage 1983, ∃ 5 QCD states in the deuteron. Dominant nuclear state is

$$|np\rangle = |(\epsilon^{abc}u_a d_b d_c)_{1_C}\ (\epsilon^{lmn}u_l u_m d_n)_{1_C}\rangle$$

- Octets unlikely? What is the mass cost of rearranging the color singlets into color octets?

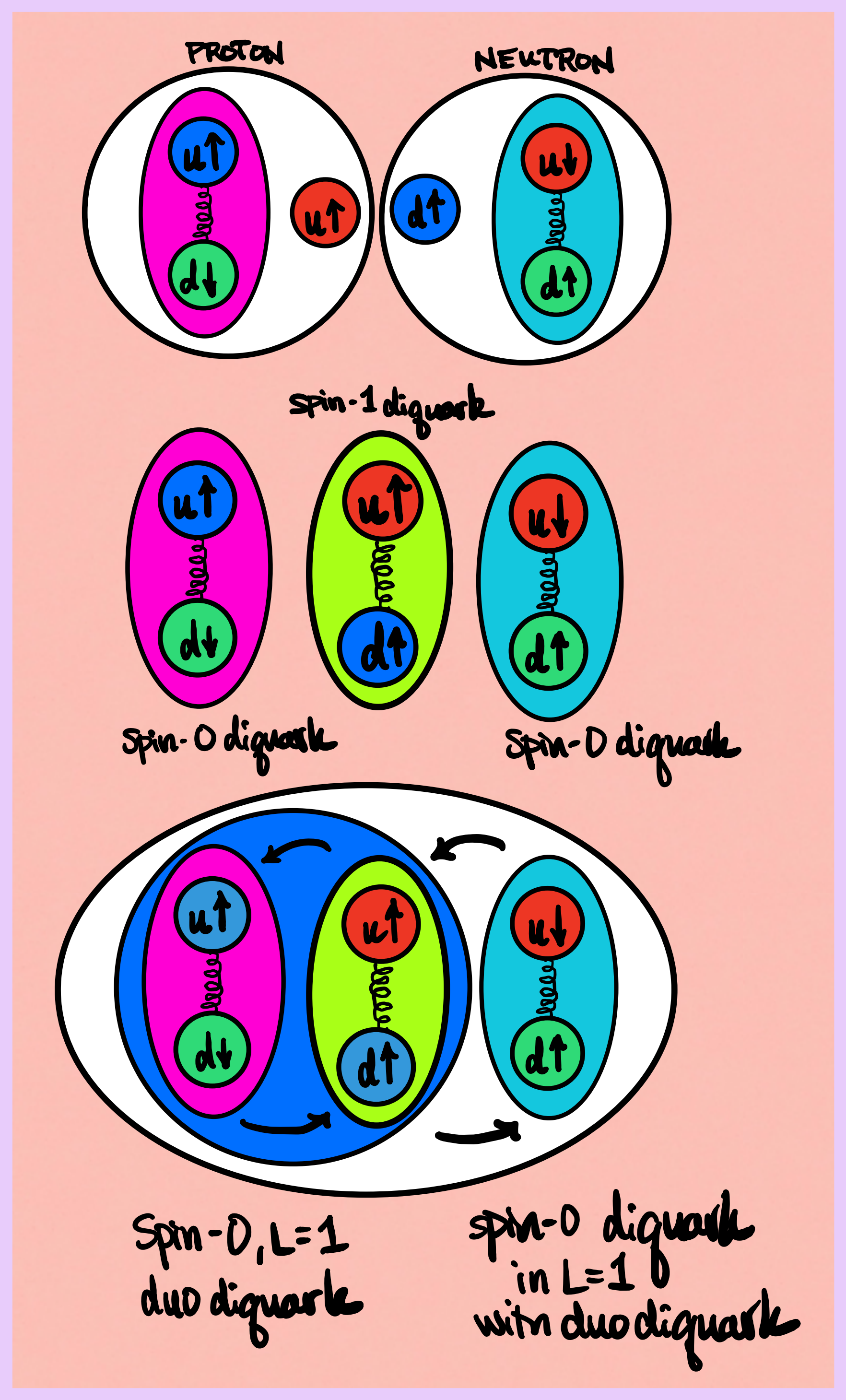
$$\left((\epsilon^{abn}u_a d_b d_c)_{8_C}\ (\epsilon^{lmc}u_l u_m d_n)_{8_C}\right)_{1_C}$$

Perhaps the most likely state:

1. 3 antitriplet diquarks: $\left(\epsilon_{prs}\ (qq)^p\ (qq)^r (qq)^s\right)_{1_C}$ where $(qq)^s = \epsilon^{abs}q_a q_b$ - requires 2 L=1!

2. ~~3 sextet (symmetric - also slightly repulsive!) diquarks: $6_C \otimes 6_C \otimes 6_C \to 1_C$~~

3. ~~2 Triplet-1 sextet combo: $\bar{3}_C \otimes \bar{3}_C \otimes 6_C \to 1_C$~~



Tri-diquark hidden color state formation in ^2H

Fin

Jennifer Rittenhouse West
Berkeley Lab & EIC Center @JLab
ECT Workshop on Spin*
11 July 2023

EIC^2
EIC Center at Jefferson Lab

BERKELEY LAB

Tetraquarks & Pentaquarks

Hidden-color in plain sight?

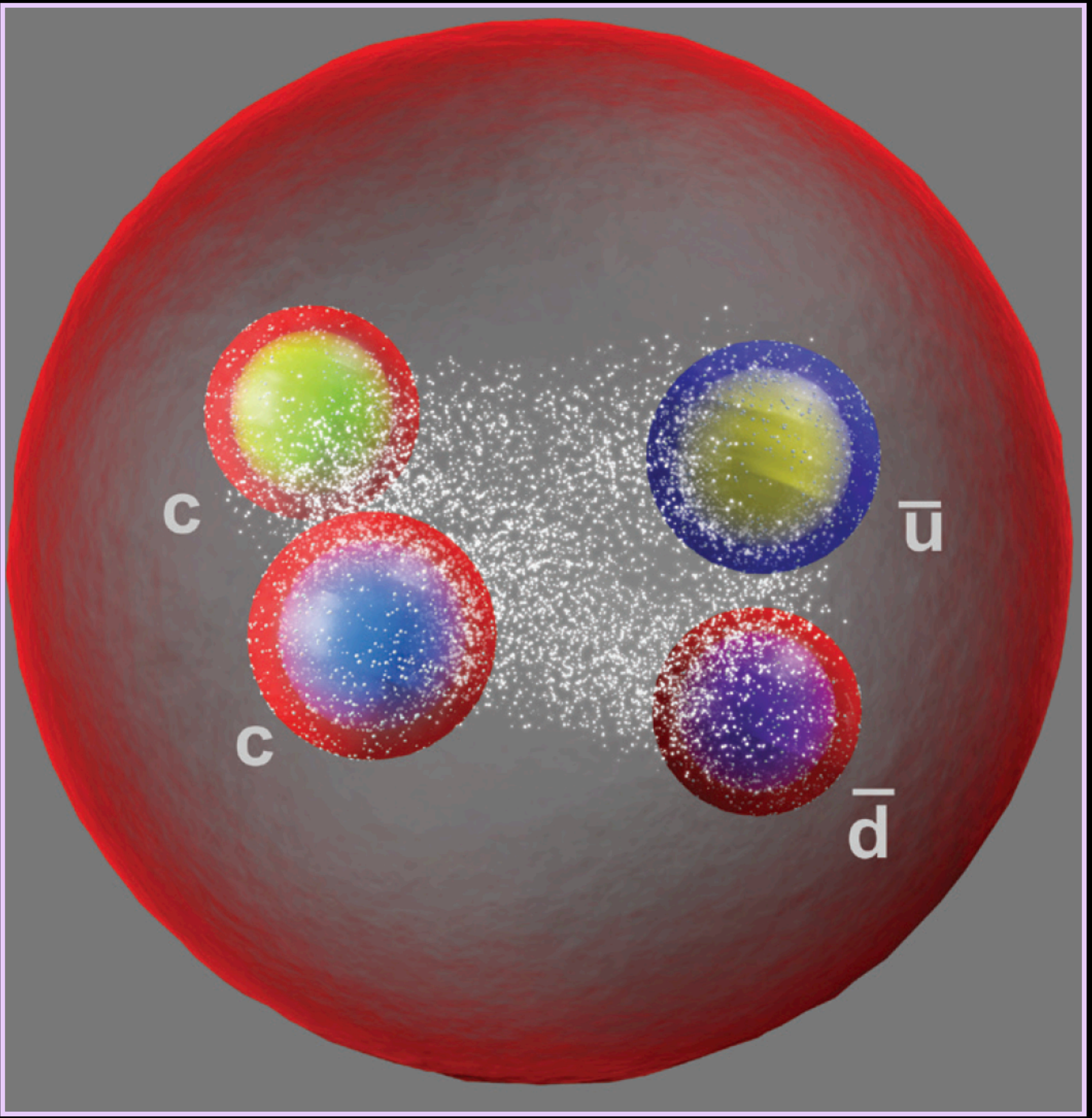
Combination of multiple color singlets vs. one color singlet. Identity of tetra- and penta-quarks an open question in QCD:

Compact configuration of diquarks?

$$cc\bar{u}\bar{d}$$

Or molecular mesonic state?

$$c\bar{u} + c\bar{d}$$



Proton wavefunction - tensor, scalar pieces

Mapping between nuclear and fundamental QCD language necessary:

$$|p\uparrow\rangle = \sqrt{\frac{2}{1+a_S^2}}\left[\frac{a_S}{\sqrt{2}}\left|u\uparrow S_0^0\right\rangle + \frac{1}{3\sqrt{2}}\left|u\uparrow T_0^0\right\rangle - \frac{1}{3}\left|u\downarrow T_0^1\right\rangle - \frac{1}{3}\left|d\uparrow T_1^0\right\rangle + \frac{\sqrt{2}}{3}\left|d\downarrow T_1^1\right\rangle\right]$$

2. Color singlets, color octets, hidden color and all that

Translating from the effective field theory of nuclear physics to QCD, the proton wavefunction becomes

$$|\, p\uparrow\rangle \;=\; \sqrt{\frac{2}{1+a_S^2}}\left[\frac{a_S}{\sqrt{2}}\,|\, u\uparrow[ud]\rangle + \frac{1}{3\sqrt{2}}\,|\, u\uparrow(ud)\rangle - \frac{1}{3}\,|\, u\downarrow(ud)\uparrow\rangle - \frac{1}{3}\,|\, d\uparrow(uu)\rangle + \frac{\sqrt{2}}{3}\,|\, d\downarrow(uu)\uparrow\rangle\right]$$

where the parentheses on (qq) represent spin-1 diquarks, brackets on $[qq]$ represent spin-0 diquarks [22], and diquarks without arrows refer to symmetric $S_z = \uparrow\downarrow + \downarrow\uparrow$ spin states.

At the fundamental QCD level, the proton wavefunction is unconstrained and written as

$$|\, p\uparrow\rangle \;\propto\; A\,|\, uud\rangle + B\,|\, u\uparrow[ud]\rangle + C\,|\, u\uparrow(ud)\rangle + D\,|\, u\downarrow(ud)\uparrow\rangle + E\,|\, d\uparrow(uu)\rangle + F\,|\, d\downarrow(uu)\uparrow\rangle$$

within unknown coefficients A, B, C, D, E, F.