QCD in Nuclei:
Hidden Color Singlets and Diquark Phenomenology

Jennifer Rittenhouse West
Lawrence Berkeley National Laboratory Postdoctoral Fellow
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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

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

- *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

Hidden color as a rigorous prediction of QCD

Building blocks: Quantum chromodynamics, color confinement, 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:

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

- Confinement $\Longrightarrow$ allowed combinations of D.o.F., e.g., the hadrons (use $\delta^a_b, \quad \epsilon^{abc}, \quad \epsilon_{abc}$ to combine):

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

- Higher Fock states (hadrons with 2 or 3 valence quarks are lowest order Fock states), e.g., the 5-quark Fock state for baryons:

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

- To get to hidden color, first build nuclei beginning with heavy hydrogen aka the deuteron, ${}^2\mathrm{H}$:

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

- Hidden color singlets carry same quantum numbers as a hadron or nucleus - subdominant components of the total wavefunction. The HC octet in the deuterium nucleus:

$$q_a\ q_b\ q_c\ q_d\ q_e\ q_f \Longrightarrow \Big((\epsilon^{abf} q_a q_b q_c)_{8_\mathrm{C}} (\epsilon^{dec} q_d q_e q_f)_{8_\mathrm{C}} \Big)_{1_\mathrm{C}} = (p^f_c\ n^c_f)_{1_\mathrm{C}} \subset {}^2\mathrm{H}$$

GPDs and higher Fock states in hadrons

Physically motivated parameterizations of Generalized Parton Distributions (GPDs) -

Reggiezed spectator model by S.Liuti, B.Kriesten, G.Goldstein & collaborators: 2101.01826, 1206.1876, 1012.3776, hep-ph/0611046

- Recall: higher Fock states (hadrons with 2 or 3 valence quarks are lowest order Fock states), e.g., the 5-quark Fock state for baryons:

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

- In Kriesten et al. PRD 2022 "Parametrization of Quark and Gluon Generalized Parton Distributions in a Dynamical Framework" they have 3 types of scattering for the proton:

1. Valence quark, leaves behind a diquark: $q_a + (\epsilon^{abc} \; q_b q_c)_{\bar{3}_C}$

   Or - possibly - an active piece of research: $q_a + q_b q_c$

2. Sea quark, leaves behind spectator tetraquark: $\bar{q}^a + q_a q_b q_c q_d$, or, $q_a + \bar{q}^a q_b q_c q_d$ - this one needs work on the theory side - What happens to half an octet? Should spilt back into a 3_C, $\bar{3}_C$ quark diquark.

3. Gluon, leaves behind proton in the octet - this is a higher Fock state of the proton: $g^a_b + \left(\epsilon^{bcd} q_a q_c q_d\right)_{8_C}$

Connection to N^* *states?*

Hidden color in $^2\mathrm{H}$

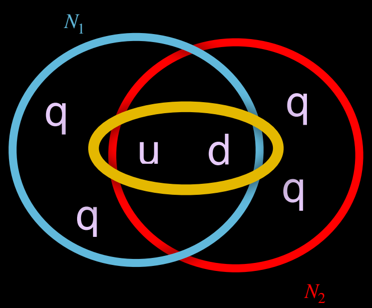
Work in progress:

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

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

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

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



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

A proposal for 3 others:

1. 3 antitriplet diquarks: $\Big(\epsilon_{prs}\ (qq)^p\ (qq)^r (qq)^s\Big)_{1_C}$, where $(qq)^s = \epsilon^{abs} q_a q_b$
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: $\overline{3}_C \otimes \overline{3}_C \otimes 6_C \to 1_C$

- However, lowest order $^2\mathrm{H}$ wavefunction is very likely the following (with $\alpha \gg \beta$):

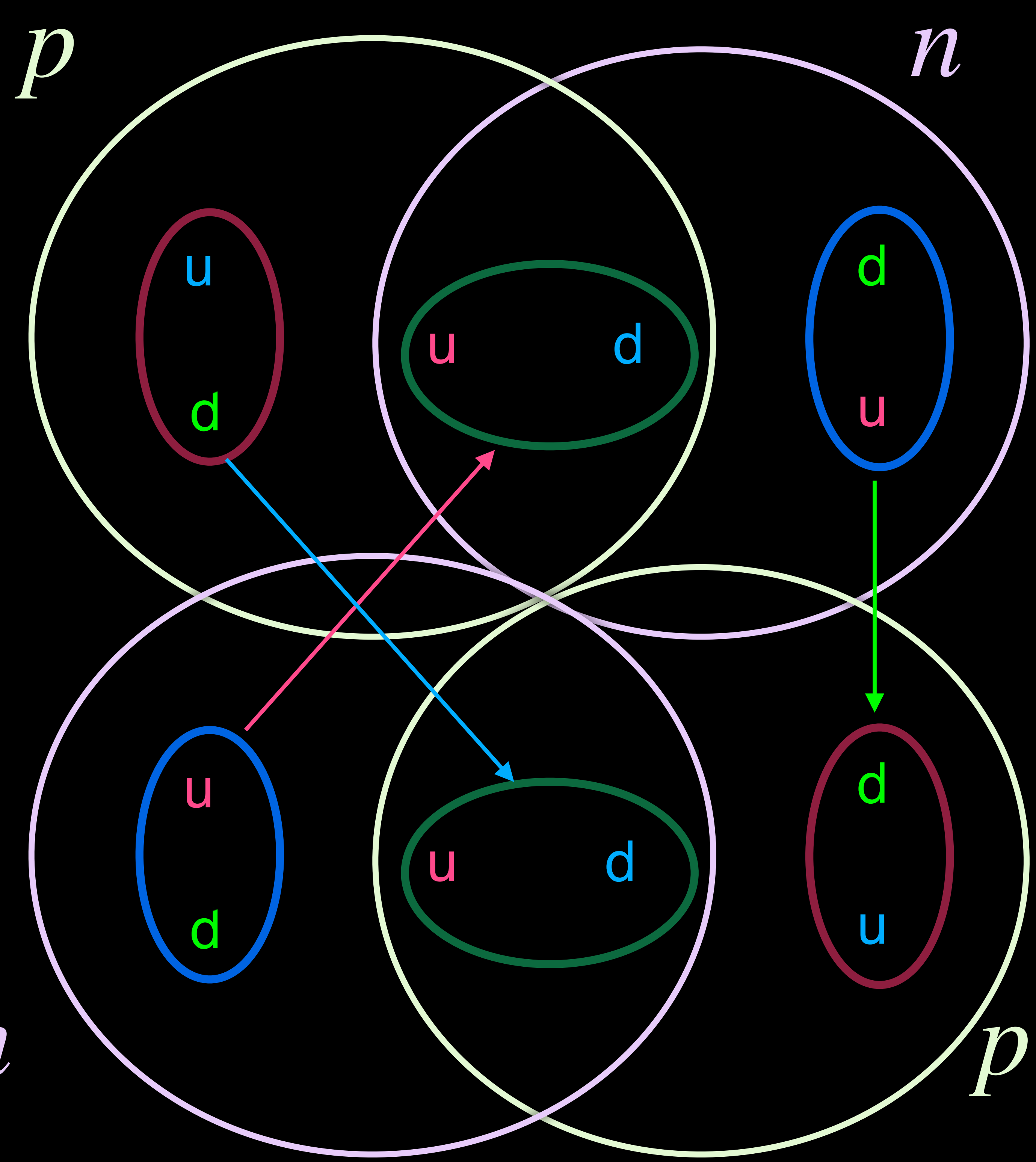
$$|np\rangle = \alpha|(\epsilon^{abc}u_a d_b d_c)_{1_C}\ (\epsilon^{lmn}u_l u_m d_n)_{1_C}\rangle\ +\ \beta|(\epsilon^{abn}u_a d_b d_c)_{8_C}\ (\epsilon^{lmc}u_l u_m d_n)_{8_C}\rangle$$

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

- $^4\mathrm{He}$ nuclear wavefunction a linear combination of nnpp and HdQ with unknown coefficients

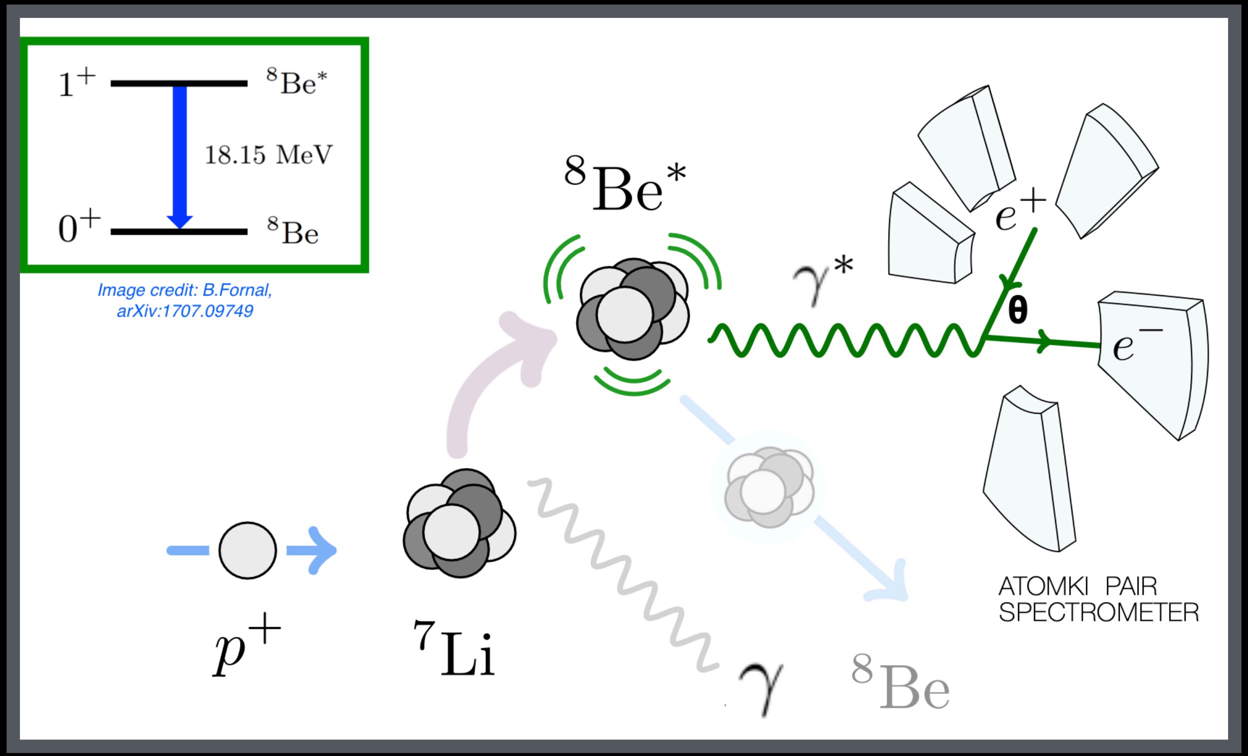
$$
\begin{aligned}
|\alpha\rangle &= C_{pnpn} \left| (u[ud])_{1_C}(d[ud])_{1_C}(u[ud])_{1_C}(d[ud])_{1_C} \right\rangle \\
&+ C_{\mathrm{HdQ}} \left| (([ud][ud])_{\bar{\mathbf{6}}_C}([ud][ud])_{\bar{\mathbf{6}}_C}([ud][ud])_{\bar{\mathbf{6}}_C})_{1_C} \right\rangle
\end{aligned}
$$

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



X17 anomaly from ATOMKI experiments: Possible Hidden Color basis - JLab to search for 3-60 MeV dark sector bosons

- *First signal in* $^{8}\mathrm{Be}$: proton capture on $^{7}\mathrm{Li}$ creates excited state of $^{8}\mathrm{Be}$. 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.



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

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

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

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

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

Fin

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Berkeley Lab & EIC Center @JLab
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