Nucleon–Nucleon binding: the Chemistry of Quarks

Bruno R Galeffi

Abstract: The emergence of quarks inside the nucleon has indubitably one objective: nucleon-nucleon (NN) binding for baryonic matter clustering. The binding energy (BE) is directly proportional to the magnitude of the quark-quark (QQ) binding network between nucleons. Yet, predicting the QQ binding network in a particular nucleus requires a deeper understanding of the "chemistry" of quarks.

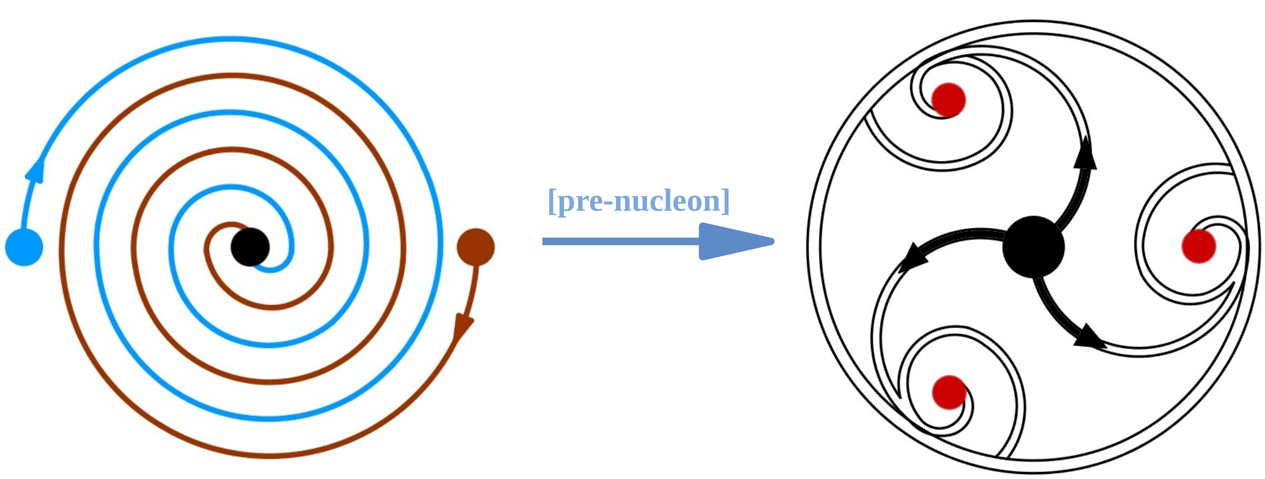
1. Introduction

Over the last decades, nucleons BE have been determined with greater accuracy. Since the precursor and ground breaking NN potential proposed by Yukawa in the 1930's, a large number of NN interaction models and NN potentials have been proposed and theorized [see for example 1-3]. Yet, there is still no consensus about a unified nucleus model. Further, the clustering of nucleons inside nuclei is still poorly predictable, even for the lightest nuclei.

Today the nucleus structural approach follows three mainstream nuclear models [4]. These are mostly known as the shell (or independent particle), liquid-drop, or cluster (FCC). The shell model, which was developed in the 1940's and formalized by Meyer & Jensen [5], suggests the existence of nucleon orbitals (shells) garnished similarly to electrons filling up quantum shells. The liquid drop model, which extracts the nucleus properties from analogy to a drop of liquid, has been extensively refined over the last 80 years. The cluster model posits a strong and localized clustering, such as the Face Centered Cubic (FCC) lattice proposed by N.D. Cook in 1976 [6]. This model views the nucleus in a face-centered-cubic network.

These mutually exclusive models work well enough for qualitative and quantitative description of a limited number of data sets, but not as a general descriptive approach to the nuclear structure puzzle. On the other hand, QCD theory describes NN binding (nuclear force) as a residual of the strong force (color force). In spite of the tremendous achievement of QCD theory at understanding the quark substructure, the theory fails to explain the emergence of nuclear constituents and the mechanism of hadronization. Murray Gell-Mann consistently remarked that quarks were only mathematical construct, and these entities had neither physical reality nor independent existence. His persistent and stunning intuition has never been acknowledged and still remains ignored by theorists. It has been posited and substantiated at [7] that quarks indeed have no self-existence since they merely stem from the spiral proton via energy/charge rearrangement and redistribution, as schematically summarized in Fig.1. This postulate provides a direct explanation for the absence of detectable free quarks in high-energy collision experiments. It also corroborates the non-existence of free particle with fractional charge.

Figure 1: From the spiral proton to the quark substructure stemming inside the pre-nucleon intermediate. As described at [7], angular momenta are actually quantized.



Spiral proton formation via double centripetal spiral motion

Emergence of quarks (in red) via triple centrifugal spiral motion

Emerging from within the spiral proton [8-9] via successive centripetal and centrifugal spiral motions with quantized angular momenta [7], quarks are therefore naturally confined. As a consequence, a color confinement principle is redundant, and speaking of “quarks confinement” becomes a tautology.

It then appears that the main purpose, and perhaps the sole purpose, for the emergence of quark entities inside nucleons is NN binding, which further paves the road for the genesis of baryonic matter. Therefore, the spatial assemblage and binding of quarks between nucleons for the purpose of NN clustering is fundamental. This highly refined way of NN clustering through internal emergence of quarks and gluons entities, and further QQ[1] binding between neighboring nucleons is undeniably a masterpiece of art and engineering.

The QQ bond between nucleons is therefore a fundamental component of the nuclear force. It operates through overlapping of the inappropriately called “color field”. This field seems to correspond to the gluon field around the constituent quark. This approach is comparable to Musulmanbekov model of Strongly Correlated Quarks (SCQM) [10].

2. QQ binding: the chemistry of quarks

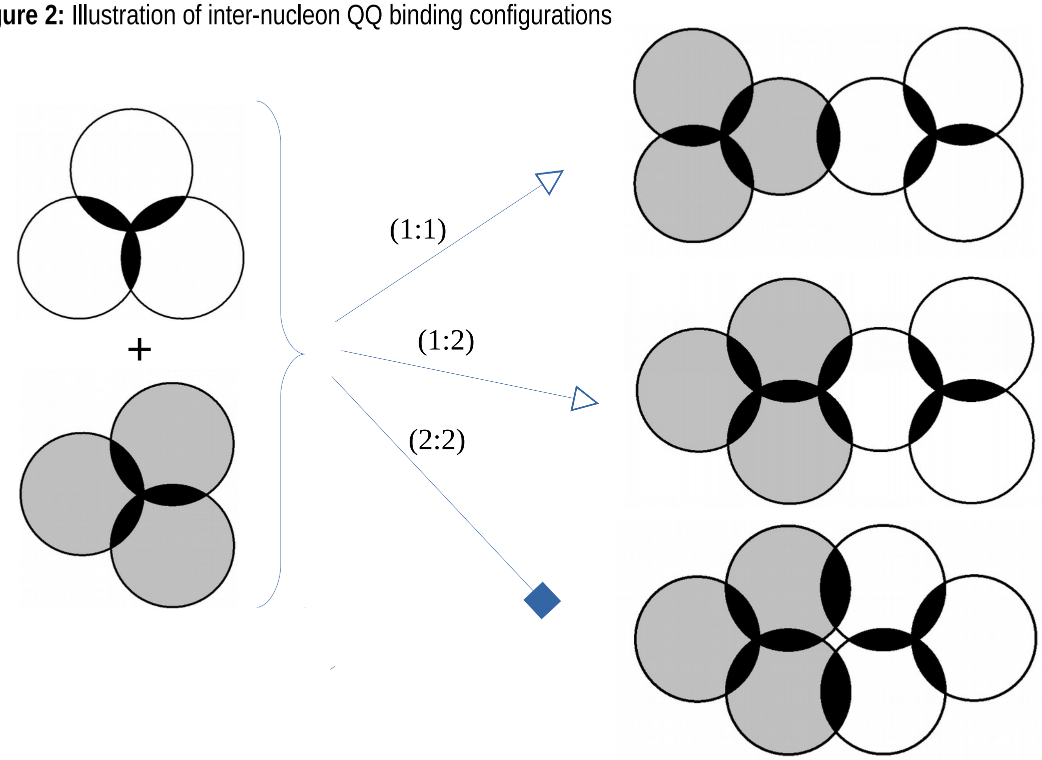
Quarks binding between neighboring nucleons are driven by a number of factors such as spin, magnetic moment, charge, flavor, isospin, etc., or the alternation of u and d flavors in the QQ binding alignment. The impact of those properties on QQ binding rules is poorly understood. The rules proposed by Musulmanbekov in his SCQM model are based on color charge, spin, and isospin symmetries or anti-symmetries [10].

In this article, different types of inter-nucleon QQ binding are reviewed and proposed from a pure “chemistry” perspective. Along this objective, it appears that two geometric factors are fundamental: the binding configuration on one hand, and the angle between quark planes on the other hand.

2.1 QQ binding configuration

There seem to be two favored configurations, which are illustrated in Fig.2 by (1:1) and (1:2). Examples of nuclei exhibiting such configurations will be presented. However, and for unknown reasons, configuration (2:2) does not seem to be privileged.

Figure 2: Illustration of inter-nucleon QQ binding configurations



1 As a convention, QQ in capital letters will refer to quark-quark link between nucleons, while qq will refer to intra-nucleon binding mediated by gluons (known as strong force).

2.2 Angle between quark planes

In the nucleon, the three quarks always end up on a plane regardless of the position of one relative to the others. Therefore the three quarks within the nucleon carry their own plane, and the binding to another set of quarks is not necessarily co-planar. The latter configuration would produce, as the mass number builds up, a linear string of nucleons and a poor packing as a result, which is incompatible with the spherical shape and charge radii (rms) of heavy nuclei.

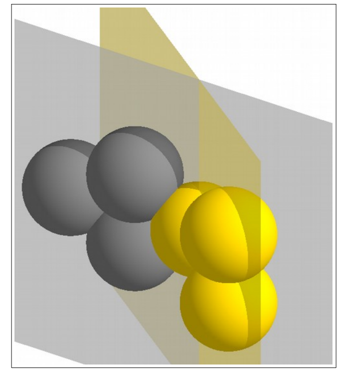


Figure 3: Illustration of non-zero angle between two quark planes

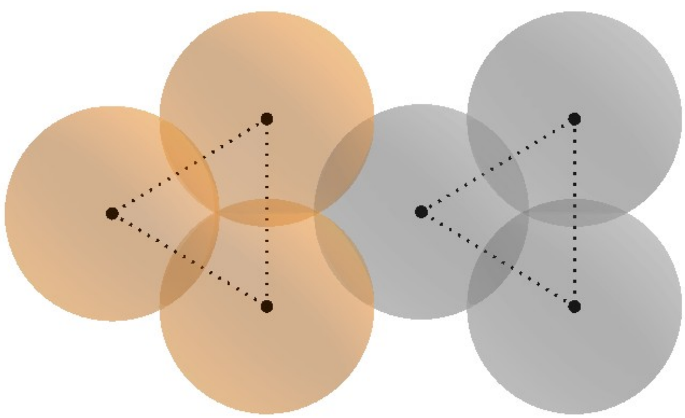
3. The deuteron

The two nucleons in the deuteron appear to be bound via the 1:2 configuration as illustrated in Fig.4, rather than 1:1 as suggested by Musulmanbekov [10], with the two planes making an angle of 37°. The compact view in Fig.4c is obtained after rotating Fig.4a around its virtual z-axis, leading to a perfect superposition of quarks.

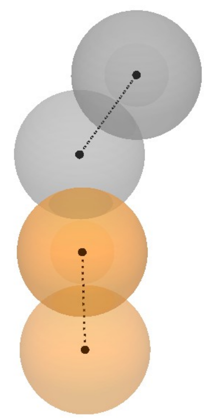
The deuteron has a rather large charge radius of about 2.13 fm, while the color field of the quark is about 0.43 fm. A perspective of the two scales is presented in Fig.4d. However, and due to his electrical quadrupole moment, the deuteron skin is not perfectly spherical.

Figure 4: Three-dimensional layout of the deuteron nucleus

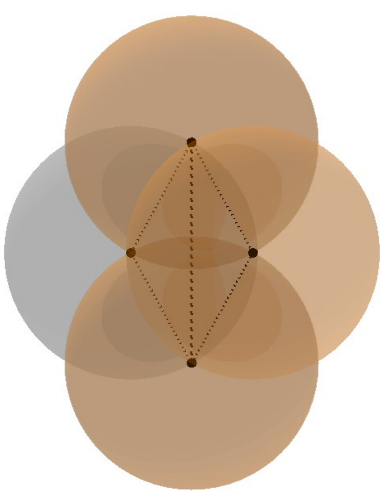
(4a) Quarks in 1:2 configuration



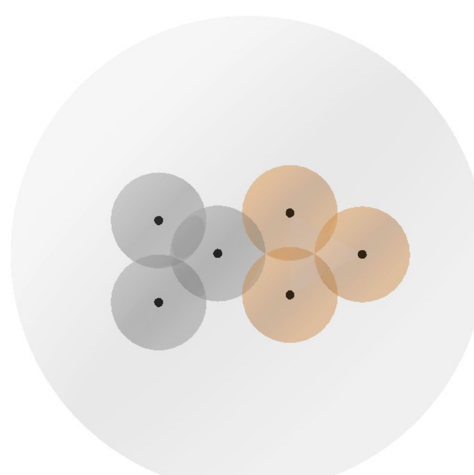
(4b) Quark planes at 37° angle



(4c) Compact view upon rotation of (4a) around z-axis



(4d) Deuteron with nucleus skin (≈ to scale)



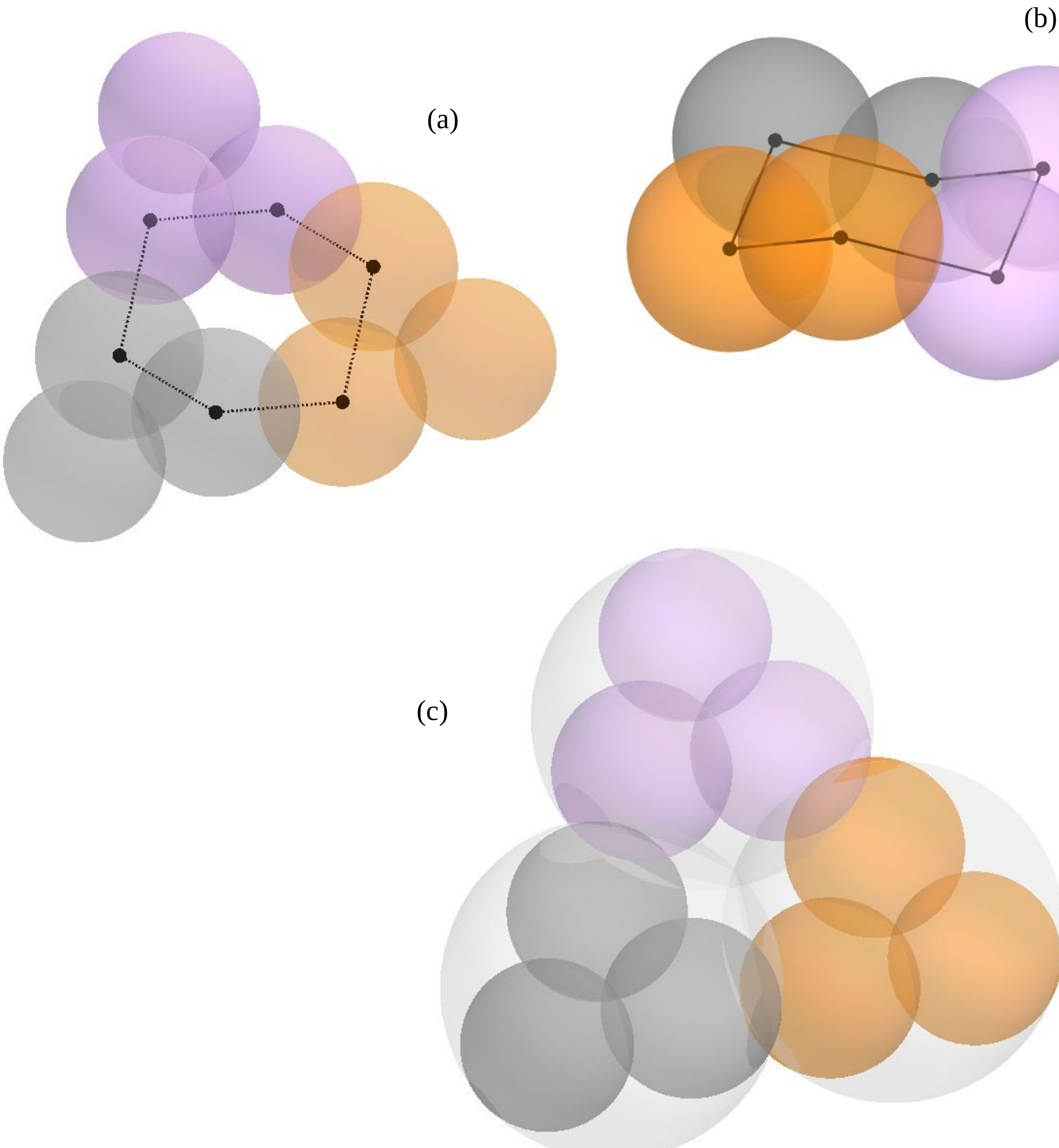
4. ^3He and ^3H. An hexagon in a “chair” conformation

Three baryons nuclei such as helion and triton are preferably arranged around 6-membered rings, as depicted in Fig.5. In this configuration, QQ binding is of the 1:1 type and therefore one quark per nucleon remains “free”. Further, quark triangles are not coplanar and the hexagon exhibits a spatial geometry similar to cyclohexane in a chair conformation. The chair conformation is presented in Fig.5b and reasons for this geometry are not likely driven by steric effects only. For the sake of clarity, only bound quarks are delineated in Fig.5b.

In cyclohexane, the angle between successive bonds is ~109°. As to the 6-membered ring found in helion and triton, this corresponding angle is unknown. However, it is estimated to be around this value. In Fig.5c, quark triads are depicted in their nucleons.

The 6-membered ring is a particularly stable unit in chemistry and biochemistry and numerous molecules contain 6-membered rings in their structure. In the macro world, a vast number of structures such as honeycomb, snow flakes, and insect compound eyes are based on hexagonal units. Certain cosmological scale structures could likely exhibit hexagonal formations.

Figure 5: The 6-membered ring configuration found in helion and triton

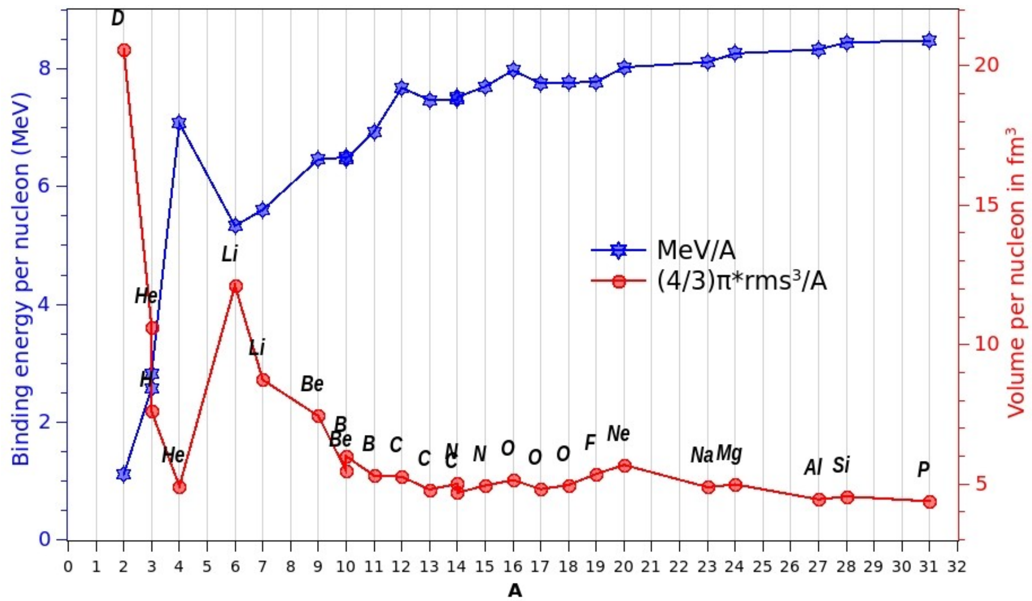


5. ^{4}He nucleus: a stellated icosahedron with a highly bound quark network

BE of isotopes exhibit puzzling properties mostly expressed in smallest nuclei. For example, one might expect that as nucleons build up in the nucleus, BE would monotonically increase. Yet, this is not necessarily the case.

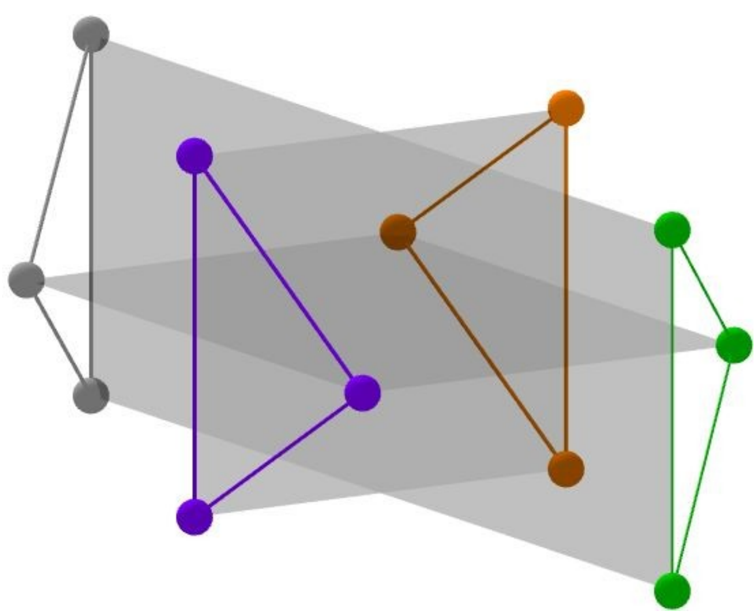
Fig.6 charts the BE of 25 lightest and most abundant isotopes [11], together with the corresponding volume per nucleon as calculated from the experimental charge radius (rms) [12] and expressed in fm^3. It can be noticed that BE and volume per nucleon act in opposite ways. This is particular striking for ^{2}D, ^{4}He, and ^{6}Li, where big bounces manifest in opposite directions. The ^{4}He nucleus is particularly striking as it has a large BE and a small volume per nucleon. This is indicative a highly bound nucleon, with a high degree of QQ binding network.

Figure 6: Binding energy and volume per nucleon for light and stable isotopes



As a matter of fact, it appears that the 12 quarks from the helium-4 nucleon are located at the vertices of a stellated icosahedron, as depicted in Fig.7. In a regular octahedron, the 3 orthogonal golden rectangles are identical. In ^{4}He nucleon, the 3 rectangles have different dimensions, and the relative rectangular areas are as follows: 1 / 1.73 / 2.53.

Figure 7: In ^{4}He nucleus the 12 quarks are located at the vertices of a stellated icosahedron

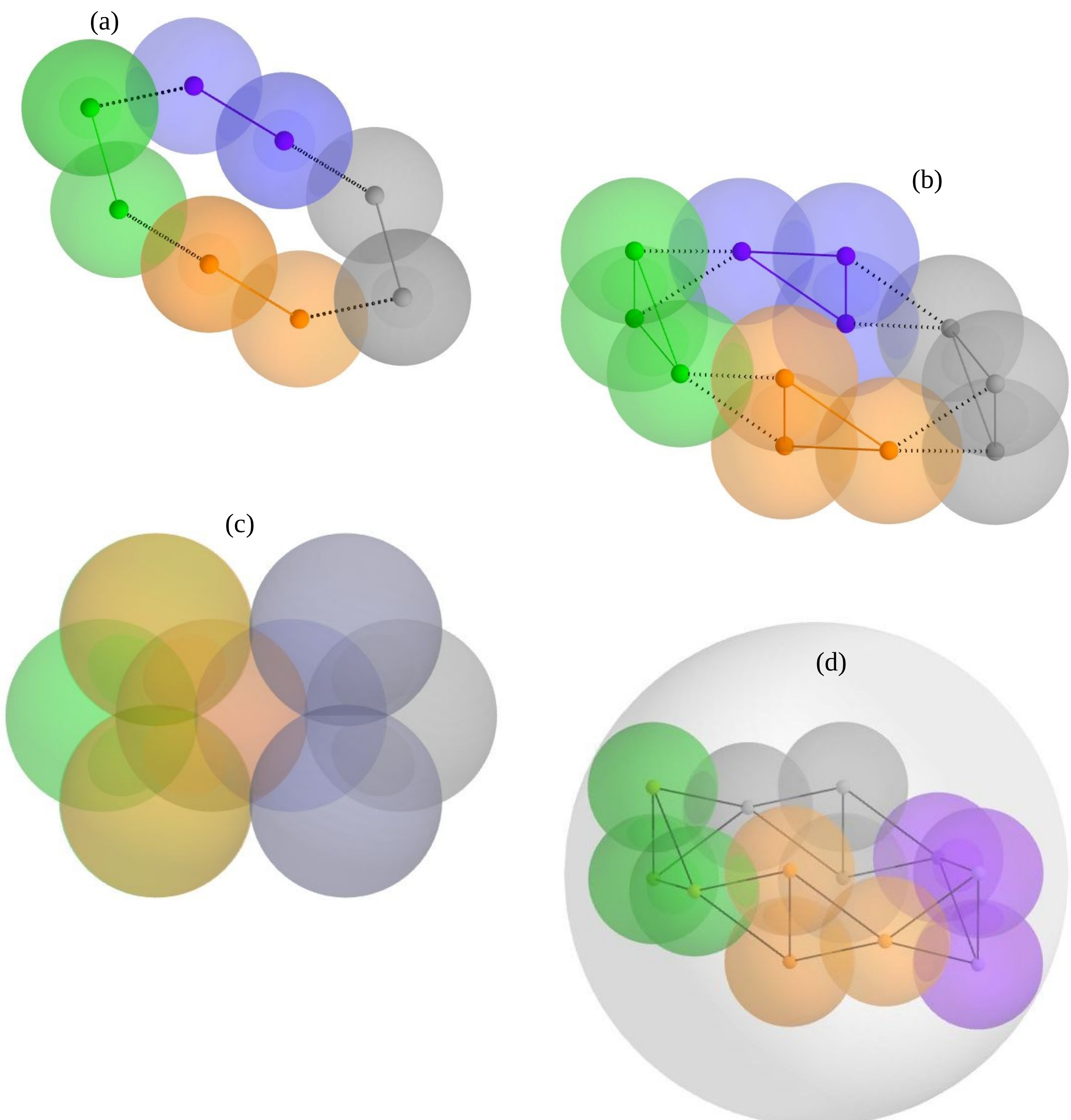


The complete spatial location of the 12 quarks is presented in Fig.8 below. All quarks are bound in a 1:2 fashion producing an 8-membered ring with an oval octagon shape. It can be seen that the structure is closely compacted, resulting indeed in a high BE per nucleon, even though it does not present a high degree of symmetry. As the matter of fact, one would expect a higher level of symmetry for a small structure with a high BE per nucleon.

Of great interest is the close proximity of quark color fields on each side of the median virtual line. This vicinity is such that the four nuclear skins ought to be interpenetrating each other.

Figure 8: Compact quark network in ^{4}He nucleus

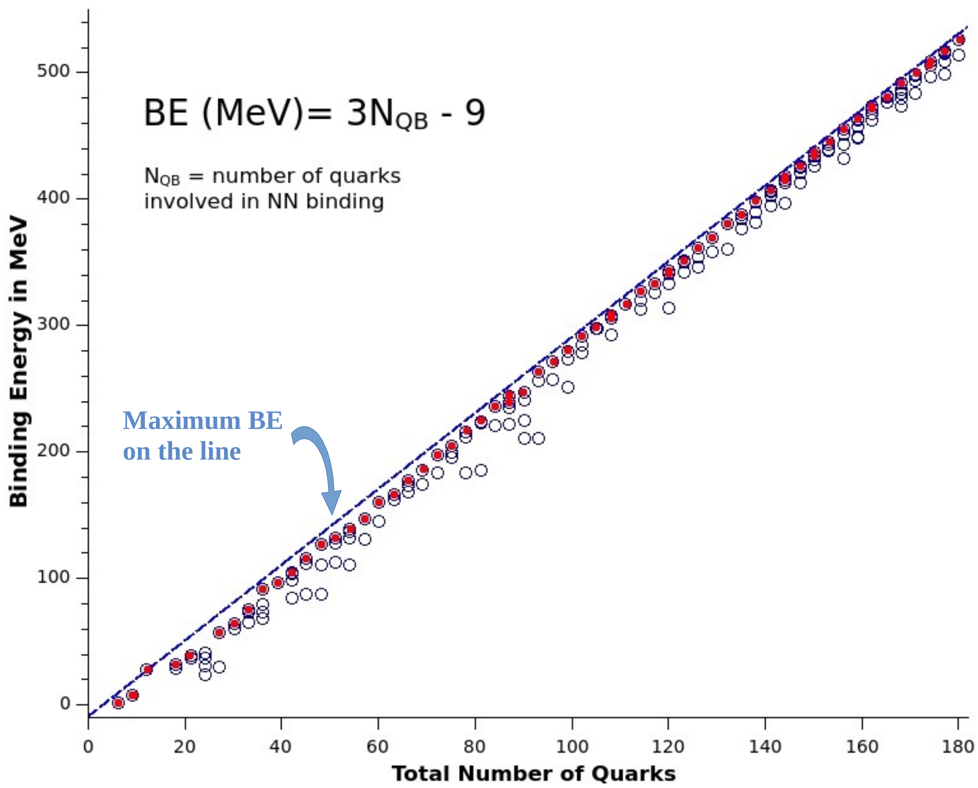
(a) Top view
(b) 3-D quarks network
(c) Compact view obtained by rotation around the z-axis of a lateral view (side view)
(d) Quarks in ^{4}He nucleus, (≈ to scale)



6. QQ binding in heavier nuclei

The three precedent structures for ^{2}D, ^{3}He / ^{3}T, and ^{4}He nuclei reveal that without a proper understanding of the chemistry of quarks, the QQ binding network within a particular nucleus remains unpredictable. The BE of a nucleus is directly proportional to the number of quarks involved in NN binding, at least up to about A≈60. Other factors arise as A grows beyond this value. This direct relationship maybe noticed in Fig.9. When all quarks are involved in NN binding, the BE of a particular nucleus would coincide with the straight line, as it is the case for ^{4}He. Further, stable nuclei (red dots) are closer to the line than unstable nuclei, expressing the fact that stable nuclei have a higher fraction of quarks involved in NN binding.

Figure 9: BE as a function of quarks involved in NN binding in nuclei up to A≈60. Stable nuclei (with red dots) are closer to the line.



From the relationship in Fig.9, the fraction of quarks involved in NN biding can be deducted as

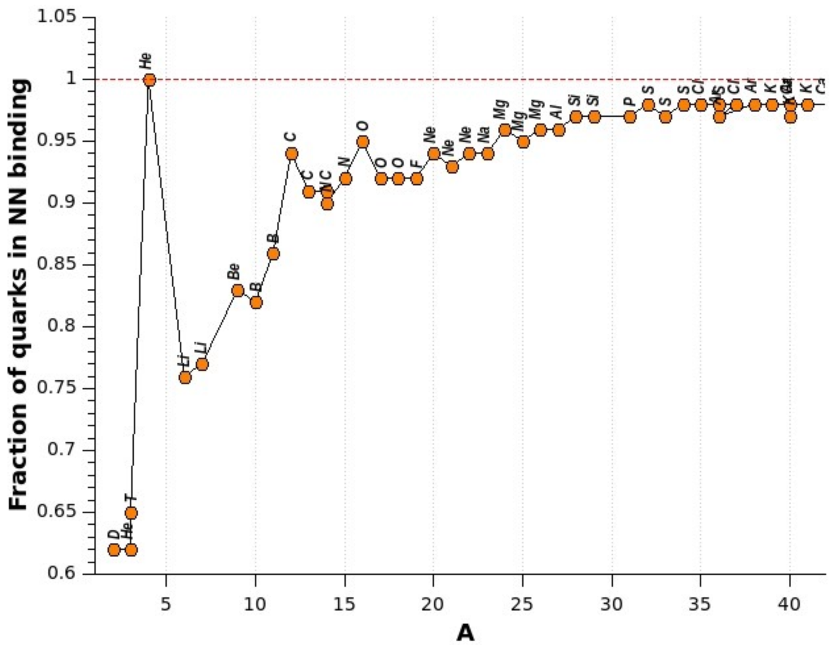
$$\frac{N_{QB}}{N_Q} = \frac{BE+9}{3N_Q}$$ with N_{QB}= number of bound quarks and N_Q=total number of quarks

This fraction, which is graphically presented in Fig.10 for mass numbers up to 40, confirms that ^{4}He, and to a lesser extent ^{12}C and ^{16}O nuclei, present the highest bound quark network amongst light nuclei. The values of N_{QB} can be of significant help for elucidating quark networks in nuclei. Further and as expected, the ratio gets naturally closer to 1 as A increases. Of interest, the fractions found for deuteron and helion are very close to φ^{-1} with φ = golden ratio.

Table 1: Fraction of quarks involved in NN binding in some light and stable nuclei

	^{2}D	^{3}He	^{3}T	^{4}He	^{6}Li	^{7}Li	^{9}Be	^{10}B	^{11}B	^{12}C	^{13}C	^{14}C	^{14}N	^{15}N	^{16}O	^{19}F	^{20}Ne
N_{QB}	3.74	5.57	5.83	12.4	13.7	16.1	22.4	24.6	28.4	33.7	35.4	38.1	37.9	41.5	45.5	52.3	56.5
N_Q	6	9	9	12	18	21	27	30	33	36	39	42	42	45	48	57	60
N_{QB}/N_Q	0.62	0.62	0.65	1.03	0.76	0.77	0.83	0.82	0.86	0.94	0.91	0.91	0.90	0.92	0.95	0.92	0.94

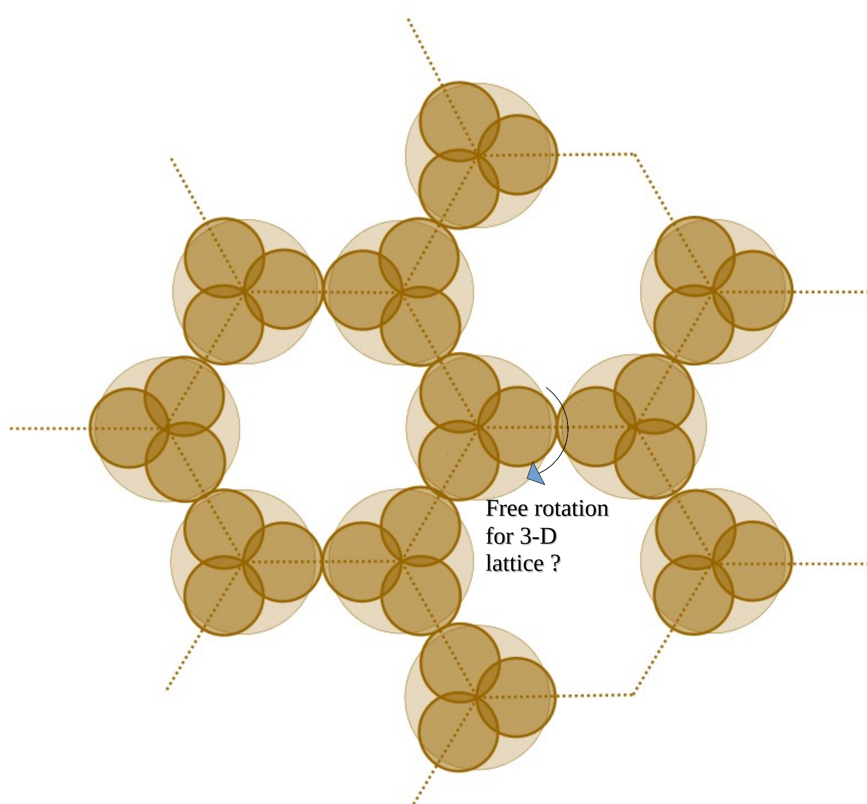
Figure 10: Fractions of quarks involved in NN binding for stable nuclei up to A≈40



7. Striving for hexagonal lattice ?

The planar geometry and 120° angles found in quark triads would perfectly fit a growing 2-D hexagonal lattice, as depicted in Fig.11. Considering that free rotation would be permitted along QQ bonds, this hexagonal network could extend into the euclidian space. However and as the mass number builds up, this lattice would, as such, quickly become inefficient due to low close-packing index.

Figure 11: Quarks triads perfectly fitting an hexagonal 2-D network



8. References

[1] M. Naghdi; "*Nucleon-Nucleon Interaction: A Typical/Concise Review*"; arXiv 0702078v4, revision 2014

[2] E. Ruiz; J.E. Amaro; R.N. Perez; "*NN scattering and NN Nuclear Uncertainties*"; Front. Phys., 28 Jan 2020

[3] *Nuclear force*, Wikipedia, https://en.wikipedia.org/wiki/Nuclear_force

[4] N.D. Cook; "*Models of the Atomic Nucleus*"; Springer, The Netherlands, 2006

[5] M.G. Meyer; J.H.D. Jensen; "*Elementary Theory of Nuclear Shell Structure*", Wiley, New York, 1955

[6] N.D. Cook; "*An FCC lattice model for nuclei*", Atomkernenergie 28, 195-199, 1976

[7] B.R. Galeffi; "*Stemming From Within The Nucleon, Quarks Are Thus Devoid Of Self-Existence*"; viXra:2101.0085 - online

[8] B.R. Galeffi; "*Angular Momentum Acquisition And Spiral Motion, A Requisite For Particle Creation. A Case Study: The Proton*"; viXra:1809.0594 - online

[9] B.R. Galeffi; "*The Spiral Proton By Numbers: Composite Angular Momentum, Mass Discrimination, And g-factor as 1*"; viXra:1901.0089 – online

[10] G. Musulmanbekov; "*From quark and nucleon correlations to discrete symmetry and clustering in nuclei*"; arXiv:1708.04437v2 - online

[11] Atomic mass adjustment, 18 Feb 2021, A=0-295 https://isospin.roam.utk.edu/public_data/nucmass/ame20/massround.mas20.txt

[12] International Atomic Energy Agency; https://www-nds.iaea.org/radii/