

An Alternating Quark Sequence Subnucleonic Structure of Stable Light Nuclei H-1 Through Li-7

Raymond J. Walsh*

ABSTRACT: The proposed subnucleonic structures of stable nuclei of H-1 through Li-7 incorporate an alternating up and down quark sequence (AQS) of equally spaced quarks around regular geometries. AQS nuclear models represent quark positions in the same way molecular ball and stick models represent the relative positions of atoms. In AQS, the ball identifies the center of quark mass and the stick length is constant and equal to the most recent radius of the proton (0.8414 fm). AQS radius predictions use accepted quark masses where necessary, and predictions demonstrate 99.3% average agreement (SD 4%) and statistical correlation of $\rho = 0.96$, $p < 0.001$, with accepted RMS charge radii. These results compare favorably to a close-packed nucleons model and a spherical nucleus model. A set of AQS parameters is included. Light nuclei tend to form ring structures corresponding to regular polyhedra, the smallest of which is the dodecagon structure of helium-4. Opposite quarks link nucleons to maintain a continuous sequence of alternating equally spaced quarks. Quark sequences may overlap so that protons overlap with neutrons. The more regular polyhedron structures of light nuclei yield better AQS radius predictions, whereas larger nuclei tend to be less regular and are thus less predictable (with the exception of the double overlapping octadecagon structure for the 36 quarks of C-12). The relative certainty in the accepted radius of helium-4, and its geometric relationship to the proton radius, allow a geometric solution to the “proton puzzle” yielding an AQS prediction for the proton radius of 0.8673 ± 0.0014 fm.

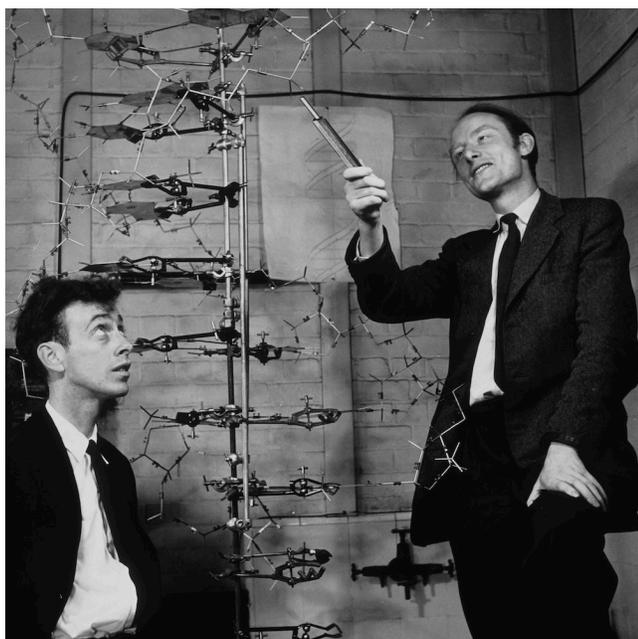


Figure 1. Molecular models represent the relative positions of atoms and are useful for communicating structure. Watson and Crick used the ball-and-stick molecular model shown above to elucidate the structure of DNA. Photo credit A. Barrington Brown, Science Photo Library.

■ INTRODUCTION

The fine tradition of the Ball-and-Stick Model dates back a century and a half,¹ and today no chemistry classroom is com-

plete without it. Though crude and simplistic, it has been an invaluable aid in helping chemists communicate molecular structure. Watson and Crick famously used ball-and-stick models to work out the structure of the double helix, including its specific ratio of base pairs and the unique x-ray crystallographic pattern.² Black and white photos from the era show the DNA model winding above the jocular pair, a testament to their towering achievement.

Traditional ball-and-stick molecular models, such as those used by Watson and Crick, are representational and are useful for conveying the relative positions of atoms within a molecular structure. The first molecular model was unveiled by von Hofmann in 1861 to illustrate the relative positions of hydrogen and carbon in a molecule of methane.¹ This model appears in the history of chemistry over a half century before Lewis dot structures would indicate a role for electron pairs in the bonding of atoms,³ and three quarters of a century before Linus Pauling would explain the quantum mechanical attractive forces holding these atoms in relative position.⁴ Von Hofmann demonstrated that purely structural or positional information can be useful, and positional information was certainly instrumental in leading Watson and Crick to the structure of DNA.

Running parallel to the elucidation of DNA, scientists were refining methods of probing the size and nature of the atomic nucleus. Ernest Rutherford discovered the nucleus by focusing alpha particles at a thin sheet of gold foil.⁵ Beams of electrons were later used instead of alpha particles to further define the nucleus. This process, known as deep inelastic scattering (DIS), not only revealed the size and shape of nuclei but also uncovered the existence of quarks and their strange fractional charges: $+\frac{2}{3}$ for the up quark and $-\frac{1}{3}$ for the down quark.

Each nucleon has 3 quarks: two up and one down for the proton yields a charge of +1, one up and two down for the neutron yields a charge of 0.

The discovery of the quark sparked an interest in quark models of the atomic nucleus, but none have entered the main stream. As the late Norman Cook puts it: "In principle, a rigorous quark (parton) theory should underlie all of nuclear physics and eventually allow for the deduction of the relatively macroscopic properties of the nucleus on the basis of a more microscopic particle theory. Since the late 1970s, various models of the quark contribution to nuclear physics have been suggested ...but have not yet had a major influence on the traditional issues of nuclear structure theory."⁶ While awaiting consensus on a comprehensive theoretical model, a limited representational model based on an alternating and equally spaced sequence of up and down quarks (AQS) within simple regular polyhedra appears consistent with experimental RMS charge radii.

The scope of this paper is limited to the elements of greatest interest to nuclear fusion theory, including the seven stable isotopes of hydrogen, helium, and lithium. Progress in the emerging field of low energy nuclear reactions (LENR) has been inhibited by lack of a viable theory,⁷ and a viable structural model might be helpful. In hot fusion the role of kinetic energy is central to overcoming the Coulomb barrier.⁸ A three-dimensional nuclear structure might reveal theoretical roles for rotational and vibrational kinetic energy in addition to the implied role of translational kinetic energy.

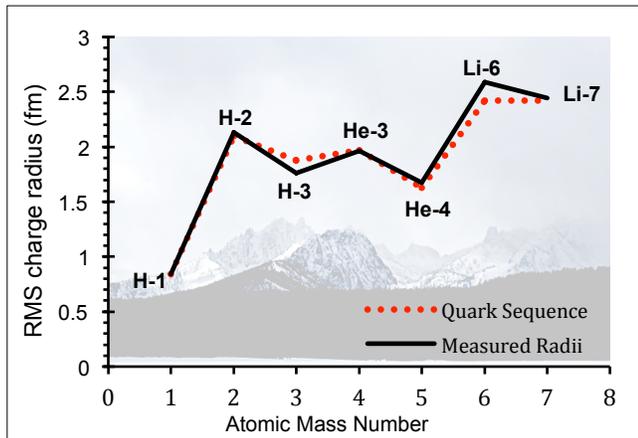


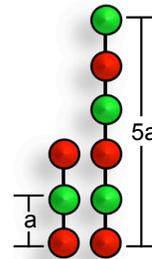
Figure 2. Correlation of the Alternating Quark Sequence model (red dots) with the measured root mean squared (RMS) charge radii of the first seven stable nuclides (black line). The plot resembles the Sawtooth Mountains of Central Idaho (background photo credit the author).

In general, the nuclear radius increases with mass number in predictable curvilinear fashion for elements above lithium-7. The graph of lighter elements resembles the Sawtooth Mountains of Central Idaho (Figure 2). An alternating sequence of equally spaced quarks (AQS) can account for this saw tooth profile using a set of ball-and-stick models. The ball will represent the center of quark mass and the stick length is constant and equal to the radius of the proton. As a predictor of size and structure, AQS compares favorably with two other familiar representational models of the nucleus, namely close-packed protons and neutrons, and the more simplistic nucleus as a single sphere.

RESULTS AND DISCUSSION

A central premise of AQS is that quark number determines nuclear structure. The number of up and down quarks within each nuclide is known from the number of protons and neutrons. The goal of AQS is to arrange the quarks of each nuclide into simple geometric shapes that best account for the measured RMS charge radius of each nuclide. A set of parameters for constructing AQS ball and stick models will follow.

Consider the first two stable nuclides. The proton, H-1, has an RMS charge radius $r = 0.84$ fm.⁹ The deuteron, H-2, has both a proton and a neutron. The two nucleons are roughly the same size so one might expect the deuteron to have a radius double that of proton ($2 \times 0.84 = 1.68$ fm). In fact, the measured RMS charge radius of the deuteron is much larger: $r = 2.13$ fm.⁹

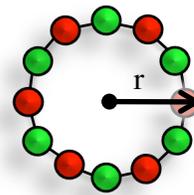


H1 H2

This numeric puzzle is more easily solved with a diagram. Red circles are up quarks and green circles are down quarks. The distance a is the distance between adjacent quarks. The predicted radius of the proton is half the distance from end to end. In this model, the center of the proton corresponds to its central down quark. Thus the interquark distance a is equal to the radius of the proton (0.8414 fm).

The distance a is also the distance between adjacent quarks in the deuteron.

From the picture it is evident that the radius r_d of the deuteron is $2\frac{1}{2}$ times the radius of the proton r_p . The product of $2\frac{1}{2} \times 0.84$ fm is 2.10 fm, representing 99% agreement with the experimental RMS charge radius of deuteron (2.13 fm). AQS is able to reconcile the anomalous size difference between the proton and deuteron only if 1.) Quarks are arranged sequentially, and 2.) Adjacent quarks are spaced 0.8414 fm apart. These are the first two parameters of AQS, and they hold for the other nuclides as well.



He-4

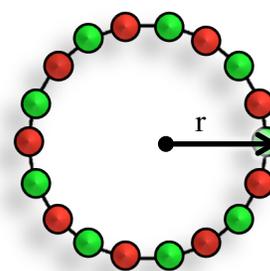
Helium-4 ($r_{He4} = 1.68$ fm)¹⁰ has twice the nucleons as the deuteron ($r_d = 2.13$ fm) but is significantly smaller. To account for this size discrepancy the 12 quarks of He-4 are arranged according to AQS in a regular dodecagon having sides $a = 0.8414$ fm (equivalent to the radius of the proton). The black arrow represents the calculated radius r . The black dot at the origin of the arrow represents the center of mass in this and subsequent drawings.

The helium-4 radius r is related to a according to the formula:

$$(1) \quad r = \frac{a}{2} \csc\left(\frac{\pi}{12}\right)$$

In this case $r = 1.63$ fm, representing 97% agreement with the measured He-4 radius of 1.68 fm.

The AQS ring structure of He-4 is consistent with model-independent analysis by J.S. McCarthy, et al, of electron scattering data that shows a significant central depression or hole in the nuclear matter distribution of He-4 (and He-3



as well) within a radius 0.8 fm.¹¹

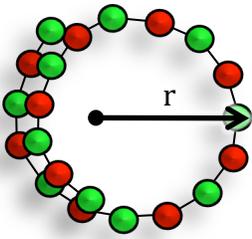
The dodecagon structure of helium-4 illustrates a third parameter: Since the vertex angle of a dodecagon is 150°, and there are no smaller circular structures in the AQS model, the lower limit of flexure of three sequential quarks is approximately 150°. (In the AQS Corrections section below it will be shown that this angle may be as low as 145.4°.) This angle results in a relatively high number of quarks per unit volume compared to heavier nuclides.

In similar fashion, the 18 quarks of Lithium-6 (2.59 fm)¹⁰ form a regular octadecagon (18-gon). The lithium-6 radius *r* is related to *a* according to the formula:

$$(2) \quad r = \frac{a}{2} \csc\left(\frac{\pi}{18}\right)$$

The calculation yields an AQS predicted radius for Li-6 of *r* = 2.42 fm, representing 95% agreement with experimental. This value improves with correction (see below).

The measured RMS charge radius of Li-7 (2.44 fm)¹⁰ is smaller than Li-6 (2.59 fm). The experimental value of Li-7 fits with a pentadecagon (15-gon) structure with six quarks overlapping (aka a split ring). The lithium-7 radius *r* is related to *a* according to the formula:



Li-7

$$(3) \quad r = \frac{a}{2} \csc\left(\frac{\pi}{15}\right)$$

Again assuming a distance between neighboring quarks *a* = 0.8414 fm (equivalent to the radius of the proton), the circumradius *r* of the 15-gon is 1.98 fm, woefully short of the experimentally determined RMS charge radius of 2.44 fm for lithium-7.

The overlapping ends, however, shift the center of mass (*cm*) towards the overlapping strands and away from the geometric center of the 15-gon according to the standard three dimensional center of mass formula:

$$(4) \quad \begin{aligned} x_{cm} &= (x_1 m_1 + x_2 m_2 \dots + x_n m_n) / (m_1 + m_1 \dots + m_n) \\ y_{cm} &= (y_1 m_1 + y_2 m_2 \dots + y_n m_n) / (m_1 + m_1 \dots + m_n) \\ z_{cm} &= (z_1 m_1 + z_2 m_2 \dots + z_n m_n) / (m_1 + m_1 \dots + m_n) \end{aligned}$$

where points (*x_n*, *y_n*, *z_n*) represent the Cartesian coordinates of each quark, and *m_n* represents quark mass. An up quark has a mass *m_u* = 2.16 MeV and a down quark a mass of *m_d* = 4.67 MeV.¹²

The distance between overlapping strands is assumed to be 0.898 fm¹³, the average distance between the nucleons within stable isotopes according to the International Data Committee.¹ The calculated center of mass, including *x*, *y*, and *z* components, is 2.42 fm from the farthest quark on the opposite side. This prediction is within 1% of the measured RMS charge radius of 2.44 fm.

The ring structures of helium-4, lithium-6 and lithium 7 illustrate additional parameters: 4.) up and down quarks

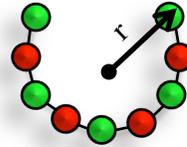
alternate, 5.) nucleons are linked by opposite quarks to maintain a continuous quark sequence, and 6.) quark strands may link indirectly or overlap in such a way that opposite quarks align and protons overlap with neutrons, and 7.) quark sequences tend to form ring structures.

He-4 and Li-6 form closed ring structures with paired up and down quarks. This is only possible if nucleons are also paired: He-4 pairs two protons with two neutrons, while Li-6 pairs three protons with three neutrons.

Li-7 underscores the assertion that closed ring structures cannot form when the number of up quarks does not equal the number of down quarks. Put another way, a ring structure cannot have an odd number of quarks because like quarks cannot link. Any quark ring structure having an odd number of quarks would require at some point in the ring that a down quark link with a down quark, or an up quark with an up quark.

If up quarks may link only link with down quarks, then circular structures must have an even number of quarks up and down quarks. This implies that the ring would also have an equal number of protons and neutrons. Helium-5 has 15 quarks and is not stable. Its half life is measured in attoseconds. By comparison, the blink of an eye would be like the age of the universe. Perhaps the reason is that a closed ring structure with 15 quarks would require a connection between like quarks, and this may not be possible.

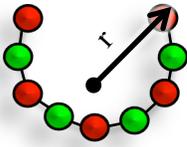
The accepted RMS charge radii for H-3 and He-3 are 1.76 fm and 1.97 fm respectively.¹⁰ These values are greater than He-4 (1.68 fm) but less than H-2 (2.13 fm). A linear structure for the nine quarks of H-3 and He-3 would result in excessively large radius predictions for each, but a circular arrangement (a nonagon) yields a circumradius of 1.23 fm, which is problematically small. A closer estimate of measured RMS charge



H-3

follows from a “U” shape.

The AQS proposed “U” shape for H-3 and He-3 are similar. Both H-3 and He-3 have nine alternating up and down quarks. The “U” structures follow from an arrangement of the nine quarks of each around the vertices of a dodecagon (12-gon) leaving 3 vertices unoccupied. The difference is that H-3 begins and ends with a down quark, while He-3 begins and ends with an up quark.



He-3

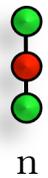
The alternation of quarks affects the center of mass. The two down quarks at the ends of H-3 versus the two up quarks at the ends of He-3 significantly alter the (*x*,*y*) coordinates of the respective centers of mass (*cm*) according to the center of mass formulas above. (The *z*-component is not required as the proposed structures are planar.)

¹³The average distance between nucleons of 0.898 fm (SD 0.0585) assumes the charge distribution has a finite surface thickness, yielding a better “goodness-of-fit” than the assuming a uniform charge distribution yielding average distance 0.954 fm (SD 0.13).¹³

Structural Models and Predicted Radii of Light Nuclei (fm)								
Light Nuclides (measured radius)	H-1 (.841)	H-2 (2.13)	H-3 (1.76)	He-3 (1.97)	He-4 (1.68)	Li-6 (2.59)	Li-7 (2.44)	Average % agreement
Spherical Nucleus (% agreement with measured radius)	 1.25 (149%)	 1.57 (74%)	 1.80 (102%)	 1.80 (91%)	 1.98 (118%)	 2.27 (88%)	 2.39 (98%)	103% (SD 24%)
Close-Packed Nucleons (% agreement) ● = proton ○ =neutron	 0.841 (100%)	 1.68 (79%)	 1.82 (103%)	 1.82 (92%)	 1.87 (111%)	 2.30 (89%)	 2.27 (93%)	95% (SD 11%)
Alternating Quarks (% agreement) ● = up quark ● =down quark	 0.841 (100%)	 2.10 (99%)	 1.88 (106%)	 1.97 (100%)	 1.63 (97%)	 2.42 (93%)	 2.46 (101%)	99% (SD 4%)

Figure 3. A representation of the atomic nucleus as an alternating quark sequence produces better average percent agreement and lower percent standard deviation (SD) with experimentally determined radii of light nuclei when compared to representational models that assume the nucleus is a sphere sans substructure, or a dense amalgam of close-packed protons and neutrons.

The centers of mass of H-3 and He-3 are not the same because the down quark is nearly twice the mass of the up quark: A down quark has a mass of $m_d = 4.67$ MeV and an up quark has a mass $m_u = 2.16$ MeV and. (These quark masses are estimates and may vary as much as 20%.¹²) This mass difference results in a slight shift in the centers of mass, which in turn results in differing radius predictions for H-3 and He-3. The AQS calculated radius of H-3 is $r = 1.875$ fm (107% agreement), and for He-3 $r = 1.969$ fm (100% agreement).



Finally, for the sake of completeness, a structure for the neutron is included. This structure is similar to the sequential arrangement of quarks within a proton, but positions an up quark between two down quarks. This structure is consistent with experimental charge density results that indicate the neutron has a positive core and negative skin.^{14,15}

STATISTICAL ANALYSIS

The purpose of statistical analysis is to quantify how well the alternating quark sequence model fits with experimentally determined nuclear radii, and to rule out the possibility that model predictions are a result of coincidence or chance.

Figure 3 below compares the percent agreement between representational models and measured RMS charge radii of the light nuclei of interest to nuclear fusion. Of the three representational models, AQS demonstrates the highest average % agreement with measured RMS charge radii (99.3% with a standard deviation of 4%). A weaker assumption is that the nucleus comprises close-packed protons and neutrons (average percent agreement 95% with a standard deviation of 11%).

The weakest structural assumption is that of a completely spherical nucleus with no substructure (average percent agreement of 103% with a standard deviation of 24%).

Percent agreement is a useful method of comparing the proposed structures of two individual nuclides, and the average percent agreement is helpful in comparing the three representational models. Correlation coefficients, however, are a preferred way to compare sets of paired data as they include a measure of statistical significance, as shown in Table 1.

Table 1. Statistical Correlation Between Measured and Predicted Light Nuclear Radii for Three Nuclear Models.

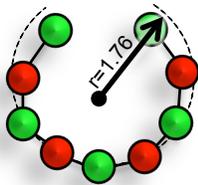
	Pearson's r	Spearman's ρ	Kendall's τ
Alternating Quarks	.99 ($p < .001$)	.96 ($p < .001$)	.90 ($p = .003$)
Close-Packed Nucleons	.93 ($p = .002$)	.67 ($p = .10$)	.49 ($p = .13$)
Single Sphere Nucleus	.82 ($p = .02$)	.63 ($p = .13$)	.39 ($p = .22$)

Of the three representational nuclear models, AQS best predicts the experimentally determined RMS charge radii of the first seven stable light nuclei. Pearson's r , Spearman's ρ , and Kendall's τ are three different methods of determining correlation coefficients, which indicate how well two sets of paired data correlate. AQS coefficients are .90 or greater, indicating very strong to near perfect correlation, and at the highest levels of statistical significance. The radius predictions

generated by close packing of nucleons and spherical nucleus models show weaker correlation and statistical significance.

■ AQS CORRECTIONS

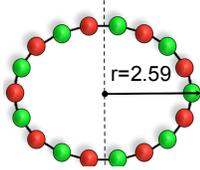
A central assumption of the alternating quark sequence model is that quark sequences assume simple geometric shapes, and the best fit between the AQS model and accepted radii occurs when this assumption is true. However, the proposed AQS models of H-3, He-4, and Li-6 may deviate from regular polyhedron structures, as the agreement in each of these three cases is greater than 1%. Simple corrections may bring the predictions in line with the experimental.



Corrected H-3

The assumed regular polyhedron for H-3 a regular dodecagon having vertex angles equal to 150° . The quarks occupy 9 of 12 vertices to form an open-ended “U” shape as illustrated. The AQS predicted radius of 1.875 fm overestimates the accepted radius of 1.76 fm by $>6\%$. Narrowing the vertex angles from 150° to 145.4° for the 9 occupied vertices, however, brings the predicted radius into 100% compliance with the accepted H-3 radius of 1.76 fm.

The statistical correlations determined above are predicated upon circular structures for He-4 and Li-6 that correspond to perfect regular polyhedra. The difference between predicted and measured radii, however, may indicate more of an oval shape.



Corrected Li-6

For example, the AQS predicted radius of Li-6 (2.42 fm) underestimates the measured value of 2.59 fm by 7%. The agreement between predicted and experimental improves by assuming a measure of flex in the circular structure that allows the circle to deform into an oval. The corresponding oval would have a

slightly greater distance from center of mass to furthest quark, thus bringing the predicted radius into compliance with the experimental radius.

A similar line of reasoning may be applied to the dodecagon of He-4. AQS predicts a radius of 1.63 fm which underestimates the measured value of 1.68 fm by 3%. He-4 ring flex into an oval would likewise bring the AQS predicted radius into compliance with measured RMS charge radii values.

■ AQS LIMITATIONS

For the stable elements H-1 through Li-7, the radius to mass number curve is erratic and resembles the Sawtooth Mountains. AQS radius predictions of these light nuclei assume quark arrangements around regular polyhedron structures as discussed previously.

For mass numbers above $A = 7$, the assumption of a subnucleonic structure comprising an alternating sequence of equally-spaced quarks may still hold true, but the power of AQS to predict the nuclear radius diminishes as nuclear quark geometries become less regular with increasing mass number.

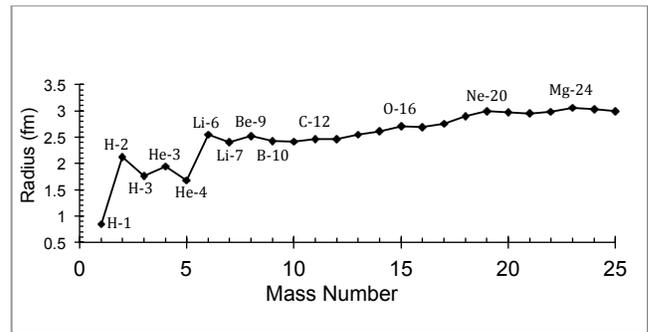


Figure 4. Nuclear radius versus mass number

For nuclear radii above Be-9, the radius to mass number curve is roughly linear, and the radius r is more amenable predicted by the number of nucleons in terms of the formula:

$$(5) \quad r = A^{1/3} R_0$$

where A is the mass number and R_0 is 1.25 ± 0.2 fm. (This formula was used to calculate the radii of the spheres in Table 3.)

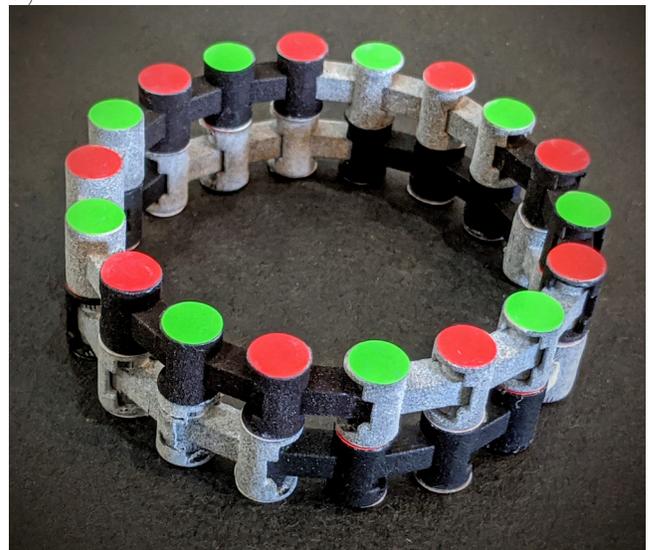


Figure 5 “Ball-and-Stick” scale model of carbon-12. The 36 quarks of C-12 are arranged as a stacked pair of 18-gons. Down quarks (green dots) alternate with up quarks (red dots), and protons (sequence of 3 black links) alternate with neutrons (3 grey links). The 18-gons stack so that protons overlap neutrons.

A notable exception may be found in the structure of carbon-12, a diamond in the rough. The framework for the 36 quarks of C-12 is a stacked pair of regular 18-gons. The regular polyhedron structure allows an AQS predicted radius of 2.464 fm, representing 99.7% agreement with the experimental RMS charge radius of 2.4702 fm.¹⁰ One octadecagon is stacked on top of the other and separated by 0.898 fm, consistent with the separation of overlapping strands proposed for the structure of Li-7 above. Just as in Li-7, alternating quark sequences between the pair of 18-gons associate in such a way that opposite quarks overlap, and protons overlap with neutrons.

■ AQS AND THE PROTON PUZZLE

The “proton puzzle” refers to the differences in proton radius measurements obtained by various investigative teams over the last decade.¹⁶ Measurements that employ high-energy

electron beams yield results 4% larger than measurements that employ beams of muons.

AQS provides a geometric means of weighing in on the puzzle. While measurements of the proton may vary depending on the type of charged particle beam probe (electron vs. muon), measurements of the helium-4 radius appear largely independent of the beam type. Of the stable light nuclei hydrogen-1 through boron-11, the uncertainty in the measurement of helium-4 is the smallest at 0.0028 fm,¹⁰ even though the reported average radius incorporates both electronic and muonic measurements.¹⁸ At a time when the radius of the proton has been so uncertain as to be called a puzzle, the measurement of the helium-4 radius is comparatively certain.

The geometric relationship between helium-4 and proton radii allows a geometric estimate of the size of the proton. As outlined above, the 12 quarks of helium-4 are arranged as a regular dodecagon (12-gon) with 12 equal sides of length a , which equals the radius of the proton. The helium-4 radius r is related to side a according to formula (1) above. Solving formula (1) for a produces formula (6):

$$(6) \quad a = 2r / \csc\left(\frac{\pi}{12}\right)$$

Substituting the accepted helium-4 radius $r = 1.6755 \pm 0.0028$ fm⁸ into formula (6) yields a geometric prediction of the proton radius equal to 0.8673 ± 0.0014 fm. (The distance between quarks a is equal to the proton radius in the AQS model). This geometric prediction falls within the range of the last two CODATA recommended values of the proton radius, namely 0.8414 fm from CODATA 2018⁹ and 0.8751 fm from CODATA 2014.¹⁷

■ AQS BALL AND STICK MODELS

The fusion reaction is shown in nearly every freshman chemistry text as the uniting of two small clusters such as H-2 and H-3 to yield a larger cluster H-4, a neutron, and energy.⁸ This depiction persists even though the quark is the most elemental unit of the nucleus, not the proton or neutron. The same fusion reaction may be depicted in AQS:

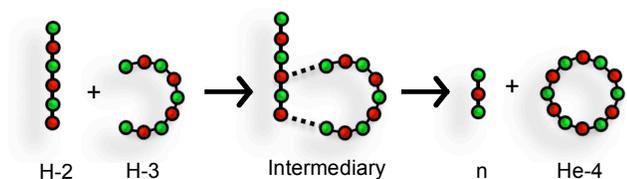
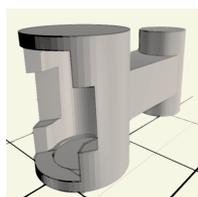


Figure 6. Nuclear fusion of H-2 and H-3.

The intermediary illustrates how H-2 and H-3 might combine in such a way as to form alternating sequences of quarks in He-4 and a neutron. This is very similar to how molecular model kits are used to illustrate simple organic chemistry reactions.



3D-print quark

Nuclear structures and reactions may be demonstrated with 3D-printed models. These models were designed as an updated ball-and-stick, representing the relative positions of quarks consistent with the parameters of AQS. 3D-printed quark pieces snap together to maintain a fixed quark-to-quark distance of 2cm, as shown by the model of carbon-12 in Figure 5. The quark design prohibits flexure less than 150°, the

vertex angle of the 12-gon of He-4. The .stl files (3-D print files) are available for free download on tinkercad, and nylon is the material of choice.¹⁹

Conclusion

The Alternating Quark Sequence model of the atomic nucleus represents a statistically significant correlation with measured RMS charge radii of light nuclei H-1 through Li-7 according to the parameters listed in Table 2. The geometric and center of mass calculations are readily verified within a couple of hours with a calculator and access to the internet.

Table 2. AQS Parameters.

<u>AQS Parameters</u>	
I.	Quarks are linked sequentially.
II.	The distance between adjacent linked quarks equals the radius of the proton.
III.	The limit of flexure of any 3-quark sequence is approximately equal to 150°, the vertex angle of the dodecagon of helium-4.
IV.	Up quarks alternate with down quarks in a quark sequence.
V.	Nucleons may directly link by opposite quarks to maintain a continuous sequence of equally spaced quarks.
VI.	Quark sequences may indirectly link or overlap so that protons overlap with neutrons.
VII.	Quark sequences tend to form ring structures.

AQS models represent the relative positions of quarks but not the forces that maintain these positions. In this way, AQS is similar to the molecular models that van Hoffmann presented decades before the discovery of the electron, proton, and neutron,¹ and well before Pauling's quantum mechanical wave equations would justify the forces maintaining atoms within molecules.⁴ Watson and Crick demonstrated the power of atomic positional information in the elucidation of the structure of DNA.²

The power of the AQS model to predict nuclear radii is strongest when the constituent quarks take on regular geometric shapes. This is especially true of light nuclei. For heavier nuclei, the parameters outlined in Table

The future role of AQS may be akin to the role of Lewis dot structures, a simple representational model that provides useful but limited information.³ Although the current treatment is limited to light nuclei, AQS may have application to outstanding questions regarding the structures of medium and heavy nuclei. AQS may inform the relationship between subnucleonic structure and other nuclear properties, including charge density, magnetic moment, the nucleon pairing

phenomenon, the structural role of neutrons in stabilizing heavier nuclei, and the strong nuclear force. Theories of alpha and beta decay may also benefit from the limited structural information provided by the AQS model.

AUTHOR INFORMATION

*Raymond J. Walsh
3556 N Lena Ave
Boise, Idaho 83429

ACKNOWLEDGMENTS

A hardy thanks to Dr Hadley Reed for his steady moral and technical support, thanks to Bill Cheman for his insightful recommendations as to the scope of content, thanks to Patrick McCormick, Laura Cromwell, Brian A. Ertz, and my son Christopher K. Walsh for reviewing the manuscript and providing feedback on readability, and finally thanks to Earl Swift for his contributions to style and composition.

REFERENCES

- Ollis, W. D. "Models and Molecules". *Proceedings of the Royal Institution of Great Britain*. 45: 1-31. (1972).
- Watson, J. D. *The Double Helix: A Personal Account of the Discovery of the Structure of DNA*. (1968) Atheneum.
- Lewis, G. N. *The Atom and the Molecule*. *J. Am. Chem. Soc.* 1916 38 (4), 762-785.
- Pauling, L. *The Nature of the Chemical Bond. Application of Results Obtained from the Quantum Mechanics and from a Theory of Paramagnetic Susceptibility to the Structure of Molecules*. *J. Am. Chem. Soc.* 1931, 53(4), 1367-1400.
- da C. Andrade, E. N. *Rutherford and the Nature of the Atom* (1964).
- Cook, N. *Models of the Atomic Nucleus*, 2nd edition, page 48.

- Ritter, S.K. *Cold Fusion Died 25 Years Ago, But The Research Lives On*. C&EN. Nov.7, 2016.
- Flowers, P., Theopold, K. *Chemistry LibreTexts*, Chapter 21.8: Nuclear Fusion - <http://cnx.org/contents/85abf193-2bd...a7ac8df6@9.110>.
- D. Newell, K. Pachuki. CODATA recommended values of the fundamental physical constants: 2018.
- Angeli, I. & Marinova, K. P. Table of experimental nuclear ground state charge radii: An update. *At. Data Nucl. Data Tables* 99, 69 (2013).
- J. S. McCarthy, I. Sick, and R. R. Whitney. Electromagnetic structure of the helium isotopes. *Phys. Rev. C* 15, 1396 - Published 1 April 1977.
- P.A. Zyla et al. (Particle Data Group), *Prog. Theor. Exp. Phys.* 2020, 083C01 (2020).
- Angeli, I. *5. Radius Formulae*. International Nuclear Data Committee, Table of Root Mean Square Radii, page 16. 1999.
- N. Cook. *Models of the Atomic Nucleus*, 2nd edition, page 131.
- Weitfeldt, F.E., et al. Measuring the Neutrons' Mean Square Charge Radius Using Neutron Interferometry. arXiv:nucle-ex/0509018v1. 14Sep2005.
- J. Karr, D. Marchand. Progress on the proton-radius puzzle. *Nature*. November 6, 2019.
- P. J. Mohr et al, CODATA recommended values of the fundamental physical constants: 2014, *Rev. Mod. Phys.* 88, 035009 (2016).
- Angeli, I. International Nuclear Data Committee, Table of Root Mean Square Radii, Appendix II, page 2. 1999.
- 3D print quark model .stl file may be downloaded at the tinkercad website by typing "Your Rayness quark model" in the search bar.

For Table of Contents only:

