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The architecture of nuclear binding energy

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Abstract

Nuclear binding energy is the best measured property of the atomic nucleus, but no previous model of the nucleus has accurately explained the experimental data for small nuclei. Current models either get the general shape of the curve right but the magnitudes wrong, or get closer to the magnitudes but deviate from the shape of the curve. We derive a new model of the binding energies of atomic nuclei largely free of these defects. Plausible internal structures of protons and neutrons deduced from their known properties lead to a natural physical interpretation of the mass defect. The structures of quarks internal to the particles determine two types of binding energy. These combine with electromagnetic forces to duplicate the binding energy of 12 isotopes from deuterium through carbon with correlation 0.999. Average absolute difference between the model and experimental data is 1.43%, compared with the next closest model at 10.95%.

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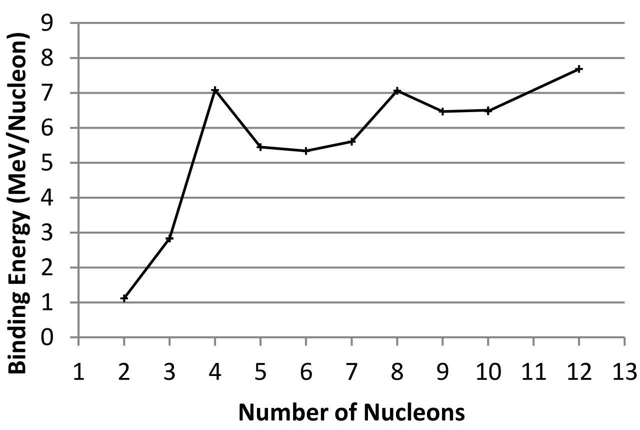
1. Introduction

When protons and neutrons combine into the nucleus of an atom, there is a loss of energy called the binding energy. It is equivalent to consider the loss of energy a loss of mass, in which case it is called the mass defect.

Consider deuterium, sometimes called heavy hydrogen. Its nucleus has one proton and one neutron. The mass of the deuterium nucleus is less than the mass of the two particles, and the difference is deuterium's mass defect or binding energy. (We shall use the terms mass defect and binding energy interchangeably.)

The binding energies of all isotopes are well known, but they exhibit a puzzling

Figure 1. Binding Energy of Small Atomic Nuclei



property most marked in the smaller nuclei: one might expect that as nucleons are added to the nucleus, the amount of binding energy would increase monotonically with each additional nucleon. But as Figure 1 shows, this is not the case.

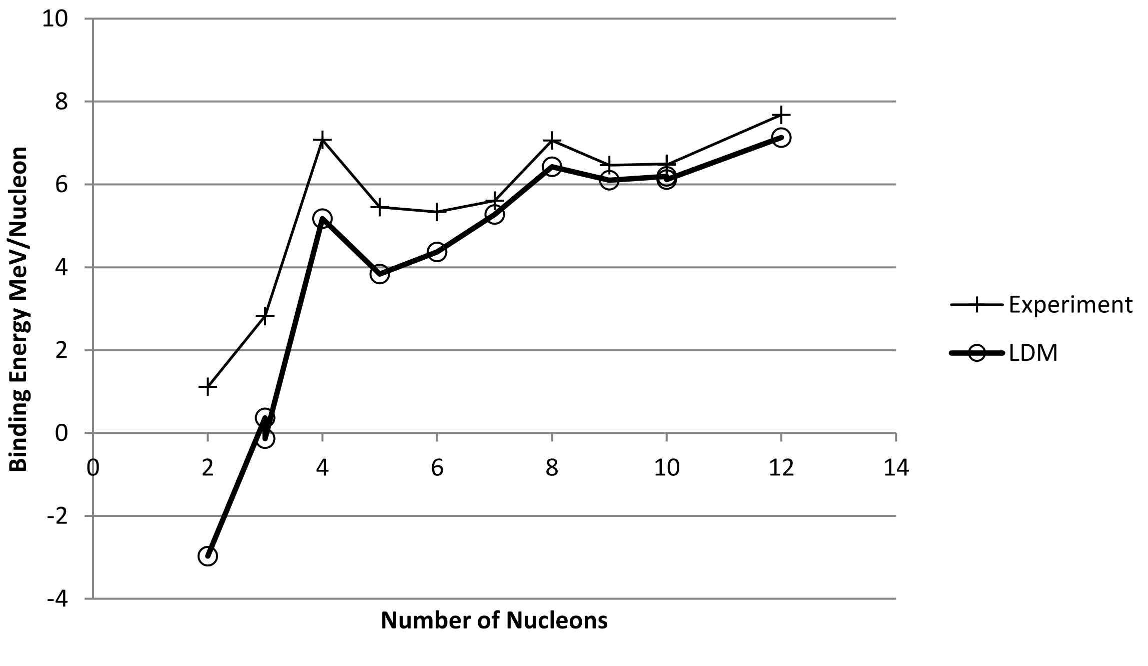
Figure 1 charts the experimental values for the binding energies of the first 12 isotopes, expressed as the amount of binding energy per nucleon. The values rise and then fall off, only to rise again. The cause of this variation has been the subject of extensive debate for decades.

There are several theories that explain various aspects of the experimental evidence on atomic nuclei. These are compared by Cook in detail in [1], and for a thorough and eloquent review there is no rival. In particular three theories have tried to explain the shape of Figure 1. These are the Independent Particle Model (IPM), the Liquid Drop Model (LDM) and the Face Centered Cubic Lattice Model (FCC.)

Mainstream nuclear theory *is* the Independent Particle Model, developed in the 1940's and formalized by Meyer & Jensen [2]. It attempts to explain Figure 1 by trying to explain the peaks. According to IPM these arise from the nucleons filling shells within the nucleus, similar to the filling of quantum shells by electrons. There are serious problems with this model, the largest being that it presupposes free travel by nucleons in the nucleus in a manner completely contradictory to all physical measurements [1]: there simply isn't room in the nucleus for nucleons to orbit about. However our problem with IPM is rather that despite its wide acceptance, it can say nothing quantitative about binding energy. Due to the total absence of any binding energy predictions from IPM, it need not concern us further in this context.

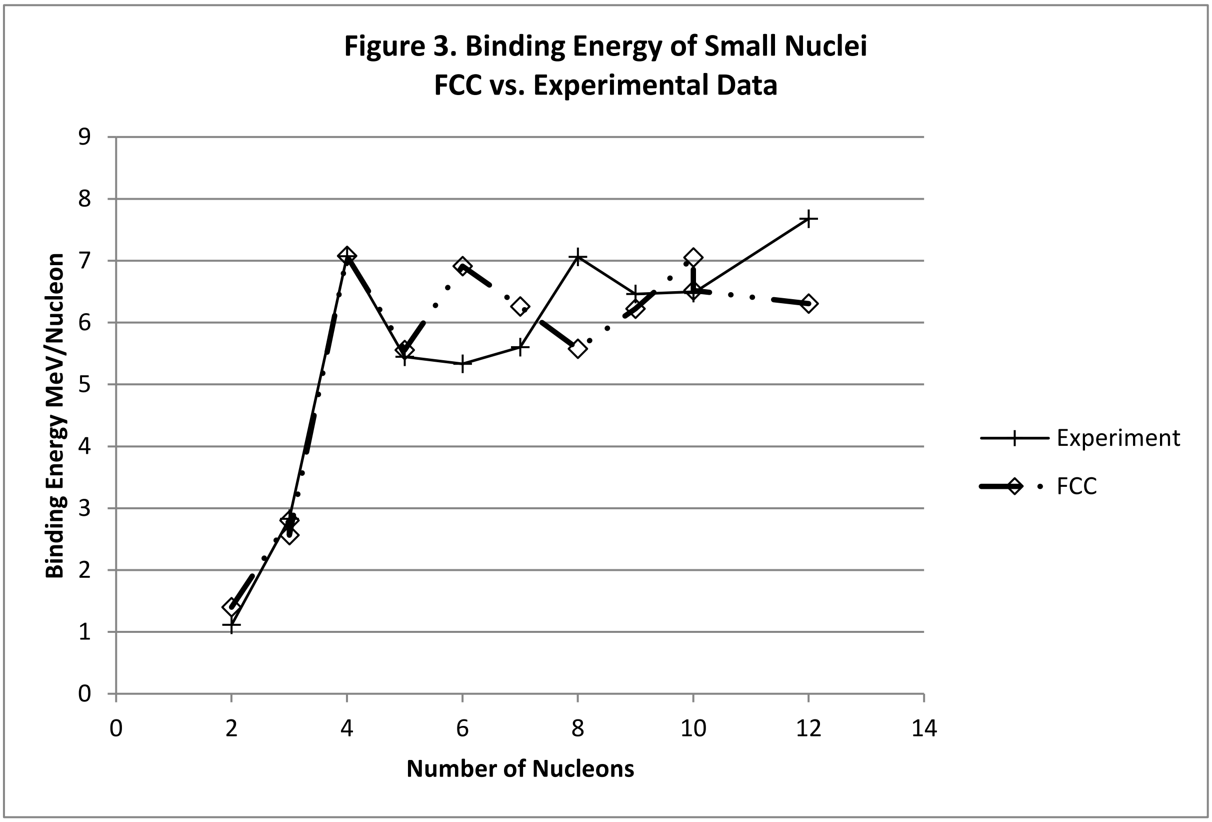
The Liquid Drop Model derives properties of the nucleus from analogy to a drop of liquid. This amazingly resilient model was first proposed by George Gamow in 1929. The model has been refined over the years, resulting in a match to the experimental data shown in Figure 2. (Data for Figure 2 are conveniently supplied by the NVS program of [1], republished there from public databases.)

Figure 2. Binding Energy of Small Nuclei
LDM vs. Experimental Data



As you can see, LDM shows an uncanny ability to match the shape of the experimental data, but the absolute error is relatively large, with an average absolute deviation from the experimental points of 55.918% (range 4.628% at ^{10}Be to 367.016% at ^{2}H.) Correlation is quite respectable at 0.981.

The Face Centered Cubic model was proposed by Cook in 1976 [3]. This model views the nucleons as bound in a face-centered-cubic lattice. Cook has shown that this structure duplicates all of the salient properties of the IPM without having to assume the nucleus has any physical properties contradicting known measurements. The binding energies of the FCC model are shown plotted with the experimental data in Figure 3 (data again supplied by NVS [1].)



FCC is a much better fit to the data than LDM, with average absolute deviation of 10.949% (range from 0.65% for ^{10}B to 29.65 for ^{6}Li.) Correlation however suffers, falling to 0.915.

Cook concludes:

> Ultimately the FCC nuclear model is still a model with adjustable parameters and plausible assumptions, rather than a formal theory built on first principles concerning the nuclear force. This is a weakness not unlike those of the other nuclear models—and one that eventually must be addressed. [1, p246].

This weakness is addressed in the following pages.

2. The New Physics

The New Physics (as we have come to call it) arose from an attempt to gain a clear understanding of the mechanism of gravitation [4, 5]. The New Physics shows how the natural size of each quantum level—the square of the integer quantum level times the radius of the first one—is a “home position” for the quantum level. When combined with the same quantum level of a second particle, they form a single quantum at the same level that attempts to restore to its home position. Gravitation is the result of the cumulative restoring forces of all the quantum levels between all the particles of both bodies. The inverse square law results.

The hypothesis of the New Physics is that when a particle is created, most of the energy in its creation goes into making a bubble in space, compressing the space outward that used to be where the particle now exists. This is analogous to placing a ball bearing into a block of foam. When a particle is created it pushes space back, cocking it like a spring. The restoring force of this spring is what has in previous models like the IPM and its derivatives been called the Strong Force.

When first encountered this concept is utterly foreign. Nonetheless (to paraphrase Cook's comment on the initial acceptance of the IPM) any science fiction is worth entertaining for a while if it leads to interesting results. Simply keep in mind that this is just another model, but one exceedingly instructive as we shall show. (If the idea of a bubble in space remains after due consideration incomprehensible, imagine instead a spherical balloon of very thin material.)

What, then, can we say about this bubble in space that we call a proton? For one thing we know it is mostly hollow. When a proton disintegrates in a collision with another particle, the only things that emerge are three quarks having together only 1% of the energy of the proton. Where does the other 99% of the formation energy of the proton go? The New Physics model says it goes into creating the bubble in space, cocking the Strong Force spring.

With two up quarks and one down quark forming the interior of a proton, nothing else inside, and space pressing in with considerable force, it is reasonable to assume that the quarks form a bracing structure that keeps the bubble in space from collapsing. This begs us suspend our disbelief for one further moment, and acknowledge that if this much were an accurate model of reality, then either space must have something like surface tension (or a balloon is installed), otherwise space would collapse inward around the quark structure.

3. Proton Structure

Can we say anything at all about the shape of this bracing structure? There are a number of constraints that any answer must meet:

1. A free neutron (outside the nucleus) decays in 14.75 minutes into a proton, an electron, an anti-neutrino (only 2 eV), and energy in the form of motion of these three particles.
2. The proton lives essentially forever, so must be highly stable.
3. The neutron must be demonstrably unstable compared to the proton.
4. The quarks that comprise protons and neutrons amount to only 1% of the mass of the particles they support.
5. A neutron is made up of two down quarks and one up quark.
6. A proton is made up of two up quarks and one down quark.
7. The down quark is about twice as large as the up quark.
8. When a neutron decays, one down quark becomes an up quark. This transition leaves a total of 2 up quarks and one down quark: a proton.
9. The quark combinations must be fairly strong and self-bracing to stand the considerable pressure from the compressive spring that is the surrounding space.
10. There must be some reason why the neutron has a long life within the nucleus, but a short life as a free particle.

And we must explain one more thing: the mass defect.

The New Physics would contend that when two particles are adjacent to each other in the nucleus, the pressure from spring of space would force their bracing structures to touch. If we visualize a bubble with an internal bracing structure, this could mean that the volume of the spherical cap that flattens when the bracing structures touch is the mass defect.

So our final constraint is this:

11. The spherical cap that is cut off when the bracing quarks of two particles are forced together must be equal to the binding energy of the resulting nucleus; said binding energy must also overcome any repulsive electrostatic forces.

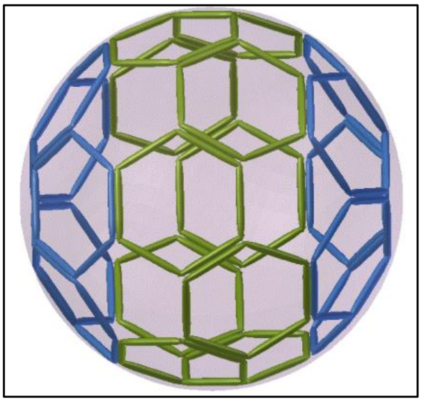


Figure 4. New Physics model of the proton, showing the bubble in space, two up quarks, and a down quark.

These constraints have led us to consider a variety of possible bracing structures. The best model we have found so far is the truncated icosahedron, also known as a buckyball, named after the famous geometrist Buckminster Fuller. The resulting model of the proton with its internal bracing quarks is shown in Figure 4.

Figure 4 is drawn to scale. The bubble in space is represented by the semi-transparent sphere complete as you can see with "surface tension" (or if you insist, a "balloon".) The up quarks are represented by the outer, dark hexagons. The light-coloured hexagons in the middle comprise the down quark. The down quark has twice the mass of a single up quark.

The truncated icosahedron is a very stable structure and hence a good candidate for bracing the proton bubble. More importantly as we shall see the spherical caps suggested by this model have just the right volumes so that, when lost, they account with good accuracy for the observed mass defects.

There are two different spherical caps suggested by the model, as described in Table 1. The PentaCap energy is the amount of energy will be lost if a particle is forced adjacent to its neighbor's bracing structure at a pentagonal quark face. It is proportional to the volume lost when the spherical cap over the pentagon is crushed.

PentaCap Energy	HexaCap Energy
1.76504×10^{-13} Nm	4.87596×10^{-13} Nm

Table 1. Binding Energy Quanta of Protons and Neutrons.

HexaCap energy is the amount of energy that will be lost if the spherical cap over the hexagon is crushed when the particles come together. It is larger because the hexagon is larger than the pentagon. Below we will discuss the calculations which yield these constants.

Before diving deep into the numbers, let's take a look at the New Physics model for the neutron.

4. Neutron Structure

Neutrons have a couple of additional characteristics that must be taken into account when constructing their model. The fact that a free neutron disintegrates spontaneously in 14.75 seconds [7] means there is some sort of instability in its structure that is not present in the proton.

The other interesting property of the neutron is that it has a positive charge at its surface. This is clear from Figure 5 [8]. This means that a neutron and a proton will repel each other if they are touching. Not all of the negative charge of the neutron is developed at the line marked "RMS Radius" (0.8768 fm.[8]) We are working inside this radius, since the most recent work on the radius of the proton puts it at 0.841840 fm [6], and with the caps collapsing the particles touch at distances even closer than that. Below we will find a linear approximation to Coulomb charge as a function of distance in these close quarters.

The best model for the neutron we have devised so far that matches these criteria is shown in Figure 6. The two down quarks are shown in slightly different shades of green. The up quark is in the centre of the down quarks, corresponding with its 2/3 charge to the positive charge of Figure 5 (bottom, yellow shading.)

The hypothesis is that with the up quark rattling about on the inside, the neutron eventually shakes itself apart and reforms as a proton.

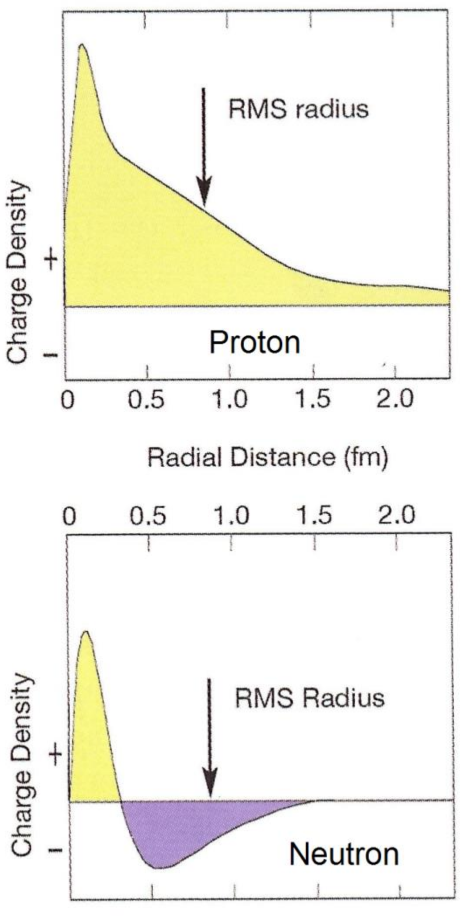


Figure 5. Proton and Neutron charge densities. RMS Radius here is the former accepted value of 8.768 x 10^{-16}.

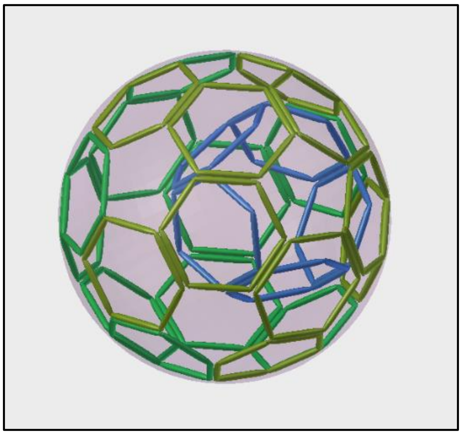


Figure 6. New Physics model of the neutron, showing the bubble in space, two down quarks, and an up quark. The up quark here is shown as a circular loop of 6 hexagons. As you can see this is a different shape from that of the up quarks in the proton in Figure 4. But it has the same mass, and as we have no idea what the actual shape might be, this seems a bit more likely than the shape in Figure 4. Either, or neither, might of course be the case in reality. We have no experimental data yet to prefer one shape over the other. And in fact the shape does not seem to make any difference at the level of abstraction of this model. Hopefully future improvements to the models will render this discussion naïve.

5. Quark Struts

Before we can apply this model to determine binding energies, we must attend to one more detail. The geometry of the truncated icosahedron dictates properties like the distance from the centre to the face of the pentagon. But the quarks in our model are real physical entities and, as such, are not composed of the infinitely thin lines of plane geometry.

Instead we are forced to admit that the struts—if such things exist—have a thickness, and this thickness has an important impact on how close together the particles can come, and more importantly on the amount of volume (mass, energy) that is lost when a spherical cap collapses. Figures 4 and 6 are drawn carefully to scale, including in particular the thickness of the struts, which we deduce later to be:

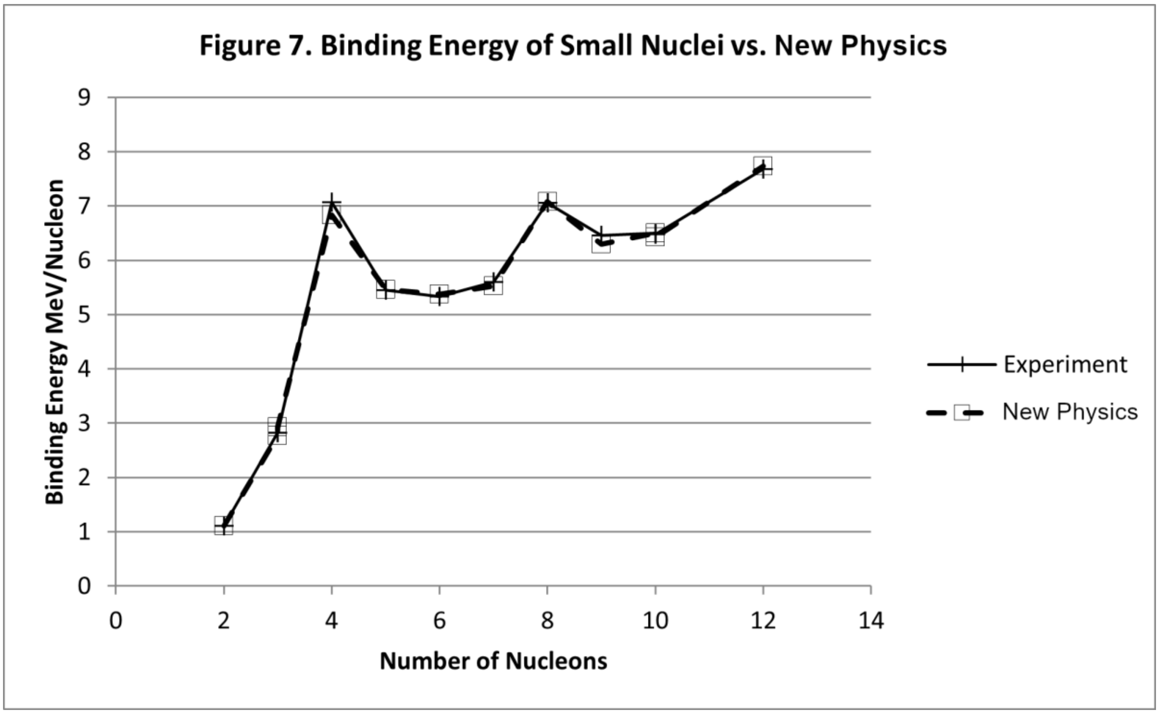
Quark Strut Thickness
0.0412111 fm

Table 2. Quarks appear to be constructed of struts of this thickness.

Cook [1] is justifiably critical of some models of nuclear structure because they simply keep adding adjustable (i.e., arbitrary) parameters until they finally match measurements. Using such an approach just about any model can eventually be made to fit experimental data. In the New Physics the thickness of the quark strut is our sole adjustable parameter, all others being given by physical constants. Furthermore the parameter is highly constrained by the other physical constants. We trust these considerations will render the model less susceptible to criticism along these lines.

6. Results

Figure 7 shows the results of applying the constants of Tables 1 & 2 to the construction of some isotopes from deuterium through carbon:



The New Physics model is a surprisingly good fit to the experimental data. As the following table shows, it is not perfect:

Nucleus	2H	3H	3He	4He	5He	6Li	7Li	8Be	9Be	10Be	10B	12C
Protons	1	1	2	2	2	3	3	4	4	4	5	6
Neutrons	1	2	1	2	3	3	4	4	5	6	5	6
Nucleons	2	3	3	4	5	6	7	8	9	10	10	12
PentaCaps	2	2	3	9	9	12	15	22	22	24	23	31
HexaCaps	0	2	2	6	6	7	8	12	12	14	15	22
Deviation from Measurement	0.00%	-1.91%	3.63%	-3.46%	0.32%	0.73%	-1.39%	0.27%	-2.59%	-0.01%	-0.69%	0.73%

Table 3. Detailed results of the New Physics model of the small nuclei.

The resulting average absolute error and correlation coefficients for the three models are given in Table 4.

Model	Average Absolute Error	Correlation Coefficient
New Physics	1.430%	0.99893
Face-Centered Cubic	10.950%	0.91500
Liquid Drop	55.918%	0.98057

Table 4. Error comparison of the three most accurate models of nuclear binding energy.

These results are sufficiently encouraging for us to explain the details of how we derived them.

7. Model construction

We include the details of our model so the reader can reproduce and improve upon our results.

Please bear in mind that this is a first order model. Our approach is to start simply, then use the results as a proof of concept to support the effort of developing a more exacting model.

It is easier for us (and perhaps for nature) to build nuclei from protons and neutrons if they are both the same size. It is okay if later we learn something more precise. With this assumption the only difference between the masses of the proton and the neutron is the more massive quarks in the neutron. If the down quark is exactly twice as massive as the up quark we have

$$m_d = 2m_u \tag{1}$$

where m_d is the mass of the down quark and m_u is the mass of the up quark. Furthermore

$$m_n - m_p = (2m_d + m_u) - (2m_u + m_d) \tag{2}$$

where m_n and m_p are the masses of the neutron and the proton, respectively. Substituting (1) in (2), we see that

$$m_n - m_p = m_u \tag{3}$$

Formation energy of the proton is 1.50328E-10 Nm and of the neutron is 1.50535E-10 Nm [7]. (Because the proton radius is only known to 6 significant digits [6] and lies at the root of our conclusions, even when our constants are known with greater accuracy we limit them to 6 digits.) This permits us to predict precisely the formation energies of the up and down quarks:

	Measurements [7]			Predictions
	Lower Bound	**Average**	**Upper Bound**	**New Physics**
Up Quark Energy (Nm)	2.2E-13	3.99E-13	5.4E-13	2.07214E-13
Down Quark Energy (Nm)	5.4E-13	8.09E-13	9.4E-13	4.14429E-13

Table 5. Measurement ranges and the New Physics predictions of quark formation energies.

The predictions by the New Physics are below the lower bounds of current measurements. Yet it is clear it is difficult to measure quark formation energy accurately, as we can see from the broad range of current measurements in Table 5. Until we know more we will pursue this simple model.

We compute the volumes of the proton and the neutron based on the assumption they are spheres. (The assumption they are spheres is supported by recent evidence that the electron is to an extraordinarily high degree spherical [11]: if the electron were as large as the solar system it would be exactly spherical to the width of a human hair. The New Physics claims the electron is also a bubble in space: the only way to get something to be perfectly spherical.)

The proton radius of 8.41840E-16 m [6] creates a spherical volume of 2.49906E-45 m^3. According to the New Physics this volume is a bubble in space created by the proton formation energy, less the energy to create two up quarks and one down quark, or 1.49499E-10 Nm. Similarly a neutron occupies the same volume created from its formation energy less two down quarks and one up quark. For simplicity we refer to the "formation energy less quarks" as the "bubble energy". This yields proton and neutron bubble energies per unit volume of 5.98220E34 N/m^2. We will return to this figure soon.

8. Electrostatic Energy

In order to compute the binding energy with some precision, we must take into account the electrostatic force between particles. The electrostatic repulsion between protons and neutrons is typically about 5% to 10% of the binding energy. The neutron has a positive charge at its surface because its neutral charge is not fully developed until well outside its radius (Figure 5.)

The repulsive electrostatic force is trying to separate the particles. This means the real binding energy is the observed binding energy plus the electrostatic energy that it must also overcome to keep the particles together.

Notice that in the region just to the right of the RMS the slope of the charge is approximately linear. To aid a simpler computation of binding energies, we take advantage of this linearity and fit regression lines to the electrostatic charges for protons and neutrons as implied by Figure 5. The linear regression formula is:

$$q\,(d) = (md + \ b) * q_0 \tag{4}$$

Where m is the slope, b is the intersect, and d is the distance from the centre of the particle in metres, and q_0 is the unit charge: 1.60218 x 10^{-19} Coulombs. We deduce from Figure 5 that in the region of the RMS:

Particle	Slope, *m*	Intersect, *b*
Proton	$6.58735\ x\ 10^{14}$	0.22240
Neutron	$-8.32155\ x\ 10^{14}$	0.88625

Table 6. Coefficients of regression fit for charges near the RMS of protons and neutrons.

As we can see from Figure 5, Eq. (4) has its limits. When applied to the proton, Eq. (4) should not exceed the unit charge; using the coefficients in Table 6, beyond a distance of 1.17920 x 10^{-15} m the proton has a unit charge. Similarly beyond a distance of 1.06375 x 10^{-15} m the neutron has 0 charge.

The Coulomb force between two particles is given by

$${}_C\boldsymbol{F}_r = \frac{Cq_1q_2}{r^2}|\boldsymbol{r}| \tag{5}$$

where C is the Coulomb constant (8.98755E9 Nm^2/C^2 in MKS units), q_i is the charge of particle i, r is the separation between them, and the unit vector between the particles is denoted by $|\boldsymbol{r}\,|$.

With q_i given by Eq. (4) within its limits, and noting that *d* = *r/2*, the equation for the Coulomb force between two particles denoted by subscripts 1 and 2 becomes

$$ {}_C\boldsymbol{F}_r = Cq_0^2\left(\frac{m_1m_2}{4} + \frac{b_1m_2+b_2m_1}{2r} + \frac{b_1b_2}{r^2}\right)|\boldsymbol{r}| \qquad (6) $$

To determine the energy required to push the two particles together to separation *s* we integrate Eq. (6):

$$ {}_CE_s = Cq_0^2\left(\int_s^\infty \frac{m_1m_2}{4}d\boldsymbol{r} + \int_s^\infty \frac{b_1m_2+b_2m_1}{2r}d\boldsymbol{r} + \int_s^\infty \frac{b_1b_2}{r^2}d\boldsymbol{r}\right) \qquad (7) $$

$$ {}_CE_s = Cq_0^2\left(\frac{m_1m_2r}{4}\Big|_s^\infty + \frac{b_1m_2+b_2m_1}{2}\ln(|r|)\Big|_s^\infty - \frac{b_1b_2}{r}\Big|_s^\infty\right) \qquad (8) $$

where here $|r|$ means absolute value of r. The evaluation of Eq. (8) as we approach separation *s* from infinity reaches several discrete breakpoints. Let us assume for clarity we are talking about a proton approaching a neutron. By the linear approximation we are using here, there is no repulsion until we get within 1.06375 x 10^{-15} m. Outside that limit the integral evaluates to 0, because beyond that distance the neutron has no charge. Assuming *s* is closer than this, we can evaluate Eq. (8) by substituting *r* = *s*, where *s* is the final separation of the centres of the touching particles once the spherical caps are gone and the quark structures are touching. We will discuss in more detail the precise geometry of these separations shortly, but first we should develop an expression for the magnetic energies that also come into play.

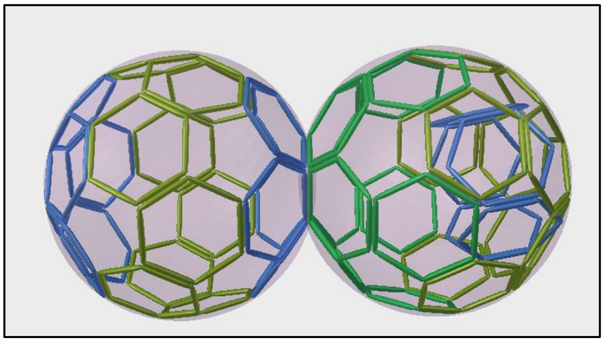


Figure 8. In the deuterium nucleus the up quark is pinned to the side of the neutron opposite the bond to the proton. Note the pentagonal spherical cap cut from each particle at the bond: the binding energy or mass defect. Details:
^{2}H: PentaCaps: 2
Bonds: P1p11-N1p11
Coulomb: -1.01600E-15 Nm
Tesla: 4.42592E-15 Nm
Binding Energy Model: 3.56419E-13 Nm
Binding Energy Data: 3.56419E-13 Nm
Error: 0.00% (calibrated)

9. Magnetostatic Energy

The measured proton magnetic moment is 1.41061E-24 J/T, whilst the neutron magnetic moment is −9.66236E-27 J/T. However the sum of these is not the deuterium magnetic dipole moment. To understand the New Physics explanation as to why this might be so, we have only to look a bit more closely at our model of the neutron, Figure 6. Observe the up quark free to move about the interior.

The New Physics model explains the fact that the free neutron disintegrates in 14.75 seconds by pointing out that the up quark within might well oscillate internally until the structure destabilizes and shatters. Yet in the deuterium nucleus this does not occur. In Figure 7 we can see the up quark with its 2/3rds positive charge is repelled by the positive charge of the proton and is pinned against the far side of the neutron, opposite the binding point of attachment of the proton to the neutron.

This shift of the up quark also affects the magnetic moment of the bond. We can compute the effect. We see that the sum of the magnetic moments of the proton and the free neutron is 4.44371E-27 J/T, but that of deuterium is 4.32852E-27. Therefore the magnetic moment of the bound neutron must be
-9.77755E-27 J/T to account for the difference. The up quark shift increases the neutron magnetic moment, so the sum

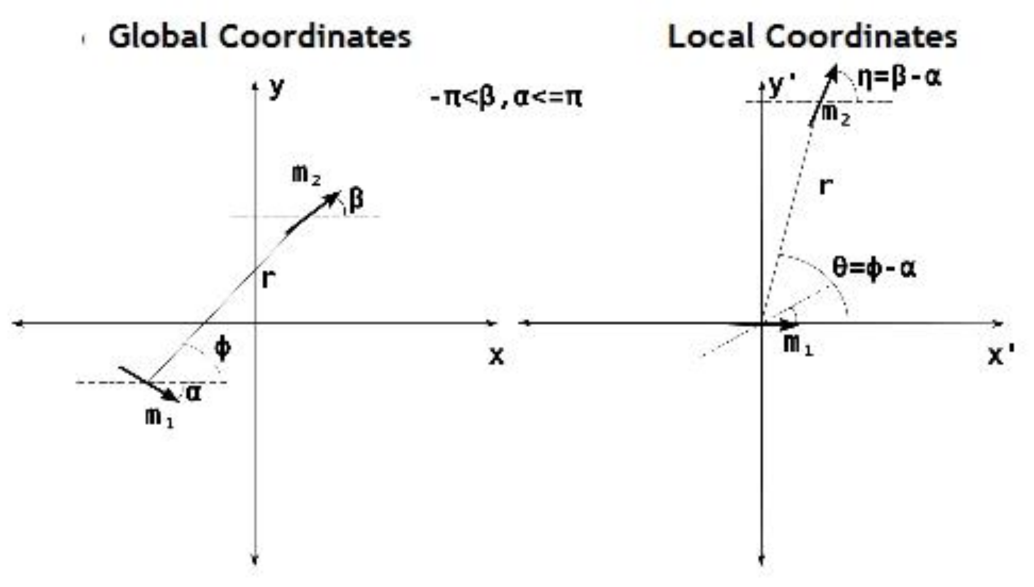


Figure 9. Magnetic forces between two dipoles [12].

is less, as observed.

We need a way to determine the magnetic repulsion between nucleons as they are added to the nucleus. We adopt a simplistic model that we can apply throughout the construction, hoping as usual that lack of sophistication is compensated by clarity of a model which can later be refined.

The magnetic forces between two dipoles are illustrated in Figure 9 and given by [12]:

$$ {}_{r}\boldsymbol{F}\,(\boldsymbol{r},\alpha,\beta) = \frac{3\mu_0}{4\pi}\frac{m_1 m_2}{r^4}\,[2\cos(\phi-\alpha)\cos(\phi-\beta) - \sin\,(\phi-\beta)] \tag{9} $$

$$ {}_{\phi}\boldsymbol{F}\,(\boldsymbol{r},\alpha,\beta) = \frac{3\mu_0}{4\pi}\frac{m_1 m_2}{r^4}\,[\sin\,(2\phi-\alpha-\beta)] \tag{10} $$

where $\boldsymbol{m}_1$ and $\boldsymbol{m}_2$ are the magnetic dipoles, $\boldsymbol{r}$ is the vector distance from the first to the second dipole, and μ_0 is the permeability of space. μ_0 may be larger than normal in the vicinity of the nucleus, due to the compression of space in the region, but the effect is small and we shall ignore it for the moment. Assuming that the particles approach along the vector $\boldsymbol{r}$ so the angles stay constant, the energy involved in Eq.(9) is:

$$ {}_{r}E\,(r,\alpha,\beta) = \int_s^\infty \frac{3\mu_0}{4\pi}\frac{m_1 m_2}{r^4}\,[2\cos(\phi-\alpha)\cos(\phi-\beta) - \sin\,(\phi-\beta)] \tag{11} $$

$$ {}_{r}E\,(s,\alpha,\beta) = -\left[\frac{\mu_0}{4\pi}\frac{m_1 m_2}{r^3}\,[2\cos(\phi-\alpha)\cos(\phi-\beta) - \sin\,(\phi-\beta)]\right]\Bigg|_s^\infty \tag{12} $$

where s is the separation between dipole centres. Similarly for Eq.(10) we have

$$ {}_{\phi}E\,(r,\alpha,\beta) = \int_s^\infty \frac{3\mu_0}{4\pi}\frac{m_1 m_2}{r^4}\,[\sin\,(2\phi-\alpha-\beta)] \tag{13} $$

$$ {}_{\phi}E\,(s,\alpha,\beta) = -\frac{\mu_0}{4\pi}\frac{m_1 m_2}{r^3}\left[\sin\left(2\phi-\alpha-\beta\right)\right]\Big|_{s}^{\infty} \qquad (14)$$

$$ {}_{M}E\,(s,\alpha,\beta) = {}_{r}E\,(s,\alpha,\beta) + {}_{\phi}E\,(s,\alpha,\beta) \qquad (15)$$

Eq. (15) gives negative energies for net repulsive magnetic forces, and positive energies for net attractive magnetic forces. Care must be exercised when incorporating these into the net binding energy. If the net force is attractive, the observed binding energy is the result of the mass defect plus the attractive force. If the net force is repulsive, the mass defect must overcome this repulsion to deliver the observed binding energy.

10. Calibration: Deuterium

Now we can use the properties of the deuterium nucleus to determine the pentagonal cap energy, the quark strut thickness, and the hexagonal cap energy. Once we have decided whether a given bond is composed of 2 PentaCaps, 2 HexaCaps, or one of each, this will imply a known physical loss of spherical cap volume. This in turn implies a known amount of lost mass in proportion to the volume lost; we will calibrate this relationship next. From this lost energy we can add the results of Eq. (8), which in this context is always repulsive and negative. We then add the result of Eq. (15)—which will add if attractive or subtract if repulsive—to obtain, hopefully, the observed binding energy.

We attempt to model deuterium with a two 2 PentaCap bond, as illustrated in Figure 8. We explored using HexaCaps but did not obtain as good a fit to experimental data.

The length of the quark strut is given by the properties of the truncated icosahedron [9]:

$$ {}_{q}a = r_p / \left(\frac{1}{4}(58+18(5)^{0.5})^{0.5}\right) \qquad (16)$$

where ${}_{q}a$ is the length of each quark strut and r_p is the radius of the proton. The distance from the centre of the proton to the pentagonal face is again by geometry

$$ {}_{p}d = {}_{q}a\left(\frac{1}{2}\left(\frac{1}{10}(125+41(5)^{0.5})\right)^{0.5}\right) + {}_{q}t/2 \qquad (17)$$

where ${}_{q}t$ is the thickness of the quark strut; we assume the geometric plane bisects the strut so we add half its thickness. For the moment we must treat ${}_{q}t$ as an unknown, but its value will shortly be determined, and ${}_{p}d$ will become 8.11290E-16 m.

The movement of the up quark shifts the centre of the charge of the neutron away from the proton. We assume by the geometry illustrated in Figure 7 that this shift moves the centre of the neutron's charge a further 25% of the radius of the proton. So the s in Eq. (8) and (15) we'll express as

$$ s = 2{}_{p}d + 0.25{}_{p}d \qquad (18)$$

which yields $s = 1.83304\text{E-}15$ m.

The measured binding energy, which is the sum of the mass defect combined with the Coulomb and magnetic forces, is

$$ {}_{obs}E = \left[{}_{D}E_{2H} + {}_{C}E_{2H} + {}_{M}E_{2H}\right] \qquad (19)$$

where ${}_{D}E_{2H}$ is the energy of the mass defect, ${}_{M}E_{2H}$ is the deuterium magnetic energy for ^{2}H which from Eq.(15) is an attractive force of 4.42592E-15 Nm, and ${}_{C}E_{2H}$ is the Coulomb energy from Eq. (8), which computes as −1.01600E-15 Nm. The observed deuterium binding energy is well-documented at 3.56419E-13 Nm [1]. So the actual pentagonal cap binding energy is 1.76504E-13 Nm: the result of solving Eq.(19) for ${}_{D}E_{2H}$ and dividing the result by 2 (since there are two PentaCaps in the bond, with each one getting half the mass defect.)

We now have a model of the deuterium binding energy that is an exact solution of Eq. (19). All we have to do is compute the binding energy of the HexaCap and we can construct Eq. (19) for the remaining nuclei.

We need to determine the volume of the spherical cap that is lost in the bond. First consider the proton formation energy, well documented [13] as 1.50327E-10 Nm. Subtracting the two up quark energies and the down quark energy given by the New Physics column of Table 5 yields proton bubble energy of 1.49499E-10 Nm. As discussed earlier the neutron bubble energy is identical by this model.

Observed deuterium binding energy expressed as a fraction of proton plus neutron bubble energies is ${}_{D}E_{2H}$ divided by the sum of the bubble energies, giving a fraction of 1.17892E-3. With the proton radius 8.41840E-16 m we get a spherical proton volume of 2.49906E-45 m^3. To include the neutron volume we double this to 4.99813E-45 m^3. Therefore the fraction of volume lost is 5.90099E-48 m^3, and half of this is our first cut lost volume of the PentaCap: 2.95049E-48 m^3.

It is useful when determining the volume of the PentaCap to know the formula for the volume of a spherical cap [10]:

$$ {}_{c}V = \frac{1}{3}\pi h^2\left(3r_p - h\right) \quad (20) $$

where h is the height of the spherical cap. From this we can compute the height of the lost volume.

The value 2.95049E-48 m^3 is the volume of the lost spherical cap on the assumption the proton is empty, but our model tells us there is an interior quark framework. We have to account for this somehow. Our method is to assume the quark struts have a thickness. We reason that surely if they exist, they must have some thickness. Therefore we adjust the height of the spherical cap to account for this thickness so that our model yields the best results. The result of this process is to adopt the quark strut thickness in Table 2 and adjust the height of the PentaCap accordingly. This gives a PentaCap volume at 2.43846E-48 m^3. This adjusted PentaCap volume is less than the volume deduced in the previous paragraph using the binding energy as a fraction of the bubble energy.

This means the binding energy lost per unit volume is 7.23834E34 Nm/m^3, larger than the proton bubble energy per unit volume of 5.98220E34 Nm/m^3. This implies that more energy is required to bust a cap than might be suggested from the energy required to create the proton. In effect the quark thickness calibrates this difference. We are not sure of the physical basis for this difference; perhaps the extra energy is used to seal the bond.

The distance to the hexagonal face from the centre of the proton can be computed from the geometry of the truncated icosahedron [9]:

$$ {}_{h}d = {}_{q}a\left(\frac{1}{2}\left(\frac{3}{2}\left(7 + 3(5)^{0.5}\right)\right)^{0.5}\right) + {}_{q}t/2 \quad (21) $$

Using Eqs. (20) and (21) gives us a volume for the HexaCap of 6.73630E-48 m^3. With our calibrated binding energy per unit volume of 7.23834E-34 Nm/m^3 we have the HexaCap energy shown in Table 1.

11. Nuclear models

Armed with Eqs. (8) and (15) and our PentaCap and HexaCap binding energies, we can evaluate Eq. (19) for other nuclei, creating Table 3 and Figure 7.

To describe the bonds between the particles, it will help to have a way to refer to specific PentaCaps and HexaCaps. This is not because we think we have selected the only proper caps, but rather to enable the work to be reproduced and refined.

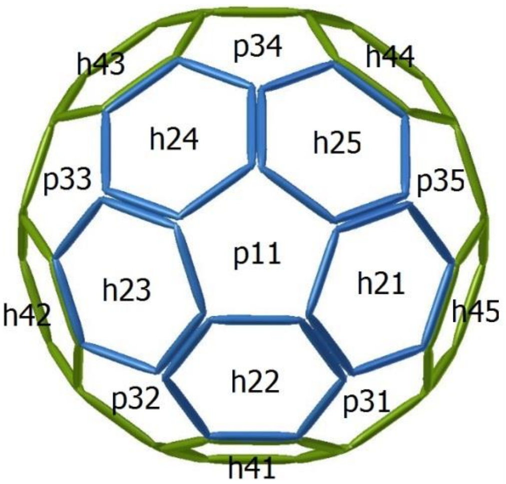


Figure 10. Numbering scheme for the front of the particle.

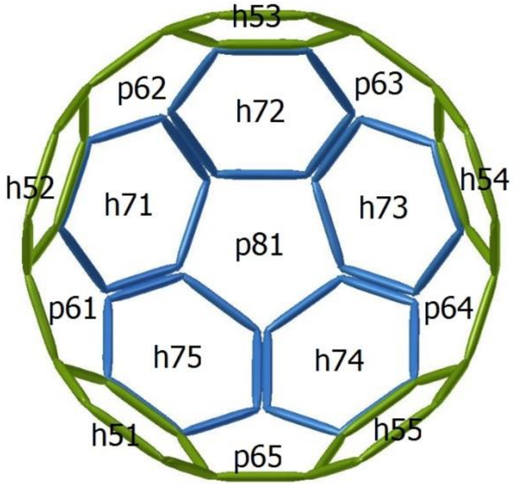


Figure 11. Numbering scheme for the back of the particle.

Figure 10 shows a way to label the caps looking at the “front” of the proton. The first numeral is the level of the cap, starting at level 1. The second numeral is the number of the cap on that level, starting at 1. As it happens each level only has caps of one type: PentaCaps or HexaCaps. The front of the particle with p11 in the centre (and closest to the reader) is chosen as the darker side on the neutron, and as the side where the initial bond is made on the proton. The first bond is arbitrarily chosen to be on the lowest numbered cap that matches the geometry of the nucleus. Figure 11 shows the back of the proton but looking at it from the front, with the front half of the quark structure cut away so the rear caps are visible. The cap p81 is furthest from the reader. The numbering scheme can be seen to extend smoothly from the front onto the back side with h51 on the back adjacent to h41 on the front.

We can label neutron caps the same way because in this model, the two down quarks of the neutron have the same geometry as the two up quarks plus the down quark of the proton.

In addition to this convention we will call the first proton added to the nucleus P1 and the first neutron N1. Looking for example at deuterium (Figure 8) we see a bond of P1p11-N1p11.

Figure 12 shows a New Physics model of ^{3}H. In the notes to the figures Coulomb stands for electrostatic energy and Tesla stands for magnetostatic energy.

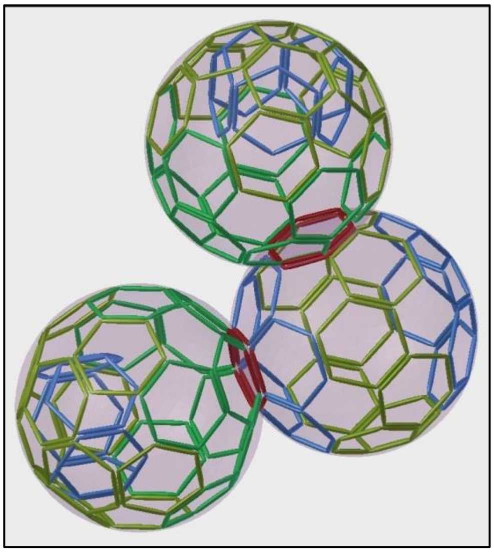


Figure 12. ^{3}H: PentaCaps: 2, HexaCaps: 2
Bonds: P1p11-N1p11 & P1h41-N2h21
Coulomb: -2.35659E-15 Nm
Tesla: 7.20862E-15 Nm
Binding Energy Model: 1.33305E-12 Nm
Binding Energy Data: 1.35897E-12 Nm
Error: -1.91%

Figure 13 illustrates ^{3}He with the unusual case where we must have two HexaCaps broken in a single bond in order for the model to have decent accuracy to measurement. The proton P2's PentaCap in the same bond seems to have room to remain intact if the proton is rotated so that the pentagonal centre line of P2 is aligned with the pentagonal vertex on N1. This model has a larger maximum span than ^{3}H, which corresponds to its larger measured size.

Let's look at the alpha particle, ^{4}He.

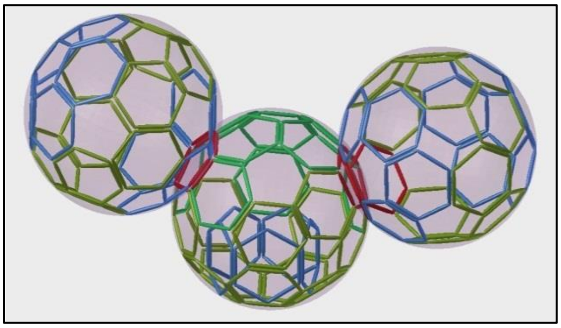


Figure 13. ^{3}He: PentaCaps: 3, HexaCaps: 2
Bonds: P1p11-N1p11 &N1p34-P2h21h45
Coulomb: -9.54685E-14 Nm
Tesla: -1.00028E-15 Nm
Binding Energy Model: 1.40824E-12 Nm
Binding Energy Data: 1.35894E-12 Nm
Error: 3.63%

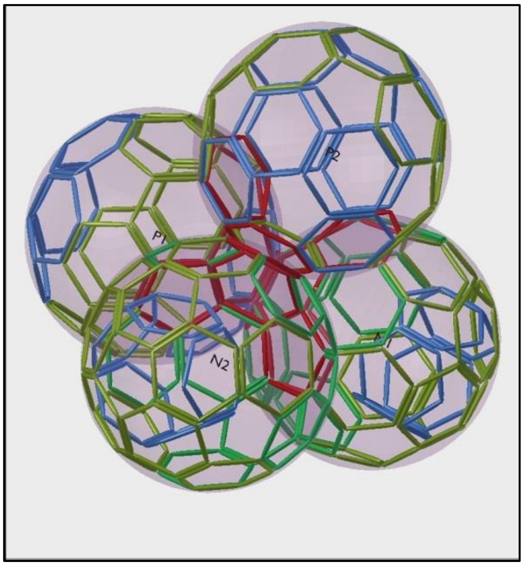


Figure 14. ^{4}He: PentaCaps: 9, HexaCaps: 6
Bonds: P1p11-N1p11 &N1p34-P2h21h45
Coulomb: -1.45992E-13 Nm
Tesla: 8.37836E-15 Nm
Binding Energy Model: 4.37650E-12 Nm
Binding Energy Data: 4.53352E-12 Nm
Error: -3.46%

The alpha particle holds a special place in nuclear structure theory. Alpha radiation is one of the primary forms of radiation which occurs when—according to the New Physics —the strong force of the compressive space surrounding the nucleus can no longer hold the nucleus together. The fact that the alpha particle seems to be bound together as a unit more tightly than other combinations of particles is also reflected in the branch of nuclear structure theory that surmises that atomic nuclei are constructed of clumps of alpha particles [1]. Our findings place us firmly in this camp.

All this circumstantial evidence is supported by our model of ^{4}He which has a large number of busted caps. To make the structure more clear we include Figure 15 showing only three of the particles.

In Figure 15 you can see that three HexaCaps are broken by their proximity in the centre of the cluster of the three particles. Their spherical caps interfere with each other, so they flatten when the particles bond. A fourth HexaCap that belongs to P2 sits on top of them and does not break because once these are flattened, there is room for the fourth cap. You can also see the three PentaCaps that P2 will bond with. P2 has three HexaCaps at the right locations to bond with these three PentaCaps, which may now be clearer if you reconsider Figure 14.

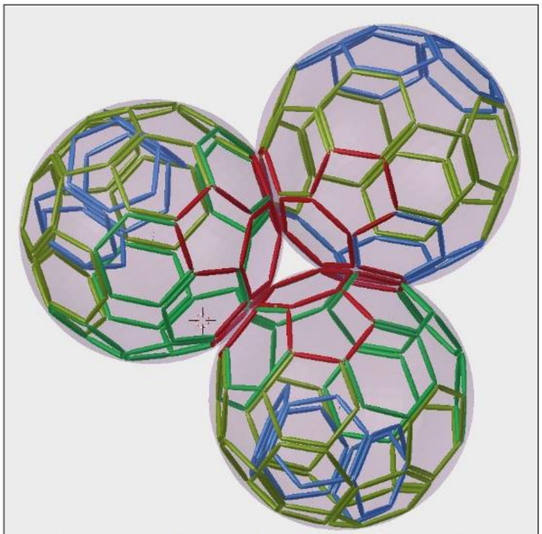


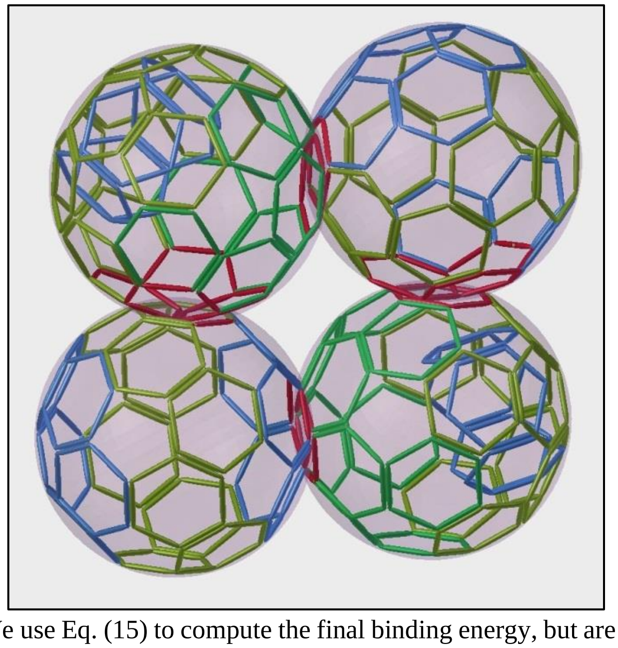
Figure 15. Three of the four particles in 4He, looking down from the top, with 2P hidden.

Figure 15. ^{4}He showing P1, N1 and N2, with P2 hidden from view. Note the slightly imperfect fit of the PentaCaps to each other. Does this mean there is a better alternative bracing structure than the truncated icosahedron? Or is some gap required by thermal motion of the nucleons? Or is there some other explanation? We don't have enough data to be sure.

A number of factors influence how we construct these models. We look at all the various combinations of HexaCaps and PentaCaps and discover those that yield matches to the data. Then we consider more closely those that are feasible to build. As a general principle we assume that nature will strive for a spherical configuration. In the New Physics this is encouraged by the nuclear skin or "quantum level 0" as we call it. The nuclear skin is a layer around the nucleus of increased density [1, p135]. The New Physics explains this as the compressed space within a quantum level 0 that immediately surrounds the particles injected into space. Its thickness is generally about 2.3 to 2.4 fm but its shape is less well understood. We assume the nuclear skin will at least tend to be spherical if not actually attaining a spherical shape. It is not always possible to construct a sphere whilst breaking a number of PentaCaps and HexaCaps that yield a match to the data.

In addition calculations of the repulsive electrostatic forces by Eq. (8) show that protons repel protons with greater force than they do neutrons. The dual PentaCap proton-proton coulomb energy is -1.20764E-13 Nm whilst the proton-neutron energy is −1.01600-15 Nm, with the negative signs indicating repulsion. This is a difference of more than a factor of 100, which we think will incline protons to bond to neutrons before protons, all other things being equal. Using the same logic the neutron-neutron dual PentaCap repulsion is another factor of 10 weaker at −1.02557E-16 Nm, so a neutron is more likely to bond with a neutron than with a proton. Note that for HexaCap bonds the numbers are higher because there is less distance between centres.

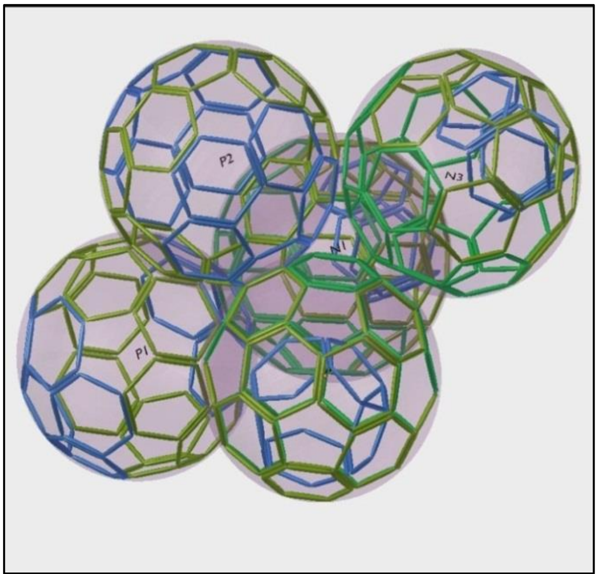
Figure 16. ^{4}He planar. PentaCaps: 6, HexaCaps: 7
Bonds: P1p11-N1p11 & N2h21h45p31p35-P1h45 & N2h24-P2p64 & N1h53-P2p11h21h22
Coulomb: -1.23447E-13 Nm
Tesla: 1.23919E-14 Nm
Binding Energy Model: 4.47144E-12 Nm
Binding Energy Data: 4.53352E-12 Nm
Error: -1.37%



Magnetic effects are more difficult to understand. We use Eq. (15) to compute the final binding energy, but are less certain how influential magnetic effects might be in determining the shape of the nucleus, and how they combine as nucleons are added, considering these an important areas for further investigation.

Does the bond between up and down quark structures have attraction? Are down quark bonds repulsive? Do particular caps have affinity for others? We don't have enough data to answer these questions yet.

Figure 17. ^{5}He: PentaCaps: 9, HexaCaps: 6
Bonds: Same as ^{4}He.
Coulomb: -1.49575E-13 Nm
Tesla: 1.39438E-14 Nm
Binding Energy Model: 4.37849E-12 Nm
Binding Energy Data: 4.36449E-12 Nm
Error: 0.32%



An alternative, magnetically stable version of ^{4}He is shown in Figure 16. We worked with this version for quite some time before returning to the tetrahedral shape. Despite the fact that this version has larger net magnetically attractive energy, we were bothered by three issues with this model: (1) the model did not extend very well to 12C; (2) the way that so many caps were involved in two of the bonds, with the precise number seeming to require very precise contortions to achieve; and (3) the way the 2-cap bonds had to be skewed so that the caps did not meet aligned. These are subjective reasons at best, and we do not really know whether this or the tetrahedral—if indeed either—is the best fit to reality. More data on the shape and size of the nuclei, along with more work to correlate the magnetic dipole and electric moments of these models with real data are required to resolve the issue.

We included this alternative structure for ^{4}He to give the reader a more complete picture of the status of this research. Although we are pleased with overall progress and believe we are on the right track, we do not want to give the impression that we have resolved all the open issues.

Next is Figure 17 of ^{5}He. It has the same number of bonds as 4He: the third neutron is just resting against the other particles. It is not hard to understand this is not a stable isotope.

In ^{6}Li N3 bonds to P1 with two PentaCaps and P3 bonds to N3 with a PentaCap-HexaCap bond.

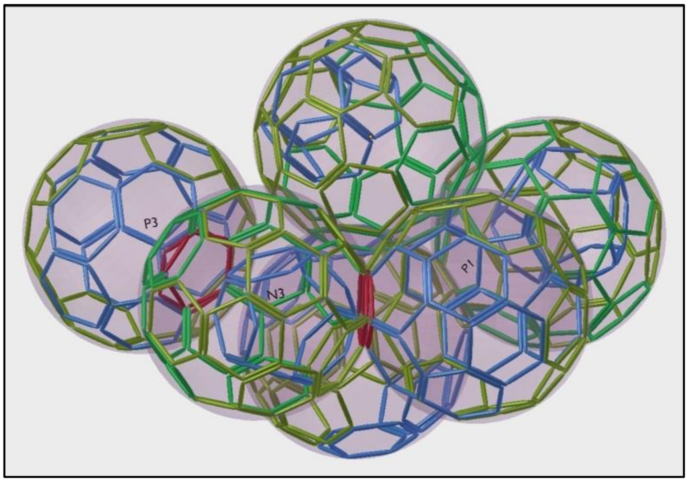


Figure 18. ^{6}Li: PentaCaps: 12, HexaCaps: 7
Bonds: Same as ^{4}He & P1p32-N3p31 & N3p81-P3h21
Coulomb: -3.73600E-13 Nm
Tesla: 5.73487E-15 Nm
Binding Energy Model: 5.16336E-12 Nm
Binding Energy Data: 5.12601E-12 Nm
Error: 0.73%

In ^{7}Li we show N3 HexaCap bonds to N1, P3 PentaCap bonds to N2, and N4 having PentaCap bonds with both N2 and P3.

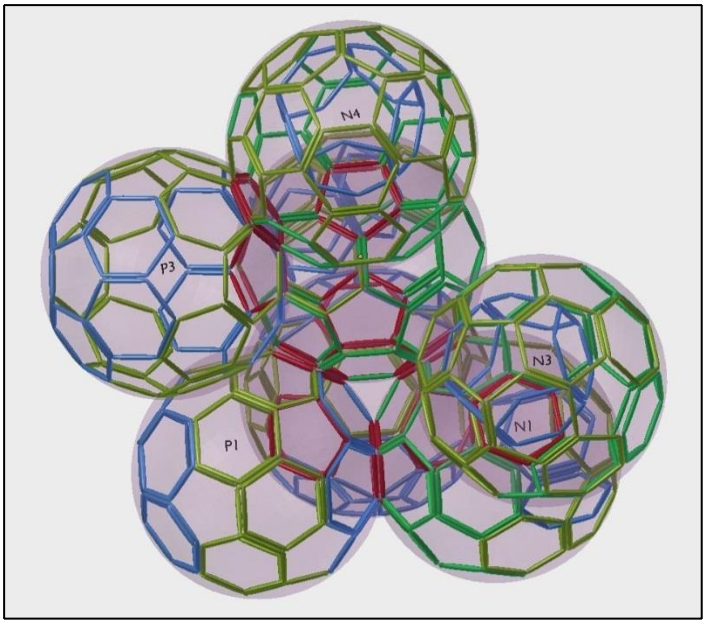


Figure 19. ^{7}Li: PentaCaps: 15, HexaCaps: 8
Bonds: Same as ^{4}He & N3h21-N1h53 & P3p11-N2p61 & N4p11-P3p31 & N4p11-N2p62
Coulomb: -3.59934E-13 Nm
Tesla: 8.51757E-15 Nm
Binding Energy Model: 6.19692E-12 Nm
Binding Energy Data: 6.28438E-12 Nm
Error: -1.39%

^{8}Be is our first cluster of alpha particles, with N4 of the second alpha particle binding to both N1 and P1 using PentaCaps.

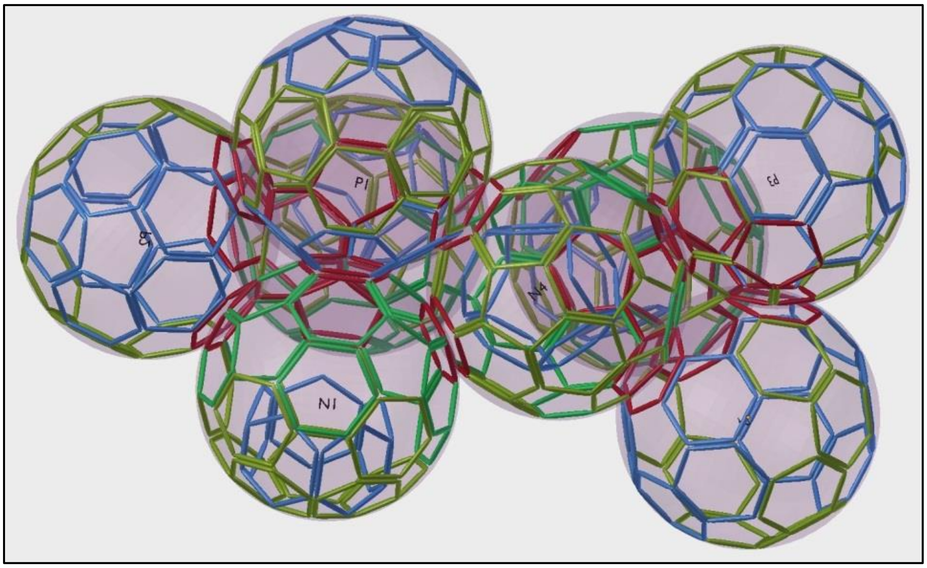
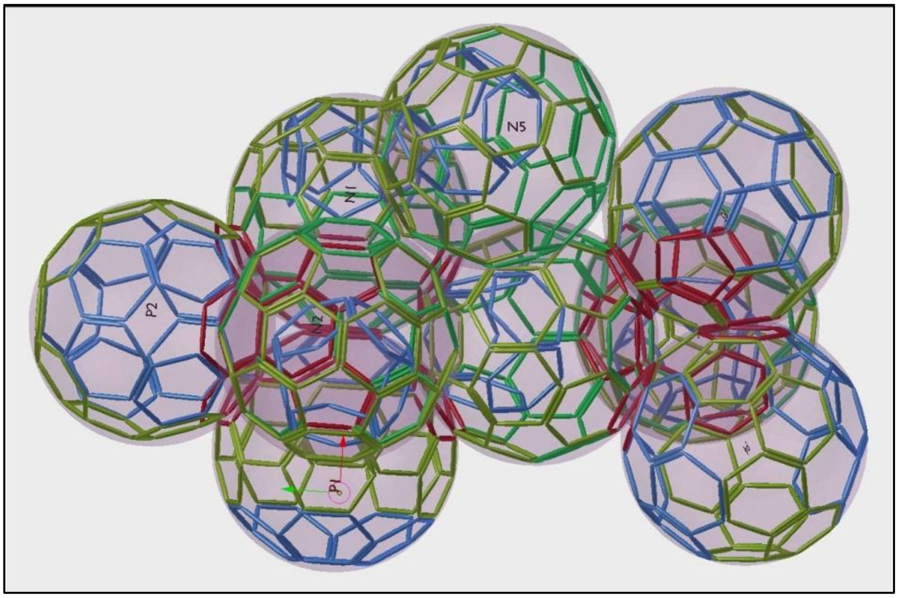


Figure 20↑. ^{8}Be: PentaCaps: 22, HexaCaps: 12
Bonds: Same as two sets of ^{4}He & N4p61-N1p32 & N4p62-P1p32
Coulomb: -6.81418E-13 Nm
Tesla: 2.39653E-14 Nm
Binding Energy Model: 9.07680E-12 Nm
Binding Energy Data: 9.05230E-12 Nm
Error: 0.27%

Figure 21↓. ^{9}Be: PentaCaps: 22, HexaCaps: 12
Bonds: Same as ^{8}Be
Coulomb: -6.81418E-13 Nm
Tesla: 2.39653E-14 Nm
Binding Energy Model: 9.07680E-12 Nm
Binding Energy Data: 9.05230E-12 Nm
Error: 0.27%

Figure 21 shows ^{9}Be is just like ^{8}Be but with an extra neutron N5 resting on the surface, unbounded. This is another unstable isotope.



N5
N1
P2
N2
P1

.

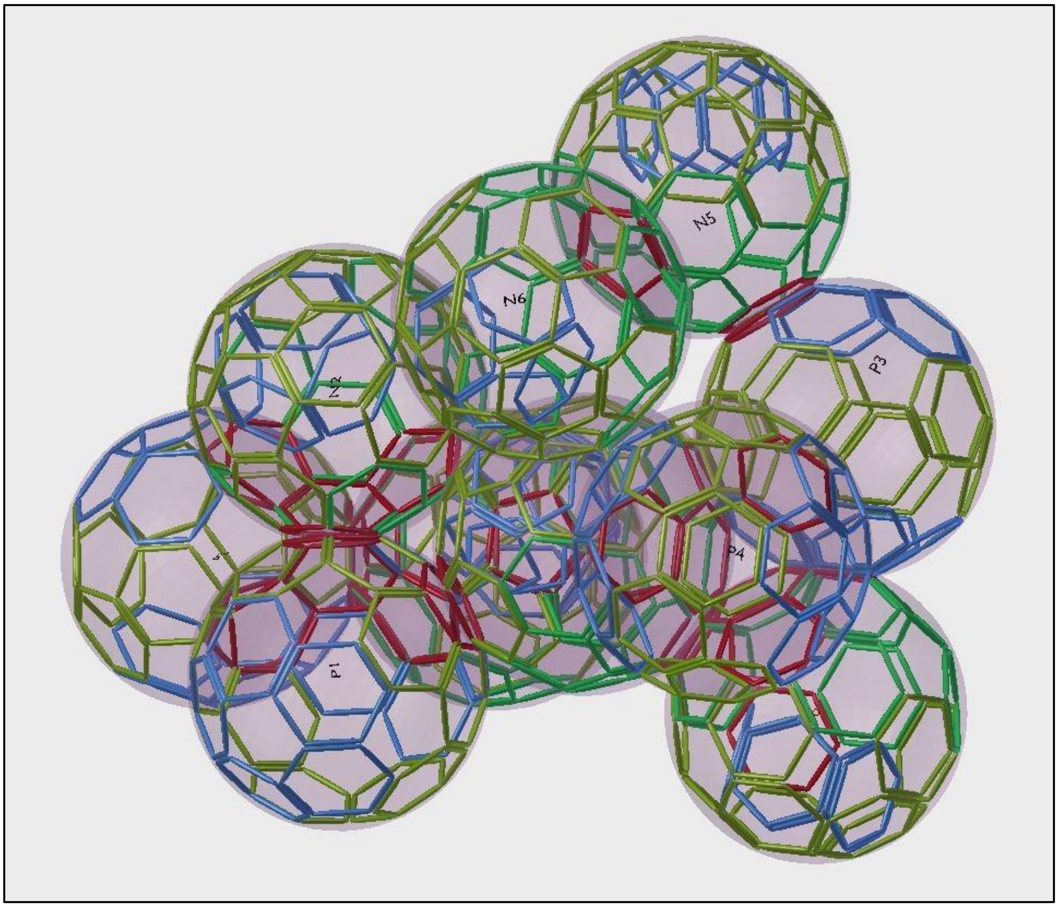


Figure 22. ^{10}Be: PentaCaps: 24, HexaCaps: 14
Bonds: Same as ^{8}Be & P3h73-N5h21 & N5p54-N6p11
Coulomb: -6.88091E-13 Nm
Tesla: 3.50962E-14 Nm
Binding Energy Model: 1.04095E-11 Nm
Binding Energy Data: 1.04105E-11 Nm
Error: -0.01%

In Figures 22 and 23 we show N5 bonded to the alpha cluster via P3 using 2 HexaCaps. In Figure 22 N5 bonds to N6 with PentaCaps. In Figure 23 P5 bonds to N5 using a PentaCap-HexaCap bond.

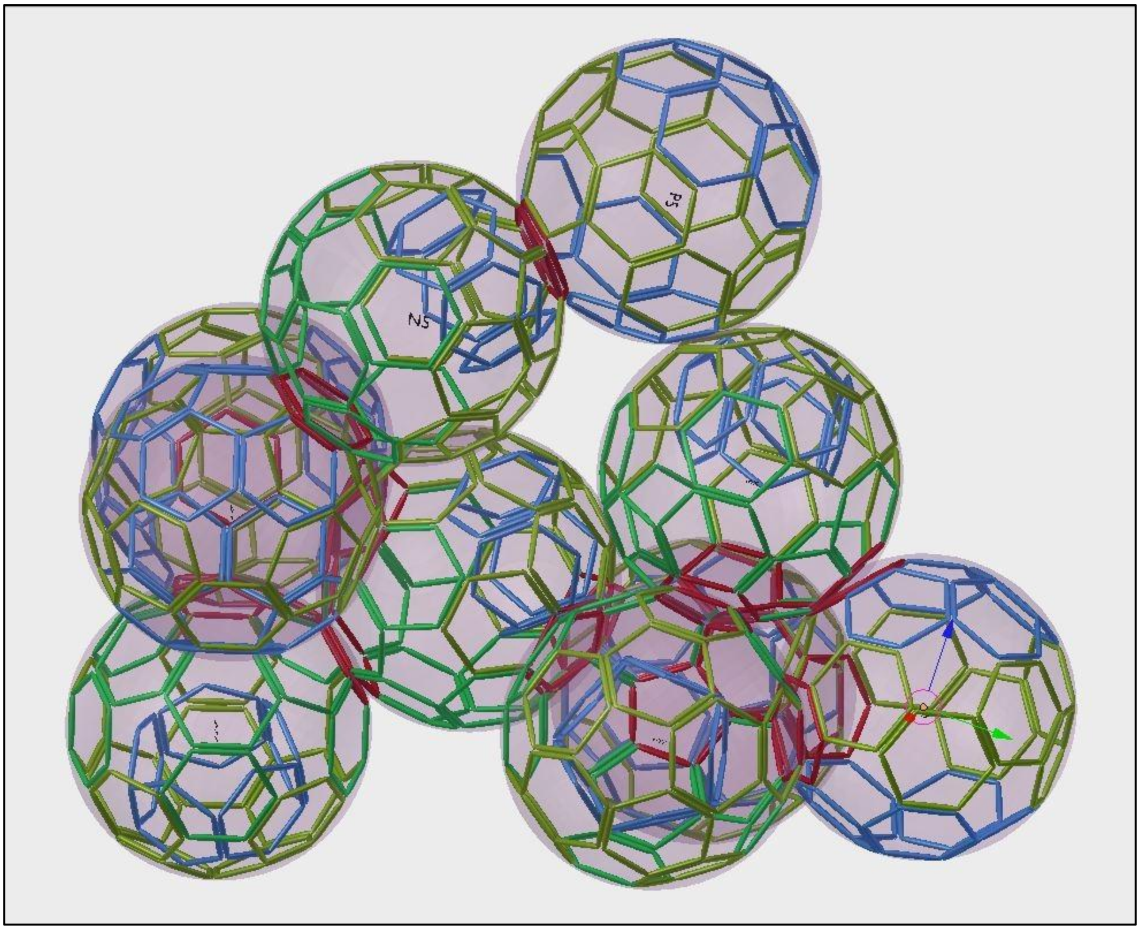


Figure 23. ^{10}B: PentaCaps: 23, HexaCaps: 15
Bonds: Same as ^{8}Be & P3h73-N5h21 & N5p81-P5h21
Coulomb: -1.09787E-12 Nm
Tesla: 2.68873E-14 Nm
Binding Energy Model: 1.03026E-11 Nm
Binding Energy Data: 1.03743E-11 Nm
Error: -0.69%

Figure 24 illustrates 12C. This is a cluster of three alpha particles with the third bonded with HexaCaps to both of the other alpha particles. Note the rough fit of the bonds between N5 and N3/N2. There may be another geometry that makes the fit more precise, but we have not discovered it yet.

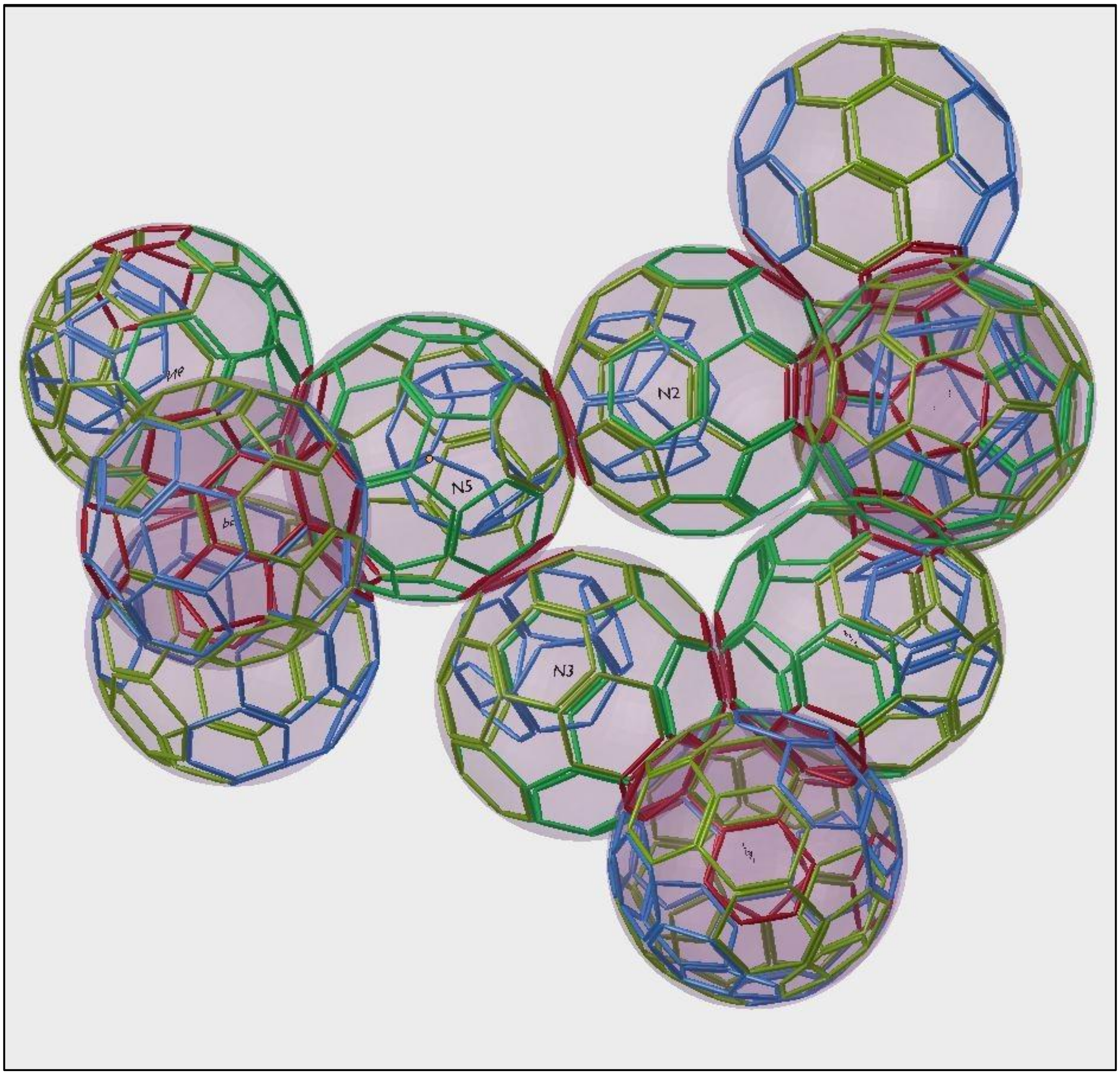


Figure 24. ^{12}C: PentaCaps: 31, HexaCaps: 22
Bonds: Same as ^{8}Be & N5h71-N2h71 N5h74-N3h72
Coulomb: -1.37286E-12 Nm
Tesla: 4.79307E-14 Nm
Binding Energy Model: 1.48738E-11 Nm
Binding Energy Data: 1.47660 E-11 Nm
Error: 0.73%

12. Implications

The model of particle physics put forth here is certainly a radical departure from conventional thinking. It has far-reaching implications which we should touch upon before closing.

For example if the particles in our lives are mostly hollow, where is the inertial mass? According to the New Physics, particles are heavy because of the cumulative restoring forces of their merged quantum levels. But why are they hard to accelerate?

The quantum levels of a particle begin creation at the moment of its insertion into space. We assume that they propagate into space at the speed of light. This means every particle that has been here for a while has a very large number of quantum levels by now. When a particle is accelerated, it is unlikely that all of its quantum levels accelerate at the same time. Therefore acceleration of a particle is a distortion of the particle's distance from its quantum levels. Just as the quantum level wants to restore to its home position (gravitation), so it also resists deformation from the home position (inertia). This is just the way space is made: the fabric of particles in space.

To create General Relativity Einstein had to assume that gravitational mass and inertial mass are the same thing. The New Physics shows that they have the same source: the tendency of every quantum level to restore to its home position.

Another question arises regarding hollow particles: other than the quarks, if it is not space inside them then what is it? Or put another way, what sort of void is inside a bubble (or balloon) in space? We don't have as good an answer to this question as to the last one…yet.

One more implication of the New Physics model of particles should be mentioned. The following diagram shows that dark matter has been transforming into dark energy over time as the universe has evolved. In our earlier work we put forth the conjecture that the New Physics permits dark matter to be composed of neutron matter [4], something not permitted by the Standard Model of particle physics.

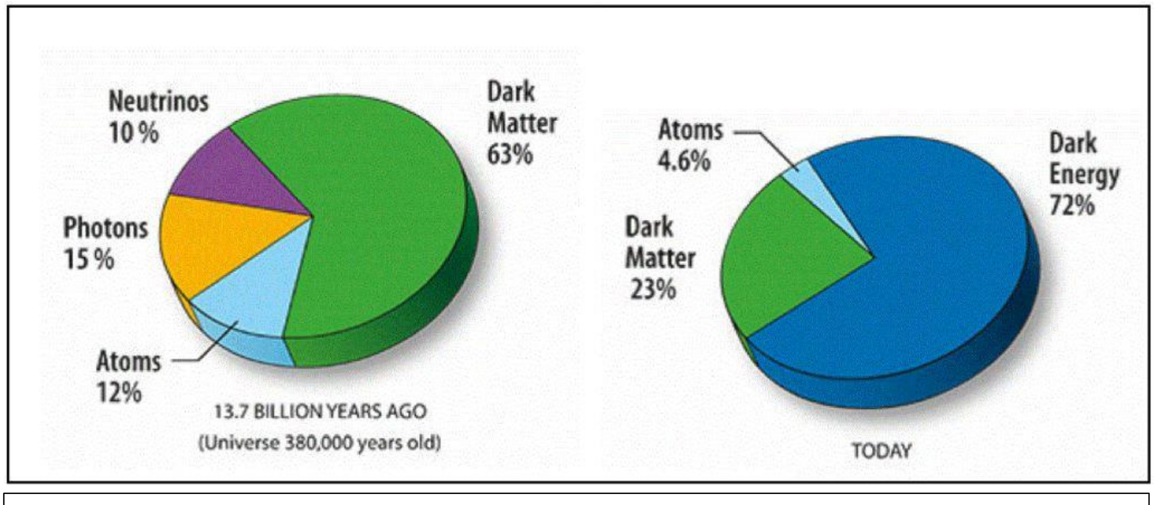


Figure 25. Changes in the composition of the Universe are explained by a simple New Physics conjecture.

A collection of neutrons in a black hole would eventually amass enough gravitational force to crush the neutron shown in Figure 6. This would leave no gravitational mass (quantum levels); only the formation energy would remain, trapped at the centre of the black hole. As the black holes of the universe gather more mass, more neutrons will be crushed and more dark energy will be formed. The resultant loss of gravitational mass then accounts for the observed accelerating expansion of the universe [14].

13. Conclusions

We have presented a model of the structure of the nucleus, and show how to build models of several of the small nuclei. The constructions are more than 7 times better match to known data than the next closest model of binding energy, a significant improvement. The model is in the same family as its predecessor the FCC model: both are crystalline structures. The FCC model is a regular structure, but the New Physics model derives its improved accuracy from growing each nucleus as demanded by the observed binding energy. As this work is extended we may see some of the FCC regularities emerge, such as FCC's alternating layers of protons and neutrons. One of the most impressive attributes of the FCC model is its replication of the properties of the IPM. We have as yet made no attempt to draw this correlation with the New Physics models.

The New Physics model is derived from work that has led to a simple, unified view of physics incorporating the strong nuclear force, light, and gravitation. The mechanism of gravitation is the quantum levels of particles restoring to their natural size; this is the first satisfactory explanation of the cause of gravitation since Newton posed the question. The accuracy of the New Physics model of the nucleus lends important credibility to that initial conclusion. With such a promising start further efforts to refine this alternative model of physics should continue to reveal new insights into the way the universe is constructed.

At CERN in Switzerland considerable effort is currently underway to discover the Higgs Boson predicted by the Standard Model of particle physics. The New Physics would say it is certainly possible for such a large particle to be created because the size of a particle is only limited by the amount of energy focused to create it. However unless additional bracing structures beyond the quark structures proposed here are discovered, it is unlikely such a large particle would last very long before collapsing. Nonetheless if the Higgs Boson is found it will likely be considered as "proof" of the Standard Model and it may be difficult to get much interest in alternative models. On the other hand if the elusive particle is not found then a promising alternative such as the New Physics will have to emerge.

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