Chapter

The Inter-Nucleon Up-to-Down Quark Bond and Its Implications for Nuclear Binding

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Abstract

This paper describes an interesting and potentially significant phenomenon regarding the properties of up and down quarks within the nucleus, specifically how the possible internucleon bonding of these quarks may affect the bonding energy of the nuclear force. A very simple calculation is used, which involves a bond between two internucleon up and down quarks. This simple calculation does not specify the shape or structure for the nucleus, rather this calculation only examines the energy of all possible internucleon up-to-down bonds that may be formed within a quantum nucleus. A comparison of this calculated binding energy is made to the experimental binding energy with remarkably good results. The potential significance and implications of this noteworthy finding are discussed.

Keywords: nuclear binding energy, nuclear force, nuclear bond, quarks, up quark, down quark, internucleon bond, quantum

1. Introduction

The nuclear force is defined as the force which binds the protons and neutrons together within a nucleus. One of the currently accepted models of the nuclear force is the liquid drop model [1]. This model of the nuclear force uses the Weizsäcker formula to predict the binding energies of nuclides. The Weizsäcker formula is a curve-fitting formula that uses five parameters, plus one conditional logic statement, in order to achieve its results [2]. These parameters are selected to empirically curve-fit an equation to match the experimental data. The liquid drop model is considered to be a "semi-classical" model of the nuclear force, rather than a quantum model [3].

Another currently accepted model of the nuclear force is the shell model, which uses magic numbers to explain certain nuclear behavior. The nuclear shell model is similar to the electronic shell model, which describes the electrons orbiting around an atom. However, the nuclear shell model does not predict the nuclear binding energy, rather the shell model defers back to the Weizsäcker formula for binding energy calculations.

A third currently accepted model of the nuclear force is the residual chromodynamic force (RCDF) model, also known as the residual strong force model.

Before describing this residual chromodynamic force, it is useful to mention a few specifics about quantum chromodynamics (QCD). Quantum chromodynamics postulates that the three valance quarks of protons and neutrons possess an attribute called "color charge." Historically, a contradiction of the quantum mechanical basis of nucleon properties with the Pauli Exclusion Principle led to the concept of the color charge for quarks [4]. The color charges of the quarks are considered to be either red, green, or blue. The words red, green, and blue are simply the names of the color charges and do not imply any type of physically visual hue for the quarks. Also, the term "charge", when referring specifically to the color charge, is not related to electric charge, which unfortunately can often be a point of confusion. Quantum chromodynamics states that a very strong bond is formed among the three color charges of the quarks inside the nucleon [5]. Both protons and neutrons have all three colors inside the nucleon.

The residual chromodynamic force model assumes that the chromodynamic force also has a weaker *residual* force outside of the nucleon. The RCDF model states that this residual force forms an internucleon bond, binding the nucleons together. The internucleon bond is formed by the residual chromodynamic force of the quarks outside of the nucleons. This is shown, in an illustrative representation, in **Figure 1**.

In **Figure 1**, the bold black line represents the chromodynamic force inside the nucleon, and the dotted gray line represents the residual chromodynamic force between two nucleons. (Note that quarks are considered to be point-like particles. Thus this drawing is not meant to be a scaled representation of the quarks, rather it is meant for illustrative purposes only.) The residual chromodynamic bond can be between any two quarks of different colors, such as between a red and blue, a green and red, or a blue and green. The residual chromodynamic bond can be between a neutron and a neutron, a proton and a neutron, or a proton and another proton.

While the RCDF model is considered to be the mechanism for nuclear bonding, the model is unable to duplicate the experimental binding energy curve. This inability of the RCDF model to reproduce this nuclear behavior is currently attributed to the extreme difficulty of modeling the multi-body interactions of the three color charges [6, 7]. This difficulty with the derivation of the nuclear binding forces from the residual chromodynamic force model is two-fold. First, each nucleon consists of three quarks, which means that a system of two nucleons is already a six-body problem. Second, because the chromodynamic force between quarks inside the nucleons has the feature of being very strong compared to the residual chromodynamic force outside the nucleons, this disproportionate ratio of strength makes a converging solution for the complicated mathematical calculations difficult to find. For nuclides with a small number of nucleons, the problem can be solved with

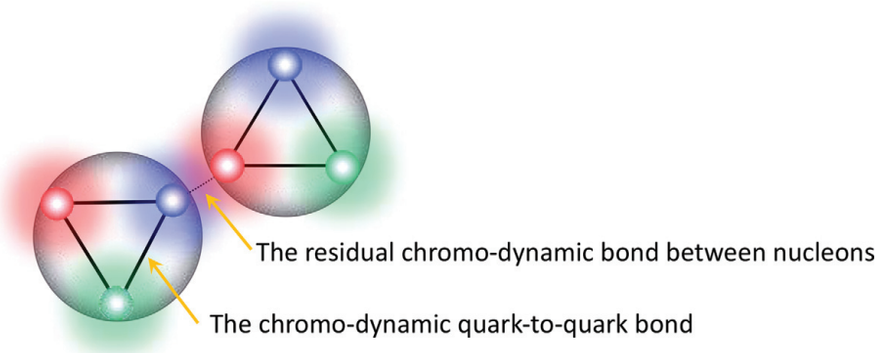

Figure 1.
An illustrative representation showing both the chromodynamic force and the residual chromodynamic force.

brute-force computing power by putting each of the quarks into a four-dimensional lattice of discrete points: three dimensions of space and one of time. This method is known as lattice quantum chromodynamics, or lattice QCD. This brute-force method for the computer calculations in lattice QCD iterates the position of each quark by assigning an x, y, z, and t position to it, calculating the resulting forces on each quark, allowing their position to change as a result of these forces, and then iterating this procedure until a resulting converging solution is found. If a converging solution is found, then these calculations are able to determine the binding energy of the nuclide in question. These computer calculations are done through extremely complex mathematical models, often using Monte-Carlo simulations [8]. Because of these computational difficulties, modeling the binding energies of only the smallest nuclides has been achieved.

However, such calculations are computationally expensive, requiring very large computers. Because of these complications, this modeling method is not normally used as a standard nuclear physics tool [7] .Thus, the RCDF model remains largely unverified when testing its binding energy predictions against experimental data.

2. Properties of up and down quarks

Besides having the attribute of color charge, there is also another attribute of quarks called flavor. From QCD theory, we know there are six different flavors of quarks: up, down, strange, charm, top, and bottom. Of these six different flavors, only two flavors are found in the stable matter of neutrons and protons: the up and down quarks [9]. (The terms of up and down do not imply any specific orientation with regard to spatial direction, and are simply the names of these types of quarks).

An up quark has an electric charge that is +2/3 the charge of a proton, and it also contains a positive magnetic moment. The up quark has a spin of ½ and a mass of about 0.3% of the proton. The color of an up quark can be either red, green, or blue. A down quark has an electric charge that is −1/3 the charge of a proton, and it contains a negative magnetic moment, which is anti-parallel to of the spin of the nuclide. The down quark has a spin of ½, and a mass of about 0.6% of the proton. The color of a down quark can be either red, green, or blue.

The magnetic moments of an up quark is estimated to be +1.85 and the magnetic moments of a down quark is estimated to be −0.97, both in units of nuclear magnetons. The electric charges of the proton and neutron are completely contained within the quarks. The proton is comprised of two up quarks and one down quark, giving it a net charge of one (2/3 + 2/3 -1/3 = 1). The neutron is comprised of one up quark and two down quarks, giving it a net charge of zero (2/3 -1/3 -1/3 = 0). **Figure 2** illustrates these properties.

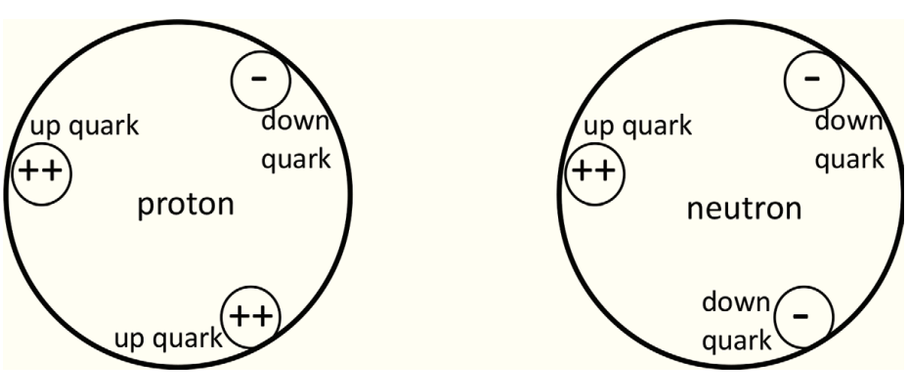

Figure 2.
An illustrative representation of the up and down quarks in a proton and neutron.

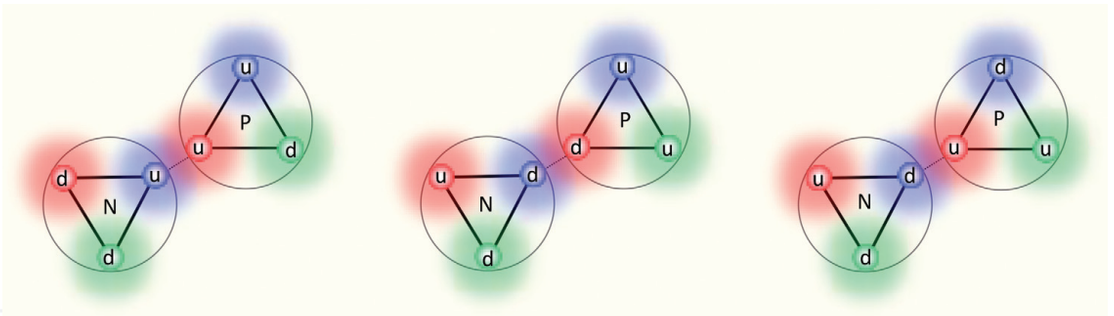

Figure 3.
Possible bonds in the RCDF model. A bond can be formed regardless of the flavor (up or down) of the quark.

The quarks inside of a proton and neutron have both attributes of flavor (up or down) and color (red, green, or blue). Thus, each quark inside of a proton or neutron is one of six types: up and red, up and green, up and blue, down and red, down and green, or down and blue [5]. Since both the neutron and the proton contain all three different colors, there is no difference between the proton and the neutron with regard to the attribute of color charges. The only difference in the quark characteristics between a proton or a neutron resides in the number of up and down quarks. Therefore, any bond between the different colors is also inherently a bond between some combination of the up and down quarks. Hence, the quantum assumptions that are made in the RCDF model about the possibility of an internucleon bond between the residual colors of quarks are also inherently applicable to the formation of an internucleon bond between up and down quarks.

Figure 3 shows three possible bonds, all of which are allowed in the RCDF model: a bond between two up quarks, between two down quarks, and between an up and a down quark. In the RCDF model, as long as the bond is between different colors of quarks, the up or down flavor of the quarks, is considered relatively unimportant.

Although it is considered relatively unimportant in the RCDF model, the up or down flavor of the quarks does indeed cause an energy difference among the three types of bonds that are illustrated in **Figure 3**. If there is an internucleon bond between two up quarks or between two down quarks, then the intrinsic electromagnetic force between these quarks is repulsive. Conversely, if there is an internucleon bond between an up quark and a down quark, then the intrinsic electromagnetic force between these quarks is attractive. Among the three types of bonds shown in **Figure 3**, this inherent difference in the electromagnetic energy may cause the two repulsive bonds to be less probable or less stable, producing a situation in which the up-to-down quark bond would be more prevalent in stable matter.

3. An additional constraint for internucleon quark-to-quark binding

As mentioned previously, the color charges of the quarks contained within a nucleon do not inherently distinguish between a neutron or proton; it is only the up and down attribute of the quarks that distinguish between the two types of stable nucleons. Thus, an examination of an internucleon bond being formed only between an up and a down quark is an appropriate possibility to explore. Specifically, this additional constraint is that not only must the internucleon quark-to-quark bond be between different colors, but also it must be between only an up and a down quark; specifically, it cannot be between two up quarks or two down quarks. If this quite reasonable constraint is made to the RCDF model, a quick calculation of

the allowed bonds can be easily made. By using the currently accepted RCDF concept of the internucleon quark-to-quark bond, and applying this additional constraint, in which bonds are only formed between up and down quarks, an interesting and potentially significant set of data emerges.

For any given nuclide, the number of internucleon up-to-down quark pairs can be determined, based on how many up and down quarks each nuclide has. This calculation, as shown in Eq. (1), is made for each nuclide.

$$\begin{aligned} Number_{up\ quarks} &= (Z \times 2) + (N \times 1) \\ Number_{down\ quarks} &= (Z \times 1) + (N \times 2) \\ Number_{possible\ pairs} &= the\ smaller\ of\ these\ two\ numbers \end{aligned} \tag{1}$$

For simplicity of this very quick and easy calculation, it is assumed that every bonded pair of up-to-down quarks has the same bonding energy. Thus, just for this simple calculation, the equation for the calculated binding energy (CBE) of a non-quantum nuclide is the number of internucleon up-to-down quark pairs times the binding energy per pair, as shown in Eq. (2).

$$CBE = (number\ of\ pairs) \times (binding\ energy\ per\ bonded\ pair) \tag{2}$$

For a representative sample of stable nuclides, this information is also shown in **Table 1**. For values of mass number with two stable nuclides, such as A = 40, both stable nuclides are shown. The following information is listed:

- The nuclide name
- The number of nucleons, A
- The number of protons, Z
- The number of neutrons, N
- The experimental binding energy (EBE) in units of MeV, as obtained from the nuclear tables in Ref. [10].
- The experimental binding energy per nucleon (EBE/A)
- The number of up quarks in the nuclide
- The number of down quarks in the nuclide
- The number or possible pairs between up and down quarks for the nuclide
- The classical (non-quantum) calculated binding energy (CBE) in MeV of the nuclide, for a fixed energy (6.000 MeV) per bond.

Figure 4 is a plot for this same a representative sample of nuclides, showing both the experimental binding energy per nucleon (EBE/A) and the non-quantum calculated binding energy per nucleon (CBE/A) for an object with a fixed energy (6.000 MeV) per bond. For this quick calculation, neither the type of bond nor the structure of these bonds comes into consideration. Simply stated, this is a

Nuclide	A	Z	N	EBE in MeV	EBE/A	# Of up quarks	# Of down quarks	# Of updown bonds, classical	Classical CBE/A
H2	2	1	1	2.225	1.11	3	3	3	9
He3	3	2	1	7.718	2.57	5	4	4	8
He4	4	2	2	28.296	7.07	6	6	6	9
He5	5	2	3	26.626	5.33	7	8	7	8.4
Li6	6	3	3	31.995	5.33	9	9	9	9
Li7	7	3	4	39.245	5.61	10	11	10	8.571
Be8	8	4	4	56.5	7.06	12	12	12	9
Be9	9	4	5	58.165	6.46	13	14	13	8.667
B10	10	5	5	64.751	6.48	15	15	15	9
B11	11	5	6	76.205	6.93	16	17	16	8.727
C12	12	6	6	92.162	7.68	18	18	18	9
C13	13	6	7	97.108	7.47	19	20	19	8.769
N14	14	7	7	104.659	7.48	21	21	21	9
N15	15	7	8	115.492	7.7	22	23	22	8.8
O16	16	8	8	127.619	7.98	24	24	24	9
O17	17	8	9	131.762	7.75	25	26	25	8.824
O18	18	8	10	139.808	7.77	26	28	26	8.667
F19	19	9	10	147.801	7.78	28	29	28	8.842
Ne20	20	10	10	160.65	8.03	30	30	30	9
Ne21	21	10	11	167.406	7.97	31	32	31	8.857
Ne22	22	10	12	177.77	8.08	32	34	32	8.727
Na23	23	11	12	186.564	8.11	34	35	34	8.87
Mg24	24	12	12	198.257	8.26	36	36	36	9
Mg25	25	12	13	205.587	8.22	37	38	37	8.88
Mg26	26	12	14	216.681	8.33	38	40	38	8.769
Al27	27	13	14	224.952	8.33	40	41	40	8.889
Si28	28	14	14	236.537	8.45	42	42	42	9
Si29	29	14	15	245.01	8.45	43	44	43	8.897
Si30	30	14	16	255.62	8.52	44	46	44	8.8
P31	31	15	16	262.917	8.48	46	47	46	8.903
S32	32	16	16	271.78	8.49	48	48	48	9
S33	33	16	17	280.422	8.5	49	50	49	8.909
S34	34	16	18	291.839	8.58	50	52	50	8.824
Cl35	35	17	18	298.21	8.52	52	53	52	8.914
S36	36	16	20	308.71	8.58	52	56	52	8.667
Ar36	36	18	18	306.716	8.52	54	54	54	9
Cl37	37	17	20	318.784	8.62	54	57	54	8.757
Ar38	38	18	20	327.343	8.61	56	58	56	8.842
K39	39	19	20	333.724	8.56	58	59	58	8.923
Ar40	40	18	22	343.81	8.6	58	62	58	8.7

Nuclide	A	Z	N	EBE in MeV	EBE/A	# Of up quarks	# Of down quarks	# Of updown bonds, classical	Classical CBE/A
Ca40	40	20	20	342.053	8.55	60	60	60	9
K41	41	19	22	351.619	8.58	60	63	60	8.78
Ca42	42	20	22	361.895	8.62	62	64	62	8.857
Ca43	43	20	23	369.828	8.6	63	66	63	8.791
Ca44	44	20	24	380.96	8.66	64	68	64	8.727
Sc45	45	21	24	387.849	8.62	66	69	66	8.8
Ca46	46	20	26	398.772	8.67	66	72	66	8.609
Ti46	46	22	24	398.194	8.66	68	70	68	8.87
Ti47	47	22	25	407.072	8.66	69	72	69	8.809
Ca48	48	20	28	415.992	8.67	68	76	68	8.5
Ti48	48	22	26	418.699	8.72	70	74	70	8.75
Ti49	49	22	27	426.841	8.71	71	76	71	8.694
Ti50	50	22	28	437.78	8.76	72	78	72	8.64
Cr50	50	24	26	435.047	8.7	74	76	74	8.88
V51	51	23	28	445.842	8.74	74	79	74	8.706
Cr52	52	24	28	456.345	8.78	76	80	76	8.769
Cr53	53	24	29	464.287	8.76	77	82	77	8.717
Cr54	54	24	30	474.009	8.78	78	84	78	8.667
Fe54	54	26	28	471.765	8.74	80	82	80	8.889
Mn55	55	25	30	482.075	8.77	80	85	80	8.727
Fe56	56	26	30	492.257	8.79	82	86	82	8.786
Fe57	57	26	31	499.905	8.77	83	88	83	8.737
Fe58	58	26	32	509.945	8.79	84	90	84	8.69
Ni58	58	28	30	506.456	8.73	86	88	86	8.897
Co59	59	27	32	517.314	8.77	86	91	86	8.746
Ni60	60	28	32	526.842	8.78	88	92	88	8.8
Zn70	70	30	40	611.08	8.73	100	110	100	8.571
Ge70	70	32	38	610.519	8.72	102	108	102	8.743
Se80	80	34	46	696.867	8.71	114	126	114	8.55
Kr80	80	36	44	695.438	8.69	116	124	116	8.7
Zr90	90	40	50	783.895	8.71	130	140	130	8.667
Ru100	100	44	56	861.929	8.62	144	156	144	8.64
Cd113	113	48	65	963.557	8.53	161	178	161	8.549
In113	113	49	64	963.091	8.52	162	177	162	8.602
Sn117	117	50	67	995.623	8.51	167	184	167	8.564
Xe129	129	54	75	1087.648	8.43	183	204	183	8.512
Ce142	142	58	84	1185.28	8.35	200	226	200	8.451
Nd142	142	60	82	1185.148	8.35	202	224	202	8.535
Sm150	150	62	88	1239.253	8.26	212	238	212	8.48
Gd150	150	64	86	1236.39	8.24	214	236	214	8.56

Nuclide	A	Z	N	EBE in MeV	EBE/A	# Of up quarks	# Of down quarks	# Of updown bonds, classical	Classical CBE/A
Dy162	162	66	96	1323.884	8.17	228	258	228	8.444
Yb172	172	70	102	1392.764	8.1	242	274	242	8.442
W183	183	74	109	1465.526	8.01	257	292	257	8.426
Pt194	194	78	116	1539.578	7.94	272	310	272	8.412
Au197	197	79	118	1559.397	7.92	276	315	276	8.406
Hg200	200	80	120	1581.207	7.91	280	320	280	8.4
Hg204	204	80	124	1608.65	7.89	284	328	284	8.353
Pb204	204	82	122	1605.343	7.87	286	326	286	8.412

Table 1.
A, Z, N, EBE, EBE/a, # up quarks, # down quarks, # possible bonds, and non-quantum calculated binding energy (classical CBE) for a representative sample of nuclides.

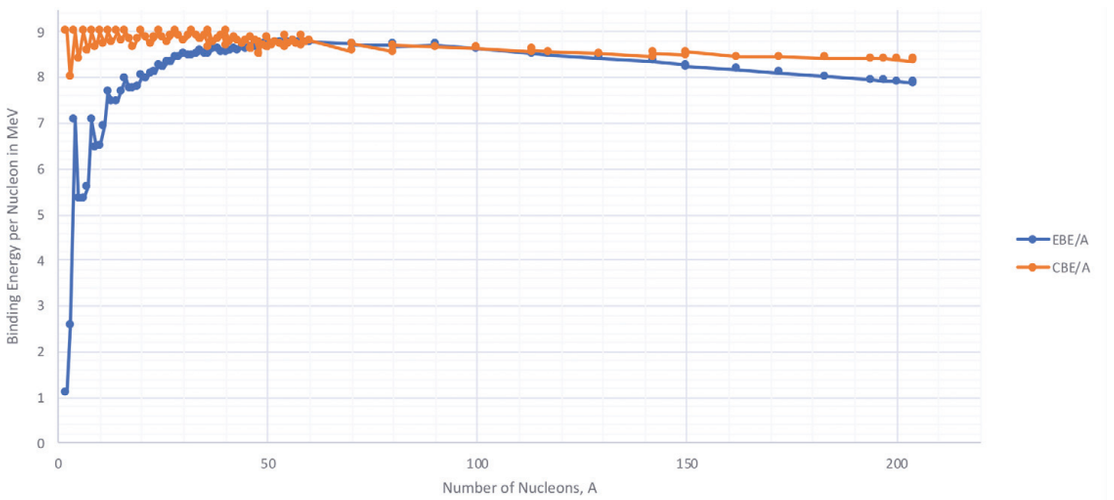

Figure 4.
In blue, a plot of the experimental binding energy (EBE) per nucleon. In orange, a plot of the calculated binding energy (CBE) per nucleon, based on the number of possible non-quantum up-to-down quark pairs and a fixed binding energy per bonded pair.

theory-independent calculation of the number of possible bonded pairs times a fixed binding energy per bonded pair.

4. Quantum considerations

A nucleus is a quantum object, and being so, certain quantum rules must apply. A known phenomenological feature of the nuclear force is the QCD hard-core repulsion. The hard-core repulsion states that nucleons, such as a proton or neutron, cannot overlap in their spatial location [11, 12]. If too many bonds are formed for either ^{2}H or ^{3}H or ^{3}He, overlap will occur. This overlap is illustrated in **Figure 5**.

To prevent this overlap, hydrogen ^{2}H can have only one bond instead of two or three. Similarly, helium ^{3}He (as well as hydrogen ^{3}H) can have only three bonds instead of four or five. Three other nuclides are subject to this constraint, those with odd-odd configurations: ^{6}Li, ^{10}B, and ^{14}N. Specifically, the odd neutron and the odd proton cannot bond twice to either each other or to another nucleon. Other stable nuclides are not affected by the application of this rule, since there are enough nucleons to prevent an overlap from occurring for the larger nuclides.

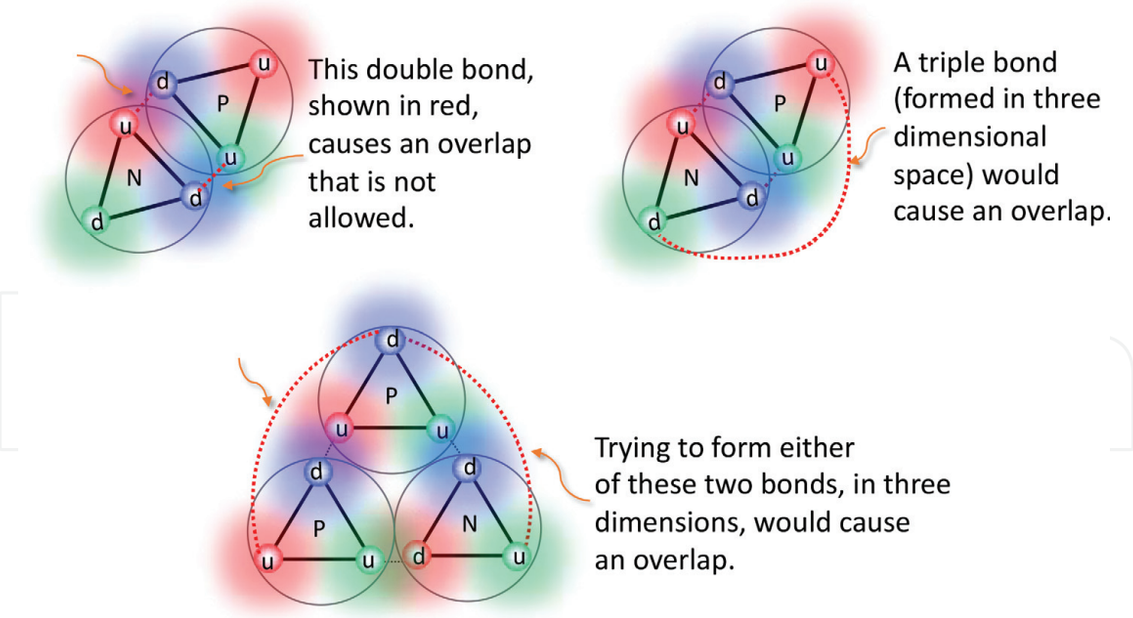

Figure 5.
An illustration of the overlapping nucleons if too many bonds are attempted. For the nuclide ^{2}H, if two or three bonds are attempted, indicated by the red bonds, an overlap occurs. Similarly, ^{3}He can form only three bonds. If four or five are attempted, an overlap occurs in three dimensions.

Quantum mechanics also states there can be no net electric dipole moment for the nuclide [13, 14]. For this second quantum rule, three more bonds must be subtracted from the number of bonds available, in order to remove the electric dipole moment. Without stating any specific configuration for the nuclide, this reduction of bonds can be best understood from the fact that the electric charge distribution of the nuclide must not have a net asymmetry in electrical charge for any of the three spatial dimensions, x, y, or z. To prevent an electric dipole moment, a bond is broken in each of these three dimensions, so that the net charge is symmetric about the x, y, and z axes. This quantum requirement removes three of the classically-allowed bonds. This rule applies to all stable nuclides, except for the three very smallest stable nuclides, ^{2}H, ^{3}He, and ^{4}He.

The inclusion of these two quantum rules is shown in **Table 2**. The first 8 columns of **Table 2** are similar to the first 8 columns of **Table 1**. Also shown in **Table 2** is the number of possible quantum bonds for each nuclide, taking into consideration the two above mentioned quantum rules. The last three columns of **Table 2** show the quantum calculated binding energy, the CBE/A, and the percent error of that calculated energy, as compared with the experimental binding energy.

As before for this simple calculation, the calculated binding energy is the number of bonds times a fixed energy per bond. The energy per bond is the only selected parameter; for this simple calculation, it is 6.000 MeV per bond. These plots take into consideration the quantum rules of hard-core repulsion and zero electric dipole moment. These data are plotted in **Figures 6** and 7. In **Figure 6**, a representative sample of all of the stable nuclides is shown, out to lead 204Pb. In **Figure 7**, only the first 60 nuclides are plotted, to show the detail. As before, when there is more than one stable nuclide for a given mass number, these additional points are plotted as well.

To reiterate, this is a very quick and easy calculation, only involving a simple numerical count of quantum-allowed internucleon up-to-down quark pairs. This calculation does not specify the arrangement of the nucleons or the mechanism of the bond. It is simply a count of the quantum-allowed up-to-down quark bonds.

Nuclide	A	Z	N	EBE in MeV	EBE/A	# Of up quarks	# Of down quarks	# Of updown bonds, classical	# Of updown bonds, quantum	Calculated binding energy (CBE) in MeV	CBE/A	%Error
H2	2	1	1	2.225	1.11	3	3	3	1	6	3	−169.66
He3	3	2	1	7.718	2.57	5	4	4	3	18	6	−133.22
He4	4	2	2	28.296	7.07	6	6	6	6	36	9	−27.23
He5	5	2	3	26.626	5.33	7	8	7	4	24	4.8	9.86
Li6	6	3	3	31.995	5.33	9	9	9	5	30	5	6.24
Li7	7	3	4	39.245	5.61	10	11	10	7	42	6	−7.02
Be8	8	4	4	56.5	7.06	12	12	12	9	54	6.75	4.42
Be9	9	4	5	58.165	6.46	13	14	13	10	60	6.667	−3.15
B10	10	5	5	64.751	6.48	15	15	15	11	66	6.6	−1.93
B11	11	5	6	76.205	6.93	16	17	16	13	78	7.091	−2.36
C12	12	6	6	92.162	7.68	18	18	18	15	90	7.5	2.35
C13	13	6	7	97.108	7.47	19	20	19	16	96	7.385	1.14
N14	14	7	7	104.659	7.48	21	21	21	17	102	7.286	2.54
N15	15	7	8	115.492	7.7	22	23	22	19	114	7.6	1.29
O16	16	8	8	127.619	7.98	24	24	24	21	126	7.875	1.27
O17	17	8	9	131.762	7.75	25	26	25	22	132	7.765	−0.18
O18	18	8	10	139.808	7.77	26	28	26	23	138	7.667	1.29
F19	19	9	10	147.801	7.78	28	29	28	25	150	7.895	−1.49
Ne20	20	10	10	160.65	8.03	30	30	30	27	162	8.1	−0.84
Ne21	21	10	11	167.406	7.97	31	32	31	28	168	8	−0.35
Ne22	22	10	12	177.77	8.08	32	34	32	29	174	7.909	2.12
Na23	23	11	12	186.564	8.11	34	35	34	31	186	8.087	0.3
Mg24	24	12	12	198.257	8.26	36	36	36	33	198	8.25	0.13

Nuclide	A	Z	N	EBE in MeV	EBE/A	# Of up quarks	# Of down quarks	# Of updown bonds, classical	# Of updown bonds, quantum	Calculated binding energy (CBE) in MeV	CBE/A	%Error
Mg25	25	12	13	205.587	8.22	37	38	37	34	204	8.16	0.77
Mg26	26	12	14	216.681	8.33	38	40	38	35	210	8.077	3.08
Al27	27	13	14	224.952	8.33	40	41	40	37	222	8.222	1.31
Si28	28	14	14	236.537	8.45	42	42	42	39	234	8.357	1.07
Si29	29	14	15	245.01	8.45	43	44	43	40	240	8.276	2.04
Si30	30	14	16	255.62	8.52	44	46	44	41	246	8.2	3.76
P31	31	15	16	262.917	8.48	46	47	46	43	258	8.323	1.87
S32	32	16	16	271.78	8.49	48	48	48	45	270	8.438	0.65
S33	33	16	17	280.422	8.5	49	50	49	46	276	8.364	1.58
S34	34	16	18	291.839	8.58	50	52	50	47	282	8.294	3.37
Cl35	35	17	18	298.21	8.52	52	53	52	49	294	8.4	1.41
S36	36	16	20	308.71	8.58	52	56	52	49	294	8.167	4.76
Ar36	36	18	18	306.716	8.52	54	54	54	51	306	8.5	0.23
Cl37	37	17	20	318.784	8.62	54	57	54	51	306	8.27	4.01
Ar38	38	18	20	327.343	8.61	56	58	56	53	318	8.368	2.85
K39	39	19	20	333.724	8.56	58	59	58	55	330	8.462	1.12
Ar40	40	18	22	343.81	8.6	58	62	58	55	330	8.25	4.02
Ca40	40	20	20	342.053	8.55	60	60	60	57	342	8.55	0.02
K41	41	19	22	351.619	8.58	60	63	60	57	342	8.341	2.74
Ca42	42	20	22	361.895	8.62	62	64	62	59	354	8.429	2.18
Ca43	43	20	23	369.828	8.6	63	66	63	60	360	8.372	2.66
Ca44	44	20	24	380.96	8.66	64	68	64	61	366	8.318	3.93
Sc45	45	21	24	387.849	8.62	66	69	66	63	378	8.4	2.54

Nuclide	A	Z	N	EBE in MeV	EBE/A	# Of up quarks	# Of down quarks	# Of updown bonds, classical	# Of updown bonds, quantum	Calculated binding energy (CBE) in MeV	CBE/A	%Error
Ca46	46	20	26	398.772	8.67	66	72	66	63	378	8.217	5.21
Ti46	46	22	24	398.194	8.66	68	70	68	65	390	8.478	2.06
Ti47	47	22	25	407.072	8.66	69	72	69	66	396	8.426	2.72
Ca48	48	20	28	415.992	8.67	68	76	68	65	390	8.125	6.25
Ti48	48	22	26	418.699	8.72	70	74	70	67	402	8.375	3.99
Ti49	49	22	27	426.841	8.71	71	76	71	68	408	8.327	4.41
Ti50	50	22	28	437.78	8.76	72	78	72	69	414	8.28	5.43
Cr50	50	24	26	435.047	8.7	74	76	74	71	426	8.52	2.08
V51	51	23	28	445.842	8.74	74	79	74	71	426	8.353	4.45
Cr52	52	24	28	456.345	8.78	76	80	76	73	438	8.423	4.02
Cr53	53	24	29	464.287	8.76	77	82	77	74	444	8.377	4.37
Cr54	54	24	30	474.009	8.78	78	84	78	75	450	8.333	5.07
Fe54	54	26	28	471.765	8.74	80	82	80	77	462	8.556	2.07
Mn55	55	25	30	482.075	8.77	80	85	80	77	462	8.4	4.16
Fe56	56	26	30	492.257	8.79	82	86	82	79	474	8.464	3.71
Fe57	57	26	31	499.905	8.77	83	88	83	80	480	8.421	3.98
Fe58	58	26	32	509.945	8.79	84	90	84	81	486	8.379	4.7
Ni58	58	28	30	506.456	8.73	86	88	86	83	498	8.586	1.67
Co59	59	27	32	517.314	8.77	86	91	86	83	498	8.441	3.73
Ni60	60	28	32	526.842	8.78	88	92	88	85	510	8.5	3.2
Zn70	70	30	40	611.08	8.73	100	110	100	97	582	8.314	4.76
Ge70	70	32	38	610.519	8.72	102	108	102	99	594	8.486	2.71
Se80	80	34	46	696.867	8.71	114	126	114	111	666	8.325	4.43

Nuclide	A	Z	N	EBE in MeV	EBE/A	# Of up quarks	# Of down quarks	# Of updown bonds, classical	# Of updown bonds, quantum	Calculated binding energy (CBE) in MeV	CBE/A	%Error
Kr80	80	36	44	695.438	8.69	116	124	116	113	678	8.475	2.51
Zr90	90	40	50	783.895	8.71	130	140	130	127	762	8.467	2.79
Ru100	100	44	56	861.929	8.62	144	156	144	141	846	8.46	1.85
Cd113	113	48	65	963.557	8.53	161	178	161	158	948	8.389	1.61
In113	113	49	64	963.091	8.52	162	177	162	159	954	8.442	0.94
Sn117	117	50	67	995.623	8.51	167	184	167	164	984	8.41	1.17
Xe129	129	54	75	1087.648	8.43	183	204	183	180	1080	8.372	0.7
Ce142	142	58	84	1185.28	8.35	200	226	200	197	1182	8.324	0.28
Nd142	142	60	82	1185.148	8.35	202	224	202	199	1194	8.408	−0.75
Sm150	150	62	88	1239.253	8.26	212	238	212	209	1254	8.36	−1.19
Gd150	150	64	86	1236.39	8.24	214	236	214	211	1266	8.44	−2.39
Dy162	162	66	96	1323.884	8.17	228	258	228	225	1350	8.333	−1.97
Yb172	172	70	102	1392.764	8.1	242	274	242	239	1434	8.337	−2.96
W183	183	74	109	1465.526	8.01	257	292	257	254	1524	8.328	−3.99
Pt194	194	78	116	1539.578	7.94	272	310	272	269	1614	8.32	−4.83
Au197	197	79	118	1559.397	7.92	276	315	276	273	1638	8.315	−5.04
Hg200	200	80	120	1581.207	7.91	280	320	280	277	1662	8.31	−5.11
Hg204	204	80	124	1608.65	7.89	284	328	284	281	1686	8.265	−4.81
Pb204	204	82	122	1605.343	7.87	286	326	286	283	1698	8.324	−5.77

Table 2.
A representative sample of nuclides, showing quantum-allowed bonded up-to-down quark pairs for each nuclide.

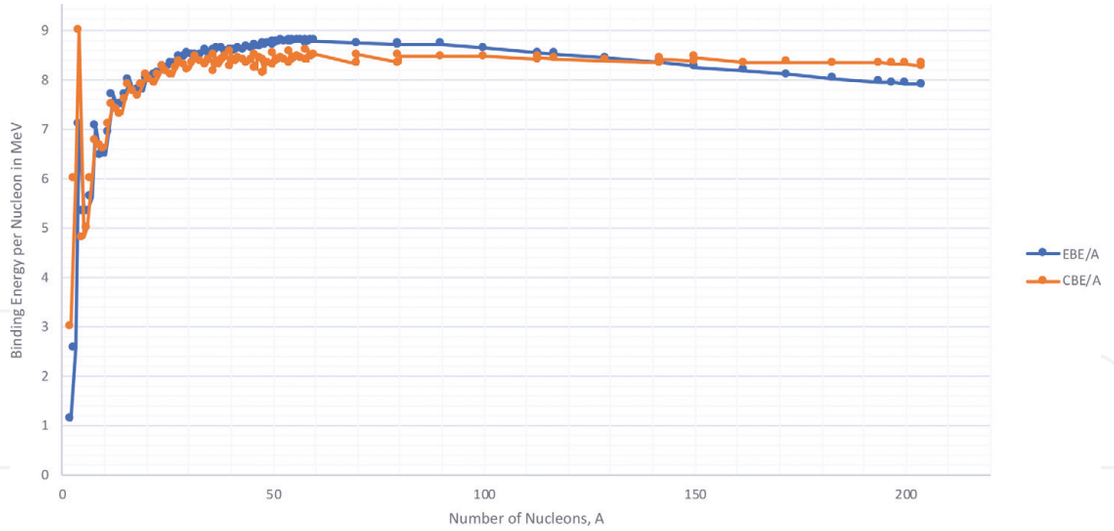

Figure 6.
A plot of the experimental nuclear binding energy per nucleon (blue) and the simple quantum calculated binding energy (orange).

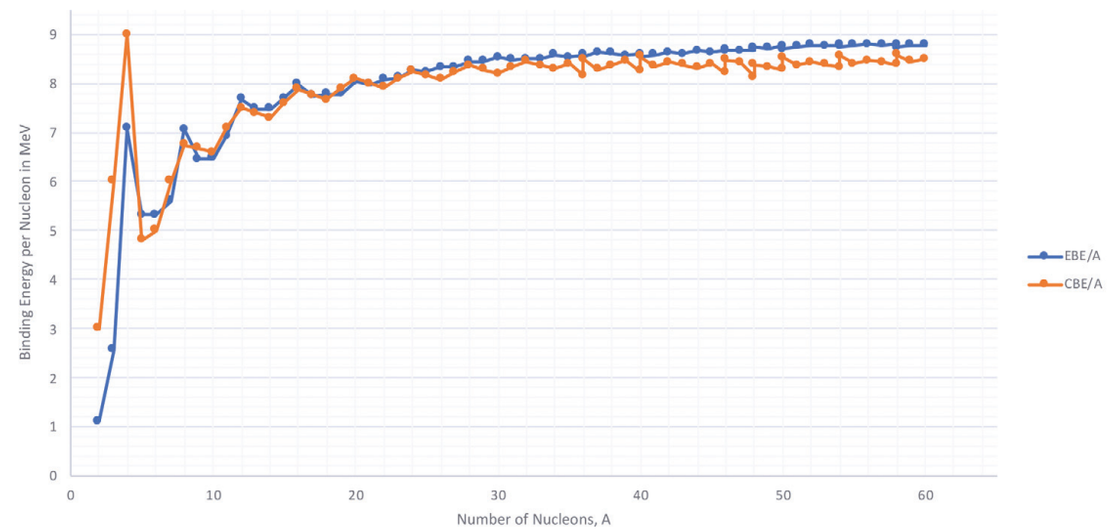

Figure 7.
A plot of the experimental nuclear binding energy per nucleon (blue) and the simple quantum calculated binding energy (orange) for only the first 60 nuclides.

Other than being quantum, this calculation is theory independent, and as such, it is not subject to theoretical criticisms or theoretical differences of opinion.

5. Discussion

The excellent reproduction of the experimental data for these calculated results is impressive, especially considering that there is only one empirically-selected variable for this calculation, the value of 6.000 MeV for the bond energy, instead of the five empirically-selected variables for the Weizsäcker formula. This reproduction of the experimental data is especially impressive considering that other currently accepted nuclear theories cannot easily duplicate this curve.

In terms of the possible mechanism for the bond, the residual chromodynamic force between the color charges for internucleon quark-to-quark bonding is one possibility. Another possibility for this bond becomes apparent when it is recalled

that the up quark has an electric charge +2/3 the charge of a proton, the down quark has an electric charge of −1/3 the charge of a proton, and both quarks carry a magnetic moment. These electromagnetic properties of the up and down quarks create a strong attractive electromagnetic force between the up and the down quarks; the strength of this electromagnetic force is dependent only on the minimum proximity between the up and down quarks engaged in the bond. Historically, it was believed that the strength of the electromagnetic force had an upper limit, based on the misconceptions that protons were homogeneously charged and that quarks did not exist. However, these misconceived notions are invalid when quarks, which contain all of the electric charge for the nucleons, are taken into consideration.

The internuclear quark-to-quark bond is most likely some combination of both the electromagnetic charge and the color charge of the quarks, but the relative percentages of these two contributions is not postulated here. Regardless of the relative percentages, the electromagnetic component of this bond should not be ignored–as is usually the case in current theories. When any internucleon quark-to-quark bond is considered, the electromagnetic component must be taken into full account, rather than being considered relatively unimportant. A more detailed analysis of the electromagnetic contribution of this internucleon up-to-down quark bonding can easily be made by using the standard electromagnetic Eqs. A detailed analysis would include the addition of the energy due to all electric charges interacting with each other. In other words, this would be a double summation of the interaction for each electric charge of each quark with every other electric charge on all other quarks [15]. This double summation calculation would inherently include the Coulomb energy of the net repulsive electric energies among the protons.

Similarly, a more detailed electromagnetic analysis would also include the variation of the electromagnetic bond due to the vector orientation of the magnetic moments of the quarks. The energy of the magnetic moments interacting with each other should be included, which again would be a double summation for the magnetic interaction for all of the magnetic moment vectors [16]. Finally, the kinetic energy of the quantum spin of the nuclide should also be included in this more detailed binding energy calculation [17, 18]. However, for this more detailed and accurate calculation to be done, the lowest energy configuration of the nuclide must be determined and specified before the electromagnetic interaction energies can be accurately calculated.

6. Conclusion

An extremely simple calculation of the internucleon up-to-down quark bonding has been made, giving excellent results in duplicating the nuclear binding energy curve, using only one parameter rather than five. The resulting errors for nuclides going up to lead ^{204}Pb are only few percent. The average error, going from A = 10 to A = 60, is only 2.32% with a standard deviation for that error of only 1.91%. Also, due to the inherent similarities of this concept to the currently accepted residual chromodynamic force model, with its quark-to-quark internucleon bonding, the existence of an internucleon up-to-down quark bond cannot be relegated as implausible.

An obvious implication of these results is that a significant part of the nuclear force is electromagnetic. To some, this may be an unexpected implication, but not unfeasible, especially when the electromagnetic attraction of the up-to-down quarks is considered. If one only considers, as is the case historically, that

homogenously charged protons cannot bond to other homogeneously charged protons, then the concept that the nuclear force could be partially electromagnetic is deemed implausible. However, with the understanding that the electrical charges of the up and down quarks are able to attract each other and bond to each other, and given that the RCDF allows a quark-to-quark internucleon bond to occur, such restrictions about the nuclear force being partly electromagnetic are no longer relevant.

The excellent reproduction of experimental binding energy data with only one empirically-selected variable strongly suggests that the internucleon up-to-down quark bonding is a concept that should be seriously considered and more thoroughly examined by nuclear physicists.

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