A Simple Calculation of 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, and how the possible inter-nucleon 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 inter-nucleon up and down quarks. This simple calculation does not depend on the type or mechanism for the bond; furthermore, this simple calculation does not specify the shape or structure for the nucleus. This calculation only examines the energy of all possible up-to-down inter-nucleon bonds that may be formed within a quantum nucleus. A comparison of this total energy is made to the experimental binding energy with excellent results. The potential significance of this finding is briefly discussed.

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 [2] 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. These five parameters are selected to empirically curve-fit the equation to the experimental data. The liquid drop model is considered to be a "semi-classical" model of the nuclear force [3].

Another currently-accepted model of the nuclear force is the residual chromo-dynamic force model (abbreviated as the RCDF model in this paper). Before describing this residual force, it is useful to mention a few specifics about quantum chromo-dynamics (QCD). Quantum chromo-dynamics hypothesizes that the three valance quarks of protons and neutrons possess an attribute called color charge--either red, green, or blue. 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]. (It should be noted that 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 electrical charge.) Quantum chromo-dynamics states that a strong three-way bond is formed among the three color charges of the quarks *inside* the nucleon [5].

The residual chromo-dynamic force model assumes that the chromo-dynamic force also has a weaker residual force *outside* of the nucleon. The RCDF model states that this residual force forms an inter-nucleon bond, bonding the two different nucleons together. The inter-nucleon bond is formed by the residual color charges of the quarks.

While the RCDF model is considered to be the *mechanism* for nuclear bonding, the model is unable to duplicate the experimental bonding energy curve. This inability of the RCDF model to reproduce any salient nuclear behaviors currently is attributed to the extreme difficulty of modeling the multi-body interactions of the three-color quark charges [6, 7].

The problem with the derivation of nuclear forces from the residual quantum chromo-dynamic force 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 chromodynamics force between quarks has the feature of being very strong compared to the lower energy scale of the residual chromo-dynamic force, this extraordinary strength makes it difficult to find converging mathematical solutions. The six-quark problem can be solved with brute computing power, by putting the six-quark system on a four dimensional lattice of discrete points: three dimensions of space and one of time. This method has become known as lattice quantum chromo-dynamics, or lattice QCD. However, such calculations are computationally very expensive and are not normally used as a standard nuclear physics tool [7]. Only the liquid drop model, with its the five empirically-fit parameters, can duplicate this experimental binding curve.

To re-iterate, the brute-force method for the computer calculations in lattice QCD puts each quark in a lattice by assigning to it an x, y, z, and t position, and then attempts to determine the binding energy. This is done through extremely complex mathematical models and often using Monte-Carlo simulations [8]. Because of the computational difficulties, binding energies of only the smallest nuclides, A<14, have been attempted. Thus, the RCDF model remains largely unverified when testing its binding energy predictions against experimental data.

2. Properties of Up and Down Quarks

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, which is parallel to of the spin of the nuclide. The up quark has a spin of ½ and a mass of about 0.3% of the proton. The color charge 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 charge of a down quark can be either red, green, or blue.

The magnetic moments of the up and down quarks are estimated to be +1.85 and -0.97 respectively, in units of nuclear magnetons. The electrical 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 +1. The neutron is comprised of one up quark and two down quarks, giving it a net charge of 0.

The quarks inside of a proton and neutron have both attributes of flavor and color. 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]. Both the neutron and the proton contain one each of the three different color charges: red, green, and blue. Thus in terms of the color charges, there is no difference between the proton and the neutron; the only difference in the quark characteristics between a proton or neutron resides in the number of up and down quarks. Any bond between the different color charges is, therefore, also a bond between up and down quarks. Thus, the quantum assumptions that are made in the RCDF model about the possibility of an inter-nucleon bond between the residual color charges of the quarks are, identically, applicable to the formation of an inter-nucleon bond between up and down quarks.

3. A Simple Calculation Involving Inter-Nucleon Up-to-Down Quarks

Using the concept of the inter-nucleon quark-to-quark bond, and applying this concept to the up and down quarks, an interesting and potentially significant set of data emerges.

Table 1 shows a spread sheet, with a representative sample of stable nuclides. The following information is listed in this spread sheet for every nuclide:

- The nuclide name
- The number of nucleons, A, which is the sum of neutrons plus protons
- The number of protons, Z
- The number of neutrons, N
- The Experimental Binding Energy in units of MeV, as obtained from the nuclear tables [10]
- The Experimental Binding Energy per nucleon
- Other columns, which are described below.

A plot of the Experimental Binding Energy per nucleon is shown in Fig. 1; this plot is similar to the usual diagrams for the nuclear binding found in textbooks.

For any given nuclide, the number of inter-nucleon up-to-down quark pairs can be determined, based on how many up and down quarks each nuclide has. For each nuclide in the table, this calculation is made, as shown in equation (1).

$$\begin{aligned} &NumberOfUpQuarks = (Z \times 2) + (N \times 1) \\ &NumberOfDownQuarks = (Z \times 1) + (N \times 2) \qquad (1) \\ &NumberOfPossiblePairs \\ &\qquad = the\ smaller\ of\ these\ two\ numbers \end{aligned}$$

This information has been incorporated into three additional columns in Table 1, showing the number of up quarks, the number of down quarks, and the number of possible up-to-down quark pairs, for each of the nuclides.

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 binding energy of a nuclide is the number of inter-nucleon up-to-down quark pairs times the binding energy per pair, as shown in equation (2).

$$\begin{aligned} &Calculated\ Binding\ Energy = (number\ of\ pairs) \times \\ &(binding\ energy\ per\ bonded\ pair) \qquad (2) \end{aligned}$$

The binding energy per bonded pair is the same value for all of the nuclides, and this parameter is selected to match the experimental data. Shown is Fig. 2 is a plot of this binding energy per nucleon for a classical (non-quantum) object.

Note that for Fig. 2, neither the *type* of bond nor the *structure* of these bonds comes into consideration; this is simply the number of possible pairs times a fixed binding energy per bonded pair.

However, 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]. The application of this phenomenon to this simple calculation reduces the number of bonds for only the two smallest nuclides. To prevent this overlap, hydrogen ^{2}H can have only one bond instead of three, and helium ^{3}He can have only three bonds instead of four. Three other stable nuclides are affected by this, the ones in which Z is odd and N=Z. These are ^{6}Li, ^{10}B, and ^{14}N. Other nuclides are not affected by the application of this rule, for this simple calculation.

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 in this very simplified calculation, this reduction of bonds can be best understood from the fact that the electric charge distribution of the nuclide must not have a net difference 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 nuclides, except for the very smallest nuclides, ^{2}H, ^{3}He, and ^{4}He.

Nuclide	A	Z	N	Experimental Binding Energy in MeV	(Experimental Binding Energy)/A	# of up quarks	# of down quarks	# of possible matched pairs of up-down quarks
H2	2	1	1	2.225	1.113	3	3	3
He3	3	2	1	7.718	2.573	5	4	4
He4	4	2	2	28.296	7.074	6	6	6
He5	5	2	3	26.626	5.325	7	8	7
Li6	6	3	3	31.995	5.333	9	9	9
Li7	7	3	4	39.245	5.606	10	11	10
Be8	8	4	4	56.5	7.063	12	12	12
Be9	9	4	5	58.165	6.463	13	14	13
B10	10	5	5	64.751	6.475	15	15	15
B11	11	5	6	76.205	6.928	16	17	16
C12	12	6	6	92.162	7.68	18	18	18
C13	13	6	7	97.108	7.47	19	20	19
N14	14	7	7	104.659	7.476	21	21	21
N15	15	7	8	115.492	7.699	22	23	22
O16	16	8	8	127.619	7.976	24	24	24
O17	17	8	9	131.762	7.751	25	26	25
O18	18	8	10	139.808	7.767	26	28	26
F19	19	9	10	147.801	7.779	28	29	28
Ne20	20	10	10	160.65	8.033	30	30	30
Ne21	21	10	11	167.406	7.972	31	32	31
Ne22	22	10	12	177.77	8.08	32	34	32
Na23	23	11	12	186.564	8.111	34	35	34
Mg24	24	12	12	198.257	8.261	36	36	36
Mg25	25	12	13	205.587	8.223	37	38	37
Mg26	26	12	14	216.681	8.334	38	40	38
Al27	27	13	14	224.952	8.332	40	41	40
Si28	28	14	14	236.537	8.448	42	42	42
Si29	29	14	15	245.01	8.449	43	44	43
Si30	30	14	16	255.62	8.521	44	46	44
P31	31	15	16	262.917	8.481	46	47	46
S32	32	16	16	271.78	8.493	48	48	48
S33	33	16	17	280.422	8.498	49	50	49
S34	34	16	18	291.839	8.584	50	52	50
Cl35	35	17	18	298.21	8.52	52	53	52
Ar36	36	18	18	306.716	8.52	54	54	54
Cl37	37	17	20	318.784	8.616	54	57	54
Ar38	38	18	20	327.343	8.614	56	58	56
K39	39	19	20	333.724	8.557	58	59	58
Ca40	40	20	20	342.053	8.551	60	60	60
K41	41	19	22	351.619	8.576	60	63	60
Ca42	42	20	22	361.895	8.617	62	64	62
Ca43	43	20	23	369.828	8.601	63	66	63
Ca44	44	20	24	380.96	8.658	64	68	64
Sc45	45	21	24	387.849	8.619	66	69	66
Ti46	46	22	24	398.194	8.656	68	70	68
Ti47	47	22	25	407.072	8.661	69	72	69
Ti48	48	22	26	418.699	8.723	70	74	70
Ti49	49	22	27	426.841	8.711	71	76	71
Ti50	50	22	28	437.78	8.756	72	78	72
V51	51	23	28	445.842	8.742	74	79	74
Cr52	52	24	28	456.345	8.776	76	80	76
Cr53	53	24	29	464.287	8.76	77	82	77
Cr54	54	24	30	474.009	8.778	78	84	78
Mn55	55	25	30	482.075	8.765	80	85	80
Fe56	56	26	30	492.257	8.79	82	86	82
Fe57	57	26	31	499.905	8.77	83	88	83
Fe58	58	26	32	509.945	8.792	84	90	84
Co59	59	27	32	517.314	8.768	86	91	86
Ni60	60	28	32	526.842	8.781	88	92	88
Ge70	70	32	38	610.519	8.722	102	108	102
Kr80	80	36	44	695.438	8.693	116	124	116
Zr90	90	40	50	783.895	8.71	130	140	130
Ru100	100	44	56	861.929	8.619	144	156	144
Cd113	113	48	65	963.557	8.527	161	178	161
Sn117	117	50	67	995.623	8.51	167	184	167
Xe129	129	54	75	1087.648	8.431	183	204	183
Nd142	142	60	82	1185.148	8.346	202	224	202
Sm150	150	62	88	1239.253	8.262	212	238	212
Dy162	162	66	96	1323.884	8.172	228	258	228
Yb172	172	70	102	1392.764	8.097	242	274	242
W183	183	74	109	1465.526	8.008	257	292	257
Pt194	194	78	116	1539.578	7.936	272	310	272
Au197	197	79	118	1559.397	7.916	276	315	276
Hg200	200	80	120	1581.207	7.906	280	320	280
Pb204	204	82	122	1605.343	7.869	286	326	286
Tl205	205	81	124	1615.095	7.879	286	329	286
Pb208	208	82	126	1636.439	7.867	290	334	290
Rn216	216	86	130	1675.891	7.759	302	346	302
Ra220	220	88	132	1696.596	7.712	308	352	308
Th227	227	90	137	1735.976	7.647	317	364	317
U238	238	92	146	1801.692	7.57	330	384	330

Table 1: A representative sample of nuclides, with the nuclide name, number of nucleons, number of protons, number of neutrons, experimental binding energy of the nuclide, and the experimental binding energy per nucleon. Also shown is the number of up and down quarks, and number of possible inter-nucleon up-to-down quark bonded pairs.

The inclusion of these two quantum rules is shown in Table 2. 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 one selected parameter; for this simple calculation, it is 6.000 MeV per bond.

These data are plotted in Fig. 3a and Fig. 3b. In Fig. 3a all of the stable nuclides are shown, going out to uranium U238. In Fig. 3b, only the first 50 nuclides are shown, to show the detail there.

To re-iterate, this is a very quick and easy calculation, involving only the simple counting of bonded inter-nucleon up-to-down quark pairs. This calculation does not specify the arrangement of the protons and neutrons or the mechanism of the bond. It is just a simple counting of the quantum-allowed bonds.

4. Discussion

The excellent reproduction of the experimental data for these simple calculated results is impressive, especially considering that there is only one variable that must be selected, instead of five variables as in the Weizsäcker formula. The excellent reproduction of the experimental data is especially impressive considering that other currently-accepted nuclear theories cannot easily duplicate this curve.

The residual chromo-dynamic force for inter-nuclide quark-to-quark bonding is one possibility for the mechanism of this bond. Another possibility for this bond becomes apparent when it is recalled that the up quark has a charge +2/3 charge of a proton, the down quark has a -1/3 charge of a proton, and they both carry a magnetic moment. These electromagnetic characteristics of the up and down quarks create an 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 a bond. (Historically, it was believed that the strength of the electromagnetic force had an upper limit. Now, however, this misconceived notion is no longer considered valid.)

The inter-nuclear bond is most likely some type of combination of both the electric charge and the color charge of the quarks, but the relative percentages of these two contributions is not postulated here. However, regardless of the relative percentages, the electromagnetic component of this bond must be taken into consideration. A more detailed analysis of the electromagnetic part of this inter-nucleon up-to-down quark bonding should be made. A detailed analysis would include the addition of the energy due to all electric charges interacting with each other, which would be a double summation of the interaction of each electric charge with every other electric charge [15]. Similarly, this more detailed analysis would also include the variation of the electromagnetic bond due to the vector orientation of the magnetic moments. Additionally, the energy of the magnetic moments interacting with each other, should be included, which is a double summation over all magnetic moment vectors [16]. And finally, the kinetic energy of the quantum spin of the nuclide should also be included in this overall binding energy calculation [17, 18]. For more detailed and accurate calculations to be done, however, the lowest energy configuration of the nuclide must be specified before the interaction energies can be accurately calculated.

5. Conclusion

An extremely simple calculation of the inter-nuclear up-to-down quark bonding has been made, giving excellent results in duplicating the nuclear bonding energy curve, using only one parameter rather than five. The resulting errors for nuclides going up to uranium ^{238}U are on the order of a few percent. The average error from A=12 to A=50 is 1.83%. Also, due to the similarities of this concept to the residual chromo-dynamic force model, the existence of inter-nucleon up-to-down quark bonding cannot be relegated as inconceivable or implausible. An obvious implication of these results is that some significant part of the nucleon-to-nucleon force is electromagnetic. The excellent reproduction of experimental data strongly suggests that the inter-nucleon up-to-down quark bonding is a concept that should be seriously considered and more thoroughly examined by mainstream nuclear physics.

Nuclide	A	Z	N	Experimental Binding Energy in MeV	(Experimental Binding Energy) /A	# of up quarks	# of down quarks	# of possible up-down quark pairs, classical	# of up-down quark pairs, quantum	Calculated Binding Energy	(Calculated Bonding Energy)/A
H2	2	1	1	2.225	1.113	3	3	3	1	6	3
He3	3	2	1	7.718	2.573	5	4	4	3	18	6
He4	4	2	2	28.296	7.074	6	6	6	6	36	9
He5	5	2	3	26.626	5.325	7	8	7	4	24	4.8
Li6	6	3	3	31.995	5.333	9	9	9	3	18	3
Li7	7	3	4	39.245	5.606	10	11	10	6	36	5.143
Be8	8	4	4	56.5	7.063	12	12	12	8	48	6
Be9	9	4	5	58.165	6.463	13	14	13	9	54	6
B10	10	5	5	64.751	6.475	15	15	15	11	66	6.6
B11	11	5	6	76.205	6.928	16	17	16	13	78	7.091
C12	12	6	6	92.162	7.68	18	18	18	15	90	7.5
C13	13	6	7	97.108	7.47	19	20	19	16	96	7.385
N14	14	7	7	104.659	7.476	21	21	21	18	108	7.714
N15	15	7	8	115.492	7.699	22	23	22	19	114	7.6
O16	16	8	8	127.619	7.976	24	24	24	21	126	7.875
O17	17	8	9	131.762	7.751	25	26	25	22	132	7.765
O18	18	8	10	139.808	7.767	26	28	26	23	138	7.667
F19	19	9	10	147.801	7.779	28	29	28	25	150	7.895
Ne20	20	10	10	160.65	8.033	30	30	30	27	162	8.1
Ne21	21	10	11	167.406	7.972	31	32	31	28	168	8
Ne22	22	10	12	177.77	8.08	32	34	32	29	174	7.909
Na23	23	11	12	186.564	8.111	34	35	34	31	186	8.087
Mg24	24	12	12	198.257	8.261	36	36	36	33	198	8.25
Mg25	25	12	13	205.587	8.223	37	38	37	34	204	8.16
Mg26	26	12	14	216.681	8.334	38	40	38	35	210	8.077
Al27	27	13	14	224.952	8.332	40	41	40	37	222	8.222
Si28	28	14	14	236.537	8.448	42	42	42	39	234	8.357
Si29	29	14	15	245.01	8.449	43	44	43	40	240	8.276
Si30	30	14	16	255.62	8.521	44	46	44	41	246	8.2
P31	31	15	16	262.917	8.481	46	47	46	43	258	8.323
S32	32	16	16	271.78	8.493	48	48	48	45	270	8.438
S33	33	16	17	280.422	8.498	49	50	49	46	276	8.364
S34	34	16	18	291.839	8.584	50	52	50	47	282	8.294
Cl35	35	17	18	298.21	8.52	52	53	52	49	294	8.4
Ar36	36	18	18	306.716	8.52	54	54	54	51	306	8.5
Cl37	37	17	20	318.784	8.616	54	57	54	51	306	8.27
Ar38	38	18	20	327.343	8.614	56	58	56	53	318	8.368
K39	39	19	20	333.724	8.557	58	59	58	55	330	8.462
Ca40	40	20	20	342.053	8.551	60	60	60	57	342	8.55
K41	41	19	22	351.619	8.576	60	63	60	57	342	8.341
Ca42	42	20	22	361.895	8.617	62	64	62	59	354	8.429
Ca43	43	20	23	369.828	8.601	63	66	63	60	360	8.372
Ca44	44	20	24	380.96	8.658	64	68	64	61	366	8.318
Sc45	45	21	24	387.849	8.619	66	69	66	63	378	8.4
Ti46	46	22	24	398.194	8.656	68	70	68	65	390	8.478
Ti47	47	22	25	407.072	8.661	69	72	69	66	396	8.426
Ti48	48	22	26	418.699	8.723	70	74	70	67	402	8.375
Ti49	49	22	27	426.841	8.711	71	76	71	68	408	8.327
Ti50	50	22	28	437.78	8.756	72	78	72	69	414	8.28
V51	51	23	28	445.842	8.742	74	79	74	71	426	8.353
Cr52	52	24	28	456.345	8.776	76	80	76	73	438	8.423
Cr53	53	24	29	464.287	8.76	77	82	77	74	444	8.377
Cr54	54	24	30	474.009	8.778	78	84	78	75	450	8.333
Mn55	55	25	30	482.075	8.765	80	85	80	77	462	8.4
Fe56	56	26	30	492.257	8.79	82	86	82	79	474	8.464
Fe57	57	26	31	499.905	8.77	83	88	83	80	480	8.421
Fe58	58	26	32	509.945	8.792	84	90	84	81	486	8.379
Co59	59	27	32	517.314	8.768	86	91	86	83	498	8.441
Ni60	60	28	32	526.842	8.781	88	92	88	85	510	8.5
Ge70	70	32	38	610.519	8.722	102	108	102	99	594	8.486
Kr80	80	36	44	695.438	8.693	116	124	116	113	678	8.475
Zr90	90	40	50	783.895	8.71	130	140	130	127	762	8.467
Ru100	100	44	56	861.929	8.619	144	156	144	141	846	8.46
Cd113	113	48	65	963.557	8.527	161	178	161	158	948	8.389
Sn117	117	50	67	995.623	8.51	167	184	167	164	984	8.41
Xe129	129	54	75	1087.648	8.431	183	204	183	180	1080	8.372
Nd142	142	60	82	1185.148	8.346	202	224	202	199	1194	8.408
Sm150	150	62	88	1239.253	8.262	212	238	212	209	1254	8.36
Dy162	162	66	96	1323.884	8.172	228	258	228	225	1350	8.333
Yb172	172	70	102	1392.764	8.097	242	274	242	239	1434	8.337
W183	183	74	109	1465.526	8.008	257	292	257	254	1524	8.328
Pt194	194	78	116	1539.578	7.936	272	310	272	269	1614	8.32
Au197	197	79	118	1559.397	7.916	276	315	276	273	1638	8.315
Hg200	200	80	120	1581.207	7.906	280	320	280	277	1662	8.31
Pb204	204	82	122	1605.343	7.869	286	326	286	283	1698	8.324
Tl205	205	81	124	1615.095	7.879	286	329	286	283	1698	8.283
Pb208	208	82	126	1636.439	7.867	290	334	290	287	1722	8.279
Rn216	216	86	130	1675.891	7.759	302	346	302	299	1794	8.306
Ra220	220	88	132	1696.596	7.712	308	352	308	305	1830	8.318
Th227	227	90	137	1735.976	7.647	317	364	317	314	1884	8.3
U238	238	92	146	1801.692	7.57	330	384	330	327	1962	8.244

Table 2: A representative sample of nuclides, showing quantum-allowed bonded up-to-down quark pairs for each nuclide, taking into consideration the QCD hard-core repulsion and the elimination of a nuclear dipole moment.

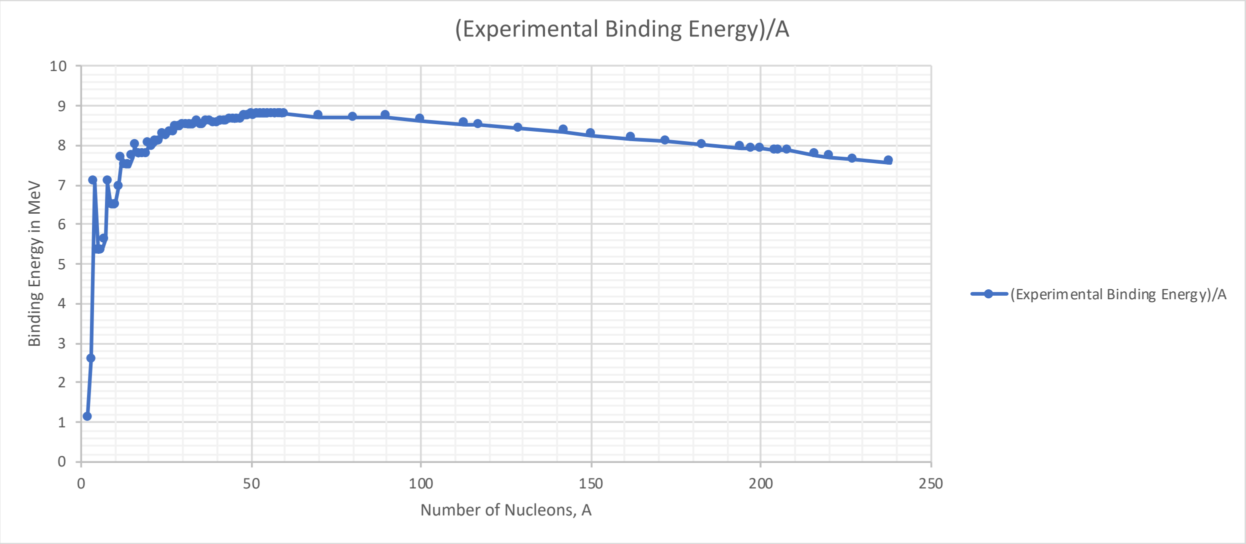

Figure 1: A plot of the experimental nuclear binding energy per nucleon, for a representative sample of nuclides.

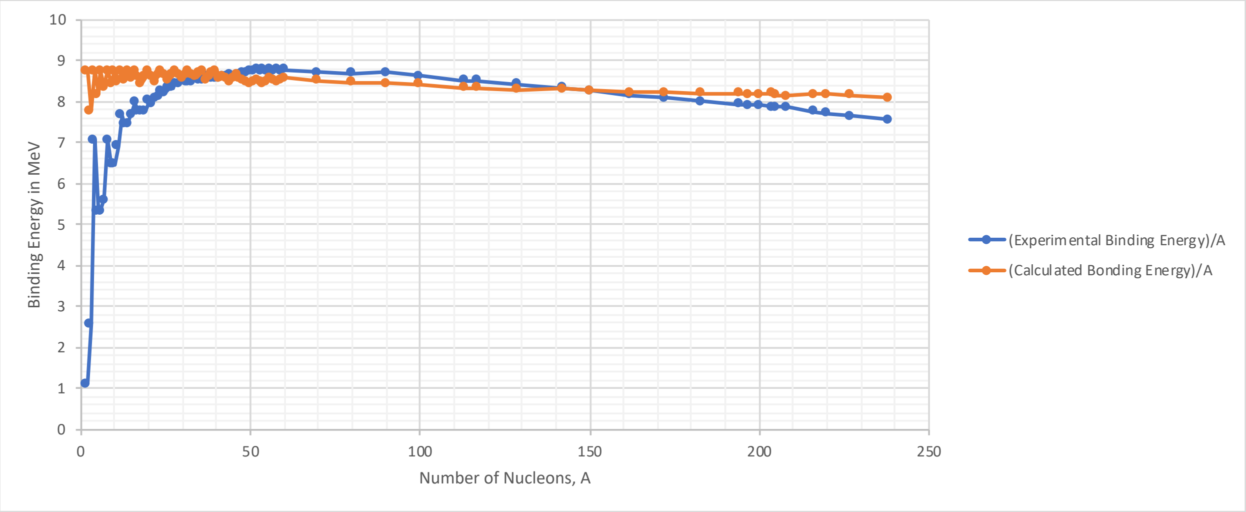

Figure 2: A plot of the experimental nuclear binding energy per nucleon, for a representative sample of nuclides, in blue. A plot of the simple calculated binding energy per nucleon, (in orange) based on the number of possible non-quantum up-to-down quark pairs and a fixed binding energy per bonded pair.

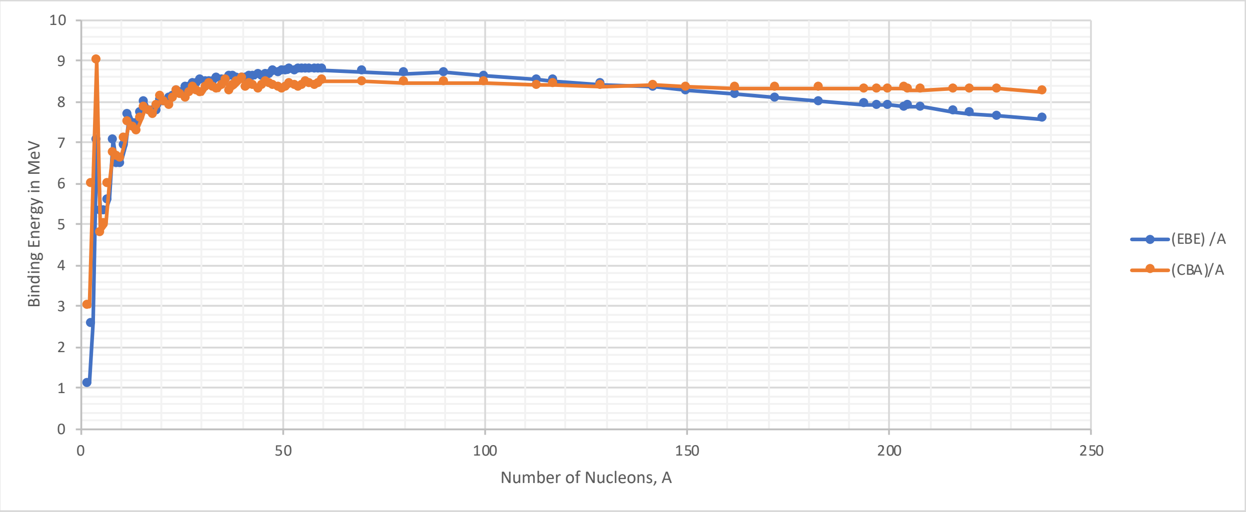

Fig. 3a. Plots of the experimental nuclear binding energy per nucleon (blue) and the simple calculated binding energy (orange), taking into consideration the quantum rules of hard-core repulsion and zero electric dipole moment. This is based on the number of possible quantum-allowed up-to-down quark pairs and a fixed binding energy per bonded pair.

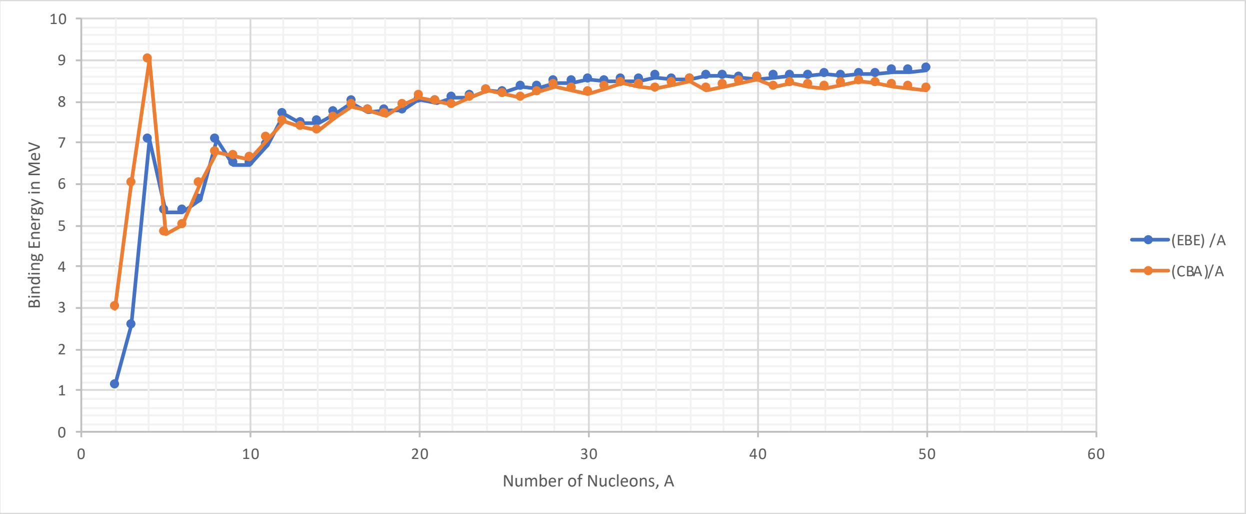

Fig. 3b. Plots of the experimental nuclear binding energy per nucleon (blue) and the simplistic calculated binding energy (orange), taking into consideration the quantum rules of hard-core repulsion and zero electric dipole moment, showing only the first 50 nuclides.

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