Nuclear bond models of some stable, unstable and fissile nuclei

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This article provides a simple introduction to some nuclear properties in a manner similar to the use of stereo-chemical models in the study of molecules. It may therefore appeal to educators. Many stable nuclei can be usefully modelled when the total nuclear bond energy of a nucleus is defined as the sum of the magnitude of the Coulomb repulsion energy and the binding energy (mass defect). These models are concentric layers of alpha particles bound together by nuclear bonds and are similar to models of liquid drops. It is also assumed that when most nuclei are excited, only the bonds between the alphas are weakened or broken because each alpha is so stable. The present paper consistently accounts for the stability of a number of nuclei in terms of the number of bonds between each layer. In addition it is shown that, whereas 5 or 6 bonds are broken in each alpha decay of an unstable nucleus, about 30 are broken in the fission of a uranium nucleus.

Introduction

All nuclei are formed in the extremely hot and dense cores of heavy stars. Our sun is only heavy enough to fuse hydrogen nuclei into helium nuclei (alphas). Each heavy hydrogen nucleus consists of a positive proton bound to one or two neutrons. Most collisions between these nuclei are elastic because of the strong electric repulsion between the positive protons. However, in the very core of the sun, hydrogen nuclei have sufficient energy to come close enough for the very short range strongly attractive nuclear bonds to not only balance the repulsion energy but also release much more energy called binding energy thereby reducing the masses of the bound protons and neutrons.

Nuclear Bonds

For the purposes of this paper a standard unit nuclear bond is defined in terms of the energy of a ^{4}He nucleus. This is done because of the stability and symmetry of ^{4}He, which is a boson.

The inter-nucleon bond energy, E_n, between two adjacent nucleons in a nucleus may be calculated in the following way. Because of isospin it will be assumed that 6 equal nuclear bonds strongly bind the 2 protons and 2 neutrons of a ^{4}He nucleus into a tetrahedron. The total nuclear bond energy, E_n, of the ^{4}He nucleus is defined as the sum of the empirically determined binding energy, E_b, of this nucleus and the magnitude of the Coulomb repulsive energy, E_c so that: $E_n = E_b + E_c$ where $E_b = 28.3$ MeV and $E_c = 0.8$ MeV. Therefore $E_n = 29.1$ MeV and it follows that the energy of one nuclear bond is 4.84 MeV.

This arbitrarily defined unit of the time-averaged bond between a pair of contiguous nucleons in an alpha particle will be used to quantify the bonds between adjacent nucleons and alphas in other nuclei. The total number of bonds in any nucleus is equal to E_n for that nucleus divided by 4.84 MeV.

"...fusion occurs when the increase in nuclear bond energy is greater than the increase in Coulomb energy..."

Nuclear Bond Models

The changes in nuclear bond data that occur during the nucleosynthesis of two light nuclei are shown in Table 1.

Nucleus	^{2}H +	^{2}H →	^{4}He	Energy change
	A	B	C	$\Delta E = C - A - B$
E_b	2.2	2.2	28.3	$\Delta E_b = 23.9$
$+ E_c$	-	-	0.8	$\Delta E_c = 0.8$
$= E_n$	2.2	2.2	29.1	$\Delta E_n = 24.7$

Table 1: Changes in nuclear bond data that occur during the nucleosynthesis of two light nuclei.

It can be seen that the definition $E_n = E_b + E_c$ leads to the identity $\Delta E_b = \Delta E_n - \Delta E_c$. This indicates that fusion occurs when the increase in nuclear bond energy is greater than the increase in Coulomb energy so that energy is released as mass is reduced.

Figure 1: Schematic illustration of the nuclear bond changes during the fusion of two deuterons to form an alpha particle

Nuclear Bond Models of Some Stable Nuclei

The data of the binding, Coulomb and nuclear bond energies as well as the derived number of nuclear bonds of 8 stable nuclei have been established in the same way as for ^{130}Te in Table 2. The total number of bonds in each of them is given in brackets as follows: ^{4}He (6), ^{16}O (29), ^{32}S (67), ^{60}Ni (136), ^{130}Te (299), ^{190}Os (450) and ^{238}U (559).

The particular isotope of each of these elements is the most abundant one.

Nucleus	E_b (MeV)	E_c (MeV)	E_n (MeV)	E_n/4.84
^{130}Te	1095.9	352.7	1448.6	299

Table 2: Nuclear Bond Data of the closed layer nucleus ^{130}Te.

As illustrated by Table 3 of models of these stable nuclei, it can be seen that the alphas form closed concentric layers. These layers became apparent as the models were constructed according to Bernal's theory of liquid drops [1]. This theory states that each particle is added as close as possible to the centre of the drop. The particle used in this paper is the alpha in accordance with Ikeda [2] and Horiuchi [3]. In their study of excited light even-even nuclei they found that the alphas were not excited but the bonds between them were weakened or broken. These ideas were subsequently modelled by Norman [4,5], who found that the alphas in each layer are not contiguous; they therefore only bond with inner layers.

> "...the alphas form closed concentric layers ... as the models were constructed according to Bernal's theory of liquid drops..."

In constructing the models it is assumed that the inner layers are stable so that the number of bonds binding an added alpha is equal to the extra number of bonds minus the 6 bonds of the alpha.

The 4 alphas of the first layer are bound together by 6 bonds to form ^{16}O. Each of the 4 alphas in the second layer is joined to the first layer by 3 bonds thereby forming ^{32}S.

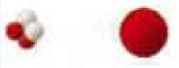
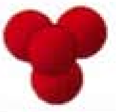
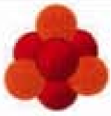
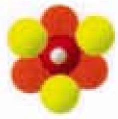
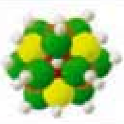
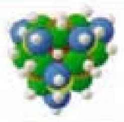
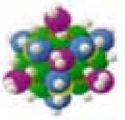
Nucleus	Model	Alphas	Neutrons	Bonds
$^4He_2$		1	-	6 (6)
$^{16}O_8$		4	-	30 (29)
$^{32}S_{16}$		8	-	66 (67)
$^{60}Ni_{28}$		14	4	134 (136)
$^{130}Te_{52}$		26	26	298 (299)
$^{190}Os_{76}$		38	38	454 (450)
$^{238}U_{92}$		46	54	558 (559)

Table 3: Closed Layer Nuclear Bond Models. The values in the last column are the values given by the model; those in parenthesis are the actual number of bonds.

The 6 alphas of the third layer are each bound to the second layer by 4 bonds to form ^{56}Ni. It appears that this model has the form of a tri-axial tetrahedron with 4 alphas as vertices, 4 as faces and 6 as edges.

However, ^{56}Ni is unstable and decays to ^{56}Fe because the electric repulsion energy, E_c, is long-range and therefore increases as the number of protons increases. By contrast, the nuclear bond energy, E_n, has a very short range. For this reason it is impossible for a heavy star to synthesise elements heavier than iron by simply fusing equal numbers of additional protons and neutrons. The giant star explodes as a supernova and, fortunately, this explosion generates a dense flux of neutrons that enables the addition of a skin of non-repulsive neutrons to the host nucleus by stabilising nuclear bonds. Accordingly, ^{60}Ni is stable because each of the 4 added neutrons provides 2 more bonds with no added repulsion. Additional protons are formed as some of the neutrons undergo beta decay.

The fourth layer of 12 alphas is also bound by 4 bonds per alpha to the third layer and has a further 22 neutrons so that now all alphas are each stabilized by 2 additional bonds to form stable ^{130}Te.

The fifth layer has 12 alphas, each bound to the fourth layer by 5 bonds; each is stabilised by an additional neutron that is held by 2 bonds to make stable ^{190}Os. However, most of these heavier nuclei are prone to undergo alpha decay because of the increased electric repulsion.

The sixth layer is even less stable despite each of the 8 alphas being bound by 5 bonds and each of the 16 outer neutrons providing a single bond to form ^{238}U.

Note that in Table 3 the total number of nuclear bonds in each of these consistently symmetrical nuclear bond models varies from the nuclear bond data (shown in brackets) by less than 2%.

Nuclear Bond Changes of some Unstable Nuclei

Alpha decay mostly occurs in light unstable isotopes of nuclei with incomplete fifth or sixth layers of alphas. Of such elements with an incomplete fifth layer there are 12, (centred on gadolinium), that have one or more alpha emitting isotopes. By contrast, all elements heavier than lead are alpha emitters because of the dominance of the repulsive Coulomb energy over the nuclear bond energy.

> **"...all elements heavier than lead are alpha emitters because of the dominance of the repulsive Coulomb energy over the nuclear bond energy."**

The natural radioactivity of ^{235}U terminates at ^{207}Pb after radiating 4 negative beta particles and 7 alphas whereas ^{238}U ends as ^{206}Pb after radiating 6 beta particles and 8 alphas. Table 4 indicates the energy changes in an alpha decay.

Nucleus	^{238}U →	^{4}He +	^{234}Th	Energy Change
	A	B	C	$\Delta E = B + C - A$
E_b	1801.6	28.3	1777.6	$\Delta E_b = 4.3$
$+ E_c$	905.1	0.8	870.9	$\Delta E_c = -33.4$
$= E_n$	2706.7	29.1	2648.5	$\Delta E_n = -29.1$
$E_n/4.84$	559	6	547	$\Delta E_n/4.84 = -6$

Table 4: The nuclear bond energy data associated with the alpha decay of uranium.

A similar analysis of the alpha decay of ^{230}Th also results in the breaking of 6 bonds whereas only 5 bonds are broken when each ^{212}Po nucleus radiates an alpha.

Since $\Delta E_c = \Delta E_n - \Delta E_b$, the data in Table 4 shows that for alpha decay, the alpha is expelled by the decrease in Coulomb energy of the mother nucleus as either 5 or 6 bonds are broken and between 4 and 7 MeV is released, mainly as kinetic energy of the daughter nuclei but also about 15 % as photons.

Nuclear Bond changes of some Fissile Nuclei.

Three different fissions of ^{235}U serve to illustrate the changes of nuclear bond structures during fission. Each fission demonstrates the uniformity of nuclear bond breaking across the bi-modal frequency distribution of daughter nuclei as illustrated in Figure 2.

The bi-modal spectrum of the daughters may also be related to the nuclear bond models in the following way. Natural fission of a uranium nucleus always results in a light nucleus with never less than 3 alpha layers and a heavy nucleus with never less than 4 alpha layers. The outer layer(s) are separated (like egg white) from the stronger core (egg yolk).

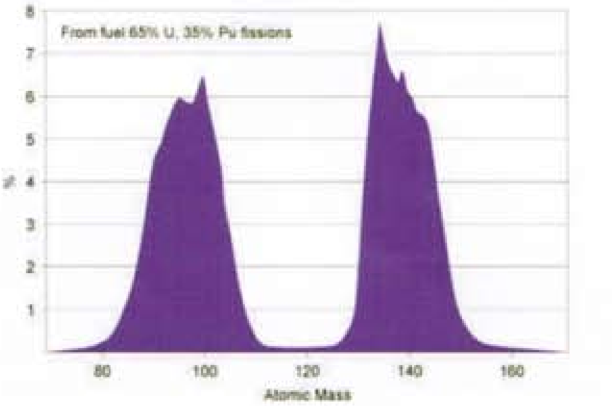


Figure 2: Combined product yields by mass for thermal neutron fission of ^{235}U and ^{239}Pu.

The fission described in Table 5 is similar to many others in that usually 30 bonds are broken such as when ^{141}Ba splits from ^{92}Kr and 1^{28}Sn splits from ^{106}Mo.

Nucleus	^{235}U →	n + ^{135}Te +	^{99}Zr	Energy change
	A	B	C	$\Delta E = B + C - A$
E_b	1783.0	1127	845.5	$\Delta E_b = 189.5$
$+ E_c$	909.0	344.6	225.1	$\Delta E_c = -339.3$
$= E_n$	2692.0	1471.6	1070.6	$\Delta E_n = -149.8$
$E_n/4.84$	556	304	221	$\Delta E_n/4.84 = -31$

Table 5: Nuclear bond energy changes during the fission of uranium to form tellurium and zirconium.

In both alpha decay and fission it is evident that the identity $\Delta E_b = \Delta E_n - \Delta E_c$ indicates that some of the short range strong nuclear bonds are overcome by the more powerful long range Coulomb force so that energy is released as mass is reduced. This is illustrated by the data from the fission in Table 5: 189.5 = - 149.8 - (-339.3). Alternatively, by substituting this data in the identity, $\Delta E_c = \Delta E_n - \Delta E_b$, we see that: - 339.3 = - 149.8 - (189.5). This indicates that the decrease in Coulomb energy causes the breaking of 30 bonds and the release of free fission energy.

Fission occurs when a uranium nucleus is destabilized either by deformation or the absorption of a thermal neutron in which case the nucleus becomes elongated until the asymmetric Coulomb force breaks 30 bonds between the fourth and fifth layers, as shown in Figure 3. This fact can be related to the nuclear bond model of uranium in Table 3 where a total of 60 bonds bind layer 5 to 4.

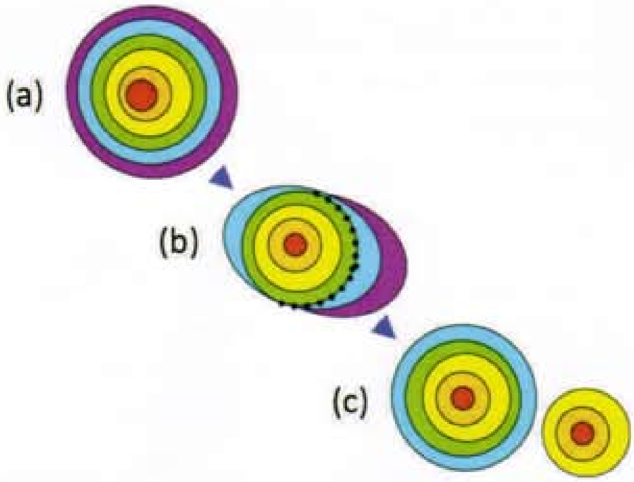


Figure 3: Schematic cross section model of uranium fission: (a) cross-section of the 6 layers of alphas of a uranium nucleus modelled as a liquid drop; (b) fission occurs as 30 nuclear bonds are broken; (c) a heavy and a light nucleus separate because of repulsive Coulomb energy.

Conclusion

The definition of nuclear bond energy makes a direct link between mass defect and changes in Coulomb energy and nuclear bond energy. That is, ΔEb = Δmc2 = ΔEn - ΔEc. Fusion occurs when ΔEn is larger than ΔEc whereas alpha decay or fission occurs when ΔEn is less than ΔEc.

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Peter Norman graduated from the University of Melbourne with a BSc in physics and completed a BEd while a secondary science master before lecturing physics and astronomy at Monash University. During this time he completed an MA(prelim.) in philosophy of science and a PhD in physics at Monash. He has presented many papers at physics conferences and jointly authored two text books.

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