Chapter 2: nuclide – a community of protons and neutrons

background reading

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Lincoln, D. (2012), *Understanding the Universe from Quarks to the Cosmos*, World Scientific, Singapore.

Mackintosh, R. et al. (2001), *Nucleus: a trip into the heart of matter*, The Johns Hopkins University Press, Baltimore, Maryland.

notes

Constructive comments are welcome.

"**I'll use the generic term**", historically, our scientific understanding has progressed inwards, as we have taken things apart, and the terms "nucleon" and "nuclide" have been derived from the term "nucleus" (derived from the Greek word "*nux*" = nut), the dense kernel of matter found at the centre of an atom. I will avoid using the word "nucleus", for that implies the centre of something bigger, which hasn't emerged yet (see, for example, Krauss 2002:79).

2.1 uncertainty and temporary existence

2.1.1 the uncertainty principle – energy and time

determining musical pitch

"**It's well known**", see Joe Wolfe at http://newt.phys.unsw.edu.au/jw/uncertainty.html .

"**The time "pips"**", https://en.wikipedia.org/wiki/Greenwich_Time_Signal. The 0.1 s pips are 100 cycles of the 1 kHz tone, but even this many cycles are not enough to perceive the musical frequency.

the energy-time uncertainty relation

"**However, a quantum particle is a dynamic entity**", this is an attempt to understand the energy-time relation in visual, rather than mathematical, terms.

The wave packet shown in **figure 2.1** is based on Penrose 2004:figure 21.10, and Carroll 2019:figure on p. 72.

"**The time interval, Δt, is a measure of the uncertainty**", Chad Orzel explains this in terms of measuring a frequency within a limited time (Orzel 2021:224)

"**This is the energy-time uncertainty relation**", some authors give $h/2\pi$ (Coughlan 2006:32, Close 2007a:53, Bertulani 2007:6, Freedman 2002:section 29-2), and others give $h/4\pi$ (Penrose 2004:524, Lincoln 2012:510, and, and Orzel 2021:224). I've followed the first set of authors ($h/2\pi$), because they calculate the pion range (section 2.2.1), even though this appears to be inconsistent with the second set of authors ($h/4\pi$), and with the position/momentum uncertainty relation, given in equation 1.2.

"**This tells us that we can't be sure**", Lincoln 2012:510.

2.1.2 virtual particles and the quantum vacuum

"**An energy fluctuation**", Gilmore 2001:120, Freedman 2002:section 29-2.

"**Quantum mechanics tells us**", Freedman 2002:section 29-2. An alternative statement is "*whatever is possible is compulsory*" (Gilmore 2001:124).

"***This result is astonishing***" and "***Pairs of every conceivable particle***", Freedman 2002:673.

"**The nothingness from which virtual particles**", Coughlan 2006:33.

"***flickering froth***", Gilmore 2001:130.

"**The quantum vacuum**", Fritzsch 2005:60.

"***there is a steady hectic activity***", Fritzsch 2005:61. However, this froth of transitory virtual particles does have discernible effects. For example, they very slightly unsettle the electrons in hydrogen atoms, and so alter certain frequencies in the hydrogen spectrum – the Lamb shift (HyperPhysics and Krauss 2012:66). Also, the pressure exerted by the quantum vacuum is very slightly less in between two metal plates than outside them, producing a very small force pushing them together – the Casimir effect (Coughlan 2006:33).

We are used to living in an environment that is full of molecules, for we are made of molecules and are sustained by molecules, and for us, a vacuum is an anomalous state. But on a larger scale, the Earth is only a speck of matter in the vast vacuum of space. For the universe, the vacuum is the default state, and stars and planets, and all concentrations of matter, are anomalies.

"***steal their own existence***", Gilmore 2001:121.

"**They come from nothing**", Gilmore 2001:120.

2.2 The strong nuclear force

2.2.1 pion clouds around nucleons

"**These virtual pions**", the calculation of the pion's range is quite straightforward, and is just finding how it can go in a given time, given that light sets a natural speed limit for any material particle. The calculation of pion range is based on Close 2007a:53 and Bertulani 2007:6.

We start with a small amount of energy (ΔE Joules) can be "borrowed" for a short time (Δt seconds), where

$\Delta E \times \Delta t \approx h/2\pi$

If we express energy in the more commonly used units of MeV (section 1.1.4), where 1 Joule = 6.3 x 10^{12} MeV, then

$\Delta E \times \Delta t \approx 6.6 \times 10^{-22}$ MeV x seconds

A pion has a mass of ~140 MeV (value from Close 2004a:232, and see section 1.1.4 on mass-energy), so it can exist as a virtual particle for a "bit" of time,

$\Delta t \approx 6.6 \times 10^{-22}/140 \approx 5 \times 10^{-24}$ seconds

This might seem to be an impossibly small time to do anything, but it does allow the pion to travel a short distance.

Light sets a natural speed limit for any material particle, so if the pion travels at close to this speed, about 3×10^{8} m/s, then the maximum distance, *d*, it can travel is given by

$d = 3 \times 10^{8} \times 5 \times 10^{-24} \approx 1.5 \times 10^{-15}$ metres, or 1.5 femtometres (fm), which is around the size of a proton.

HyperPhysics, at http://hyperphysics.phy-astr.gsu.edu/hbase/Forces/exchg.html does the same calculation, and gives a range of ~0.7 fm, because it uses the term $h/4\pi$.

Originally, the calculation was done the other way round (Close 2007a:53, Bertulani 2007:6). Since the maximum range of the strong nuclear force was known to be $\sim10^{-15}$ m, this suggested an exchange "force-carrying" particle with a mass-energy of ~140 MeV.

Pions are mesons, and so are unstable (section 1.3.3), but their virtual lifetime is much less than their natural lifetimes, which are $\sim10^{-16}$ s for the neutral pion, and $\sim10^{-8}$ s for the charged pions (Close 2004a:232).

"***three quarks***", Heyde 1998:94.

Figure 2.2 shows a pion cloud around a nucleon, based on Heyde 1998:figure 4.12, and Leinweber at http://www.physics.adelaide.edu.au/theory/staff/leinweber/VisualQCD/OriginMass/index.html.

2.2.2 pion exchanges bind nucleons together

"***the sum of the effects***", Smith 2003:42.

"***fluttering back and forth***", Smith 2003:150.

"***an invisible, evanescent web***", Close 2004a:73.

Figure 2.3 is based on Smith 2003:figure 3.6, Dunne 2002, Duff 1986:figure 6.17 and Close 2007a:figure 5.1.

"**Figure 2.3 shows**", Smith 2003:43, Heyde 1998:figure 2.3.

"**Part (b) shows**", Bertulani 2007:81. You can draw a version of figure 2.3 to show quite easily that a proton can't exchange a charged pion with another proton, because one of them would be transformed into an impossible combination of quarks.

"***a square dance***", Smith 2003:47.

"**The exchange of pions**", David Lindley describes it thus: "*A proton could turn into a neutron plus a positively charged meson, and a neutron could turn into a proton plus a negatively charged meson. … so that neutrons and protons were constantly switching identities*" (Lindley 1993:108).

"**The strong nuclear force**", Tipler 1999:1327 describes the strong nuclear force as a "*residual*" strong interaction. Fritzsch 2005:77 descibes it as "*the indirect consequences of gluonic interactions inside the nucleons*". Close 2004a:170 describes the parallels between the nuclear force and the electromagnetic force: "*it is the colour within the proton and neutron that attracts them to each other to build nuclei. This process may have similarities to the way that electrical charge within atoms manages to build up complex molecules. Just as electrons are exchanged between atoms bound within a molecule, so are quarks and antiquarks – in clusters we call 'pions' – exchanged between the protons and neutrons in a nucleus*". We'll encounter atoms and molecules in chapters 3 and 4.

"***the collective manifestation***", Han 1999:119.

"***a residual color force***", HyperPhysics at http://hyperphysics.phy-astr.gsu.edu/hbase/particles/expar.html.

2.2.3 the nuclear force profile

Figure 2.4 is based on Bertulani 2007:figure 3.3, Smith 2003:figure 3.1. A common potential curve is the Reid potential (Bertulani 2007:78), which can be found at https://en.wikipedia.org/wiki/Nuclear_force.

I've given the plot of the potential of the strong nuclear interaction, rather than the size of the force it exerts. This is because it is more useful to deal with energies of bound systems, rather than the forces on their component parts. It is fairly straightforward to go from potential energy to force. The slope of the potential energy graph gives the size and direction of the net force on the nucleon. Where the slope is zero, at 3.0 and 0.9 fm, the net force is zero. For distances greater than 0.9 fm the slope is positive (that is, upwards and to the right) and the net force is attraction; for distances less than 0.9 fm the slope is negative and the net force is repulsion.

The curve is broadly explained in terms of the exchange of pions. At distances greater than about 2 fm single pions are exchanged; between 1 and 2 fm, the interaction is strongly attractive and is due to the exchange of two pions; and at shorter distances the interaction is due to the exchange of three pions, and it becomes repulsive (Bertulani 2007:91, Smith 2003:chapter 3, and Williams 2001:179).

The strong nuclear interaction is approximately independent of nucleon type (Bertulani 2007:75).

"***two nucleons will be oblivious***", Smith 2003:35.

"**So we have a simple description**", this is a bit like the way velcro, hook-and-loop fabric, locks two objects tightly together, yet you can hold the two mating velcro fabrics just out of contact, and there is no interaction between them. The strong nuclear force resembles "nuclear velcro" – see, for example, the cartoon in Williams 2001:169.

2.3 Bound systems – mass and binding energy

2.3.1 magnets and binding energy

"**Imagine a simple system**", normally the friction between the magnets and the surface they are resting on prevents movement, unless the magnets are very close together. But if you float the magnets on still water in a plastic bathtub, using aluminium foil or plastic lids, then you see that the magnetic fields extend a long way, and that magnets quite far apart will slowly rotate, so that opposite poles line up, and then be drawn together.

"**Just before their collision**", When I was teaching I would demonstrate this by heating a piece of lead pipe simply by hammering it. The students could handle the hot pipe and see the transfer of kinetic energy from the hammer to the lead atoms. Some would be surprised to feel the lead's warmth when it had not been heated in a familiar way with a flame.

2.3.2 a simple nuclide – an alpha-particle, [2p,2n]

Here I'm considering the formation of a [2p,2n] He-4 nucleus in the simplest way possible – directly from 2 protons and 2 neutrons. This is distinct from the formation of helium in the sun, which is from only protons via the proton-proton chain (Williams 2001:350).

nuclide binding energy

The numerical data in **figure 2.6** is based on AME2020 (Wang 2021). The [2p,2n] nuclide shown here is also known as a helium-4 nucleus, He-4.

Data on nuclides is available in NUBASE2020 (Kondev 2021), which is based on the Atomic Mass Evaluation, AME2020 (Wang 2021), provided by the Atomic Mass Data Center (AMDC), at https://www-nds.iaea.org/amdc/. Both databases are available as pdf downloads, and as ASCII files, which can be imported to EXCEL spreadsheets.

I have followed common practice and used the Einstein equivalence of mass and energy, and taken mass (m) and rest mass-energy (mc^2) to be interchangeable (Williams 2001:56). So, particle masses are given in units of MeV; they should strictly be given in units of MeV/c^2, but I've shortened this to MeV for simplicity, as is common practice.

The figures in this chapter are for nuclides and not atoms. The AME data given in NUBASE2020 is for atoms, as is customary, and the nuclide masses have been calculated as follows:

$m_{\text{nuclide}} = m_{\text{atom}} - m_{\text{electrons}}$ + binding energy of all the electrons (Wang 2021:equation 1)

The binding energy of the electrons is very small compared to the electron masses, and they have been ignored here.

I've used these mass values for the basic particles: 1 atomic mass unit, u = 931.494 MeV; m_{proton} = 938.27 MeV; m_{neutron} = 939.56 MeV; m_{electron} = 0.511 MeV.

"**Consequently, the mass**", Bertulani 2007:102.

"**The "missing" 28.4 MeV of mass**", Baggott 2015:94.

from mass loss to binding energy

"**The equivalence of mass and energy**", Bertulani 2007:101. The magnet example is analogous to chemical reactions between atoms. For example, when two hydrogen atoms come together to make a hydrogen molecule there is a tiny loss of mass (Cox 2011:153). The standard teaching that mass is conserved in all chemical reactions is effectively true because the mass loss is so small as to be unmeasurable (Atkins 2002:F73).

"**In fact, the mass loss**", the formation of [2p,2n] from free nucleons, shown in figure 2.6, results in a mass loss of about 0.76%, or nearly 7.6 g per 1,000 g of free nucleons.

The relation $E = mc^2$ tells us that the energy equivalent to 7.6 g of matter is about 7 x 10^{14} J.

In 2013 Greater London's total energy consumption was about 132,000 GWh, of which about 31% was electricity, according to the Association for the Conservation of Energy, at https://www.theade.co.uk/assets/docs/resources/Energy-Efficiency-in-London.pdf. London's annual electricity consumption was about 40,000 GWh/year, or about 1.5 x 10^{17} J/year, which is about 4 x 10^{14} J/day.

We know that the density of nuclear matter is about 2.3 x 10^{17} kg/m^3, and so we can estimate that 1 kg of nucleons will pack into a spherical cluster with a radius of ~0.001 mm (http://hyperphysics.phy-astr.gsu.edu/hbase/nuclear/nucuni.html#c4).

mutual repulsion between protons

"**The energy of this proton-proton repulsion**", Williams 2001:56.

the three factors that determine nuclide mass

"***creates a rich arena***", Hogan 1998:10.

neutrons are stable within a nuclide

"***effectively lighter***", Krauss 2002:34.

we leave quarks and pions behind

2.4 simple models of nuclides

2.4.1 marbles in a string bag

"**Most nuclides are spherical**", treating the nuclide as a liquid drop explains many features of real nuclides (Williams 2001:56; Mackintosh 2001:50).

Figure 2.7 is based on Mackintosh 2001:48 and 50, and does not show all 58 nucleons. The nuclide density plots are based on Mackintosh 2001:50, Williams 2001:figure 3.5, Bertulani 2007:figure 4.2 and Heyde 1998:figures 3.4 and 3.5. The nucleon diameter is taken as about 2 fm. Nuclides of all sizes have roughly the same density, and the approximate nuclide radius (r_n fm) can be calculated from the number of nucleons (A) with a simple formula, $r_n = 1.2 \times A^{⅓}$, so the nuclide radius is roughly proportional to cube root of the number of nucleons it contains. The effective nuclide size is taken as the radius at half the internal density – see Williams 2001:51 and http://hyperphysics.phy-astr.gsu.edu/hbase/nuclear/nucuni.html#c4.

The element names of these nuclides have been left out of the text, and they are:

[2p,2n] = helium, He-4; [6p,6n] = carbon, C-12; [28p,30n] = nickel, Ni-58; and [82p,126n] = lead, Pb-208.

Nuclei are traditionally known by their chemical names, and the nuclide [2p,2n] is usually known as a helium-4 nucleus. But we have only just seen the nucleons' ability to cluster into nuclides; there are as yet no atoms, and the concept of a chemical element is meaningless. These nuclides are just dense nuggets of matter, differing only in their size and the amount of positive electric charge they carry, due to their proton content. Chemical identity comes only with the acquisition of a community of electrons, and we will see this happen in Level 3, covered in the next chapter.

"**Nuclides pack a huge amount of mass**", the density of nuclides is about 2.3 x 10^{17} kg/m^3 – see http://hyperphysics.phy-astr.gsu.edu/hbase/nuclear/nucuni.html#c4.

"**The tiny grains of granulated sugar**", the volume of a 1 mm cube is $(10^{-3})^3 = 10^{-9}$ m^3, and using the formula mass (kg) = density (kg/m^3) x volume (m^3), the mass of a nuclide grain would be 2.3 x 10^{17} x 10^{-9} = 2.3 x 10^8 kg, or about 230,000 tonnes.

"**A nuclide the size of a football**", Mackintosh 2001:49.

2.4.2 nuclide composition and size

"**We can use this simple 2–D model**", this is a very simplistic, but useful approach that is treated rigorously in Williams 2001:chapters 4 and 5.

varying the proton:neutron (p:n) ratio

Figure 2.8 broadly follows the argument in Williams 2001:73 and figure 5.6, which is based on a semi-empirical formula for nuclide mass (Williams 2001:59, and Bertulani 2007:121 gives another version, known as the Weizsäcker formula). I follow a qualitative argument, which simply considers the relative contributions of the proton-proton repulsions and the proton-neutron mass difference to the mass of the nuclides in a cluster family. **Figure 2.8** shows the cluster-12 nuclides, while Williams 2001:figures 5.6 and 5.7 show the mass valleys of the cluster-101 and cluster-100 families, and Bertulani 2007:figure 5.2 does the same for generic odd and even numbered cluster families.

varying the cluster size – competition between the nuclear and electrical forces

Figure 2.9 takes a similar approach to Lincoln 2012:figure 4.4, and follows a simple argument that considers the repulsion forces on one proton at the edge of the cluster, where the number of repulsions is roughly proportional to the number of protons, which in this case is half the cluster size. So, for our edge proton in a cluster of 20 nucleons, there will be 20/2 – 1 = 9 repulsions, and in a cluster of 40 nucleons, there will be 40/2 – 1 = 19 repulsions.

However, the *total* number of proton-proton repulsions goes up a lot faster than this. In cluster-8 we can work out the number of repulsions as 3 + 2 + 1 = 6; the first proton repels protons 2 to 4, proton number 2 adds repulsions of protons 3 and 4, proton number 3 adds a repulsion of proton number 4, and we don't count proton number 4, because it's already been considered. The total number of repulsions is the sum of the consecutive series of numbers, 1 + 2 + 3 = 6, where we stop the series at 1 less than the number of protons. So, the total number of repulsions in a cluster containing *P* protons is 1 + 2 + 3 + … + (*P*−1). This is an arithmetical series, whose sum $S = n(a_1 + a_n)/2$, where *n* is the number of terms, a_1 is the first term, and a_n is the last term. So, for cluster-8 the total number of repulsions is (4–1)x(1 + (4−1))/2 = (3 x 4)/2 = 6. The total number of repulsions in cluster-16 is 28. So, doubling the cluster size more than doubles the total number of proton-proton repulsions.

three predictions

2.5 real nuclides

2.5.1 the cluster-12 family of nuclides

Figure 2.10 is based on data in NUBASE2020 (Kondev 2021) and AME2020 (Wang 2021), and see the notes to figure 2.6. The NUBASE note on isobar [3p,9n] adds a question mark "?" to the statement "ejects a neutron", and this has been left out of the figure.

a nuclear valley

"**Every second the numbers will halve**", the number of nuclides is reduced to ½ in one half-life, and to ½ x ½ = $1/2^2$ in two half lives. In 10 half-lives the number is reduced to $1/2^{10}$, which is about 1/1,000, so in this time one thousand nuclides will reduce to a single nuclide.

four modes of decay

"**The cluster of nucleons in isobar [4p,8n]**", nuclides are commonly known by their chemical names; for example nuclide [6p,6n] is known as carbon-12, or C-12, and the nuclide [7p,5n] is known as nitrogen-12, or N-12. These element names are familiar to working scientists, but not to the general reader. So, if I write that N-12 decays to C-12, it's not at all clear what's happening, but if I write that [7p,5n] decays to [6p,6n] the decay process is clear, even though the wording is more cumbersome.

tumbling down the mass-valley slope

"**Of the 13 isobars in this family**", all cluster families with an odd number of nucleons have only one stable isobar, but cluster families with a even number of nucleons can have more than one stable isobar (Williams 2001:73).

"***Nature seeks the state of lowest energy***", Close 2004b:40.

2.5.2 introducing the recognised nuclides

Figure 2.11(a) shows the recognised nuclides, as given by the NUCLEUS2012 program (v. 2.1, dated 16.11.2012), based on NUBASE2012 (Audi 2012), with nuclides colour-coded according to their principal decay mode. The global view shown records 3379 nuclides, of which only 195 are colour-coded black to show that they are stable. This view of nucleon-space is known as a Segrè nuclide plot. The NUCLEUS program (Nucleus-Win, version 2.1, 16.11.2012) has been created and made available by the Atomic Mass Data Center (AMDC).

NUCLEUS is a PC application that displays the contents of the NUBASE database in 2−D and 3−D formats, and is available at http://amdc.in2p3.fr/web/nubdisp_en.html.

NUBASE2012 includes all nuclides with half-lives longer than 100 ns. Some particular nucleon clusters are not truly stable in any p:n combination, for example, clusters with 5, 8, 144, 146−149, 151, 182−184, 186 and 204 nucleons, as shown in the NUCLEUS program, and these show as gaps in figure 2.11.

The NUCLEUS2012 display in **part (a**) colour-codes as black the 195 stable nuclides whose decay is energetically forbidden, and these define the arc of stability. There are another 62 nuclides, whose decay is energetically permitted, but for which no definite half-life values have been found, though they are very long, in excess of 10^{12} years. These nuclides are indicated as stable in NUBASE2012, but are colour-coded by their possible decay mechanism in the NUCLEUS display.

NUCLEUS2012 states the 3 lead isotopes, Pb-206, Pb-207, and Pb-208, to be stable, making Pb-208 the largest stable nuclide. NUBASE2020 (Kondev 2021) indicates these 3 isotopes as "STABLE", but possibly undergoing alpha-decay (indicated as "α?") , with half-lives longer than 10^{21} years, and NUCLEUS2020 (v. 2.1, dated 24.02.2017) colour-codes them as alpha-emitters (α?).

All the nuclides in the 209-cluster family are unstable, and the closest to stability is [83p,126n], the nucleus of bismuth-209, which is a definite alpha-emitter, and has has a very long, but definite half-life of about 20 x 10^{18} years.

The three lead isotopes have enormously long, indeterminate half-lives, and no definite decay mode, and so I have taken them as stable, and shown the NUCLEUS2012 display of nuclides. Beyond lead-208, there are no stable nuclides, and so I state in the text that the nuclide [82,126] is the largest stable nuclide.

the arc of the stable nuclides

six modes of decay

walking the arc of stability

the nuclide mass plot

The plot of average nucleon mass in **figure 2.11(b)** is for the stable nuclides shown in part (a), and is based on data in NUBASE2012 (Audi 2012). The NUBASE2012 database was downloaded as a CSV text file, imported into EXCEL, the stable nuclides selected, and their average nucleon masses calculated and plotted against nucleon number.

It's also fairly common to plot the binding energy per nucleon (for example, Williams 2001:figure 4.6 and Bertulani 2007:figure 5.1), but this is the mirror image of the plot of average nucleon mass. I've plotted the average nucleon mass so as to be consistent with the 3−D nuclear valley that we will view soon, and also because the picture of unstable nuclides "rolling" downhill towards stability goes along with with our everyday experience of things rolling down slopes under gravity.

"**If we plot the average nucleon mass**", the three nuclides with the least average mass per nucleon are (1) nuclide [26p,30n], otherwise known as iron-56; (2) nuclide [28p,32n], known as nickel-60; and then nuclide [28p,34n], known as nickel-62 (Wang 2021).

We must be careful with average nucleon mass as opposed to binding energy, because the lowest nuclide in the nuclear valley is not the most tightly bound. The figures for mass and binding energy for selected nuclides in AME2020 (Wang 2021) are given in the table.

nucleons	*p*	*n*	**common name**	**mass/nucleon MeV/nucleon**		**binding energy/nucleon MeV/nucleon**	
56	26	30	iron-56	930.174	(1st)	8.790	(3rd)
58	26	32	iron-58	930.193		8.792	(2nd)
60	28	32	nickel-60	930.181	(2nd)	8.781	
62	28	34	nickel-62	930.187	(3rd)	8.795	(1st)

The nuclide [26p,30n], otherwise known as iron-56, has the smallest average nucleon mass of 930.174 MeV/nucleon, closely followed by nickel-60, with nickel-62 coming third. However, it is nickel-62 that is most tightly bound, with the highest binding energy of 8.795 MeV per nucleon, closely followed by iron-58, and then by iron-56. The reason for the difference in order is that nickel-62 has a slighly higher proportion of heavier neutrons than does iron-56, and so even though it has a higher binding energy its average nucleon mass is greater.

The 3 nuclides with the least average nucleon mass, marking the lowest point in the nuclear valley, have 56, 60, and 62 nucleons. So, I've used the round number 60, in keeping with the literature.

2.5.3 the nuclear valley

Figure 2.12 is a screen capture of the NUCLEUS2012 3−D display of nuclides, which plots the average nucleon mass of the known nuclides against their proton and neutron numbers. This gives a 3−D version of the 2−D nuclide plot and is the standard way to represent nucleon-space. Similar views of the nuclear valley have been given by Mackintosh 2001:74 and Marx 2001. The NUCLEUS display used here had an original resolution of 1024x768. The NUCLEUS program (Nucleus-Win, version 2.1, 16.11.2012) has been created and made available by the Atomic Mass Data Center (AMDC).

An article in the CERN Courier, shows an image of the heavy elements in the valley, with clouds overhead and the super-heavy elements as mountains in the distance. The nuclides are referred to as species - "*Of the thousands of known nuclear species, only about 300 are stable, that is they exist along the so-called "valley of stability". The unstable species forming the valley "walls" - those with an overabundance of protons or neutrons - tend to decay quickly, sometimes within milliseconds.*" – CERN Courier, Feb 22, 2002, at http://cerncourier.com/cws/article/cern/28587.

NUCLEUS controls: You need a basic 3−D graphics card to display the 3−D version of NUCLEUS. The controls are: **Q/A** to increase/decrease altitude; **V/B** to "step" left or right; **cursor keys ↑/↓** to move forward/backward, and this can also be done with the mouse scroll wheel; **S** to stop any movement; **cursor keys →/←** to turn your "look" left or right, and this can also be done by clicking and dragging the reticule; **Home/End** to zoom in or out, though these give extreme movements; **Page Up/Page Down** to "look" up or down.

"***boulders perched up the side of the valley***", Mackintosh 2001:74.

the nuclear valley is defined by three curves

"**The nuclear valley is defined by three curves**", the "*energy valley … has an overall smooth structure which can be summed up in just three curved lines*", Mackintosh 2001:100.

a network of decay pathways

"**Every stable nuclide is the last "descendent"**", the universal hierarchy reveals parallels between disparate communities. It may appear fanciful to compare nuclides and biological species, but they show a number of parallels (Dennett 1996, Patterson 1999, Clayton 2003). Clayton 2003:2 reflects on the parallels between nuclear and biological species.

(1) Both have descent down a continuous ancestral line. Living organisms are descended from ancestral species, which are extinct if you go back far enough, and every organism has an unbroken ancestry of creatures that have successfully reproduced. Similarly, every stable nuclide is at the end of an unbroken decay chain of unstable ancestral nuclides. The evolutionary reproductive pathways of biological species form a network in biological species-space; nuclides form decay pathways in nucleon-space in the nuclear valley. Nuclides differ from biological species in that a nuclide can be on more than one decay chain, each coming from a different ancestral nuclide. Also, all biological organisms can trace their ancestry back to a common ancestor.

(2) Both show descent with modification. Biological offspring differ slightly from their parents, and competition with other organisms means that the fitter organisms have a better chance of survival, so living species evolve. Similarly, every daughter nuclide has a smaller average nucleon mass than its parent nuclide, and is thus one step closer to stability, and more "fit" in its competitive nuclear environment.

(3) There is no overall aim or purpose in biological evolution. The course of evolution is determined by local factors, and species evolve to increase their fitness under the pressures acting on them there and then. Similarly, the path of a nuclide decay chain has no pre-determined end point, and is decided by the local options and constraints acting at each step of the way.

2.6 why are the "stable" nuclides stable?

2.6.1 three options for changing cluster size

fusion – two smaller nuclides merge into a larger nuclide

"**It is only at enormously high temperatures and pressures**", fusion temperatures are given by Williams 2001:section 14.3, Bertulani 2007:sections 12.7−12.9 and Delsemme 1998:table 3.1.

"**For example, it requires a temperature**", this is the proton-proton chain (Williams 2001:section 14.4, Bertulani 2007:section12.5).

alpha-decay – ejection of a [2p,2n] nuclide

"**Consequently, up to a size of about 150 nucleons**", rigorous calculations, based on sophisticated nuclide models, show that alpha-decay only becomes energetically possible at a cluster size of about 150 nucleons (Williams 2001:76, Bertulani 2007:122).

"**In alpha-decay**", Williams 2001:chapter 6, Bertulani 2007:chapter 7.

"**The bigger the mass loss**", this empirical relation is known as the Geiger-Nuttall rule (Williams 2001:figure 6.1).

"**For example, NUCLEUS2020**", NUCLEUS2020 puts these nuclides on the arc of stability, and NUBASE2020 marks them as STABLE, but also as potential alpha-emitters ("α?"). These nuclides are: 145-Nd, 187-Os, 188-Os, 189-Os, 190-Os, 192-Pt, and 195-Pt.

Williams states that in the size range 144−206 "*7 alpha-emitters are known amongst the naturally occurring nuclides. Their existence implies* *mean lifetimes comparable to or greater than at least the age of the earth (about 4 x 10^9 years)*" (Williams 2001:76).

spontaneous fission – splitting into two smaller nuclides

"**A nuclide cluster is always wobbling**", Williams 2001:95, Bertulani 2007:320. We've seen that the p:n ratio decreases as nuclides get bigger, so when a big nuclide fissions, the smaller daughter nuclides are unstable, and there are some free neutron "leftovers".

2.6.2 motive, means and opportunity

The mass plot in **figure 2.13** is the same as in figure 2.11.

2.7 review of levels 1 and 2

"**So, out of all the possible proton-neutron combinations**", NUCLEUS2012 has 195 nuclides on the black arc of stability. NUBASE2012 lists 257 nuclides as "stable", which includes these 195 stable nuclides, and another 62 whose decay is energetically permitted, but for which no finite half-life values have been found, though they are very long, in excess of 10^{12} years.

"**If we go beyond the arc of stability**", NUBASE2020 (Kondev 2021) and the NUCLEUS program gives Einsteinium-252 (with [99p,153n] and $t_{½}$ ≈ 470 days) as the nuclide with the largest number of protons and a half-life of more than 1 year.

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