Nucleosynthesis

Nucleosynthesis is the process of making the elements of the Periodic Table, starting from protons (nuclei of hydrogen-1) and working up. In the lectures, we discussed five different nucleosynthesis processes, one taking place in the early universe, and four in stars.

# Big Bang Nucleosynthesis

Big Bang nucleosynthesis (BBN) takes place a few minutes after the Big Bang, when the universe has cooled sufficiently to allow deuterium (2H) nuclei to be stable (at higher temperatures, deuterium nuclei are broken up by the process 2H + γ → p + n). At this time, the universe consists mostly of protons and free neutrons (free neutrons are unstable and decay, but their half-life is about 10 minutes, so at this point most of them are still there). There are more protons than neutrons, because protons are lighter than neutrons so it is energetically favourable to make them.

Simple two-body collisions produce first deuterium (p + n → 2H + γ) and then 3He (2H + p → 3He + γ, 2H + n → 3H + γ followed by 3H → 3He + e− + ν), 4He (variety of reactions: 4He is very stable and therefore very easy to make) and a small amount of 7Li (3H + 4He → 7Li, 3He + 4He → 7Be → 7Li). However, there are no stable nuclei with mass number 5, so adding a proton or a neutron to 4He doesn’t work (the produced nucleus decays back to 4He immediately); there is also no stable mass 8, so colliding two nuclei of 4He doesn’t work either (the produced nucleus falls apart into two helium nuclei again). Therefore the principal outcome of BBN is to incorporate practically all the free neutrons into 4He. Since there are about 7 protons for every neutron at this time, this gives one helium nucleus for every 12 hydrogen nuclei, or about 25% 4He by mass.

All present-day deuterium, and about 90% of present-day 4He, was made by BBN. By comparing calculated and measured abundances, it is possible to determine the density of ordinary matter in the universe. Dark matter does not involve itself in nuclear reactions, so these calculations do not tell you how much dark matter there is.

# Fusion

Stars generate energy by fusing light elements to produce heavier ones. As long as the mass of the product is less than the mass of the input, this will generate energy by *E* = *mc*2. For example:

*Hydrogen fusion* 4 1H → 4He + 2e+ + 2ν
Masses (in amu) 4×1.0073 4.0015 + 2×0.00055
 4.0292 4.0026
Difference 0.0266 = 0.66%

*Helium fusion* 3 4He → 12C
Masses 3×4.0015 11.9967 (remember these are *nuclear*, not *atomic*, masses)
 12.0045 11.9967
Difference 0.0078 = 0.065%

Hydrogen fusion is the easiest fusion process, because the Coulomb repulsion caused by the fact that both nuclei are positively charged is obviously smaller for hydrogen than for nuclei with more protons. Therefore it “turns on” at the lowest temperature (about 107 K), and hence is the first fusion process to take place in stars[[1]](#footnote-1). As it is also the most efficient fusion reaction, and furthermore hydrogen is the most abundant element, the hydrogen fusion stage lasts far longer than other fusion processes.

The CNO cycle mechanism of hydrogen fusion also yields 14N as a by-product, because the reaction that makes 14N is faster than the other reactions in the cycle.

Helium fusion is the next easiest process, turning on at about 108 K (note that that’s 10 times the temperature required for hydrogen fusion: that’s why, when the hydrogen in a star’s core runs out, it is *much* easier to heat up the star enough to fuse the hydrogen just outside the depleted core than it is to heat it up enough to ignite the core). Helium fusion initially makes 12C, in a two-step reaction that requires the formation of the extremely unstable nucleus 8Be as an intermediate stage.

Because the formation of 12C is *resonant* (there is an excited state of the 12C nucleus that has a total rest-mass energy that exactly matches the total energy of 4He + 8Be), this is the dominant nucleus produced in helium fusion. However, reactions like 12C + 4He → 16O, 16O + 4He → 20Ne, 20Ne + 4He → 24Mg, etc., do take place (with steadily decreasing frequency as the charge increases). The plot on the right (from Suess and Urey, *Rev. Mod. Phys.* **28** (1956) 53) shows the measured abundances of naturally occurring isotopes as a function of atomic mass *A*, up to just over 60. You can see that these **α-process isotopes** are more abundant than their neighbours – e.g. 16O is more common than equally stable 18O, 20Ne than 22Ne, etc.

## Higher Fusion Processes

Stars that start out with masses above about 8 solar masses can fuse elements heavier than helium. The later stages are, successively,

* carbon fuses to produce sodium, neon and magnesium (needs *T* ~ 5×108 K);
* oxygen fuses to produce silicon, and secondary fusion reactions then produce sulphur, argon, and calcium (needs *T* ~ 2×109 K);
* silicon fuses to produce iron (needs *T* ~ 7×109 K).

At these high temperatures, nuclei can be broken up by reactions with high-energy photons, so many other isotopes are produced indirectly as a consequence of such reactions.

## Iron Peak

As seen in the plot on the right, 56Fe is the most stable nucleus (highest binding energy = lowest mass per nucleon). Therefore, if nuclei were being produced “democratically”, instead of sequentially starting from hydrogen, we would expect that 56Fe would be the most common isotope. This *does* happen in the interior of a supernova, which is so hot that all the pre-existing elements are broken down, and so dense that elements do not have to be produced by simple two-body collisions. This process produces the “iron peak” in the abundance plot.

In fact, the iron-peak elements are *not* produced very efficiently by core-collapse supernovae of massive stars, because this very high-density region is the bit that proceeds to collapse into a neutron star or black hole. It is believed that most of the iron in the universe is produced by Type Ia supernovae (SNe Ia). SNe Ia occur when a white dwarf in a close binary accretes enough mass to cause gravitational collapse, initiating runaway carbon fusion. Because the *whole* star is disrupted in an SN Ia, leaving no compact remnant, iron peak elements are produced and disseminated into the interstellar medium.

# The S-Process

Elements above the iron peak are not produced by fusion, as this would consume rather than produce energy (as can be seen in the binding energy plot). However, it is possible to produce these heavy elements by the addition of neutrons. Neutron capture does not require extraordinarily high tempera­tures, because neutrons have no charge and therefore do not see any electrostatic potential barrier.

## Production of Free Neutrons

Free neutrons can be produced in stars by the reactions 13C + 4He → 16O + n and 22Ne + 4He → 25Mg + n. Therefore, production of isotopes by neutron capture only starts during the helium fusion stage of a star’s life (the horizontal branch and beyond), because during hydrogen fusion there aren’t any free neutrons.

## The S-Process Path

The above reactions are rare, and free neutrons are unstable, so neutron capture in hydrogen-fusing stars is a rare process. In consequence, neutrons are added to a “seed” nucleus *one at a time*. If the produced isotope is unstable (usually to β-decay, $+e^{-}+\overbar{ν}$, where X is the parent isotope and X΄ is the daughter; occasionally to electron capture, $+ν$), it will almost always have time to decay before another neutron arrives. Therefore, the **s-process path** follows the decays of unstable nuclei, remaining close to the line of maximum stability. The plot on the right (from Wikimedia Commons) shows part of the s-process path from silver to antimony. Only stable isotopes are shown (the darker the colour, the more abundant the isotope). The s-process makes only the isotopes on the red line: the five isotopes of tin from 116Sn to 120Sn are all made by the s-process, but those below *A* = 116 and above *A* = 121 are not.

The s-process path can make elements up to bismuth (*Z* = 83). Bismuth has only one stable isotope, 209Bi. Adding a neutron to this gives 210Bi, which β-decays to 210Po. However, 210Po then *alpha*-decays, emitting a helium nucleus: $\rightarrow +$. The s-process can add neutrons to 206Pb, producing sequentially 207Pb (stable), 208Pb (stable) and 209Pb, which β-decays to 209Bi, and we’re back where we started. Therefore it is not possible to produce elements with *Z* > 83 by the s-process. (In fact, there *are* no truly stable elements with *Z* > 83 – but the half-lives of $$, $$ and $$ are so long that they can be regarded as stable for the purposes of nucleosynthesis. These three isotopes are the only ones heavier than bismuth which are formed in stars and occur naturally on the Earth: the elements in between – Po, At, Rn, Fr, Ra, Ac and Pa – do occur naturally, but have short half-lives and are produced by the radioactive decay of either thorium or uranium.)

# The R-Process

Isotopes off the s-process path *do* occur naturally, often in quite high abundance: 123Sb, which is off the s-process path as shown in the previous diagram, is nearly as common as 121Sb (their respective abundances are 57% and 43%), and in the next higher element, tellurium (*Z* = 52), neither of the two commonest isotopes, 128Te and 130Te, is made by the s-process. Therefore, there must be a process that can overcome the problem of intervening unstable nuclides. This is the **r-process**.

The r-process is believed to occur in supernovae, where the neutron flux is *much* higher than in helium-fusing stars (1022 n cm−2 s−1, as opposed to 1011 at best in the s-process). Therefore, nuclei capture *lots* of neutrons, creating extremely unstable isotopes with far too many neutrons, as in the figure below[[2]](#footnote-2).



The solid line in this figure is the s-process path, and the black dots represent stable isotopes produced by the s-process, the r-process, or both. The shaded band represents the isotopes produced *directly* by the r-process: these are obviously incredibly unstable and will β-decay in a fraction of a second.

This explains why some isotopes, such as 116Sn in the previous diagram, cannot be produced by the r-process. Any attempt to make 116Sn starting from the shaded region will hit 116Cd first (as shown by the red arrow above), and since 116Cd is stable the process will stop there. The r-process stops in principle at the point where the super-heavy nuclei produced are so large that they immediately decay by spontaneous fission, as shown in the plot: in practice, all the transuranic (*Z* > 92) elements are so unstable that they do not occur naturally on Earth (the longest half-lives above uranium are about a million years, which is negligible compared to the age of the Earth; in contrast, 235U has a half-life of 704 million years, and 238U of 4.5 *billion* years – the Earth still has half of its original 238U).

# The P-Process

Most of the common isotopes of heavy elements are made by both the s-process and the r-process. Neutron-rich isotopes which cannot be made from a stable isotope either by the addition of a single neutron (e.g. 120Sn from 119Sn) or by the decay of an isotope which can be made by the addition of a single neutron (e.g. 116Sn, the decay product of 116In, which is made by adding a neutron to 115In) *must* be made by the r-process, as must elements heavier than bismuth. Nuclei which have the same atomic mass *A* as a stable nucleus with smaller *Z* (e.g. $$ compared to $$) *cannot* be made by the r-process, so they must be made only by the s-process.

However, there are some rare stable isotopes which lie to the *left* of the s-process path. These cannot be made by the s-process, by definition (since the s-process path links all nuclei made by the s-process), and they clearly can’t be made by the r-process, because the stable s-process nuclei are in the way. They must be made by a different route, known as the **p-process**. In the original work of Burbidge, Burbidge, Fowler and Hoyle (B2FH), the p-process was presumed to involve the capture of protons, hence the name. Currently, proton capture *is* believed to be responsible for the lighter p-process isotopes (below *A* = 105): it probably occurs where matter is being accreted on to a neutron star, and is nowadays referred to as the **rp-process**3 (for rapid proton capture). The p-process proper, which makes heavier neutron-poor isotopes, is now thought to arise when high-energy photons knock neutrons out of heavy nuclei: thus 115Sn might be made by removing a neutron from 116Sn. This process takes place in supernovae, where the high temperatures provide a high flux of energetic photons.

# Production by Cosmic Ray Spallation[[3]](#footnote-3)

You may have noticed that, apart from 7Li made in BBN, we have not accounted for the light elements between helium and carbon. These are noticeably uncommon, as can be seen in the first plot on page 2, but they do exist, so they must be formed somehow. They are definitely not made by fusion, since (as shown in the second plot on page 2) they are actually less tightly bound than 4He. It is believed that they are made when cosmic rays (highly energetic protons) hit nuclei of interstellar gas. In such collisions, bits can be knocked off the target nucleus – a process known as **spallation**. The light isotopes 6Li, 9Be, 10B and 11B are made entirely by this process, and it contributes to certain isotopes of other light elements as well. On Earth, naturally-occurring carbon-14 is made by cosmic rays (the current terrestrial inventory of 14C is augmented by quite a bit that was made by atomic bombs during the bomb-testing era of the 1950s and 60s: its half-life is 5730 years so it’s still with us).

# Summary

The table on the next page presents a summary of nucleosynthesis. The main points to remember are the following:

* the lightest nuclei (2H, 3He, 4He, 7Li) are produced a few minutes after the big bang (BBN);
* other elements lighter than carbon are made by cosmic rays;
* elements between carbon and iron are made primarily by fusion processes and secondary reactions;
* for elements heavier than iron:
	+ the **s**-process involves **s**low addition of neutrons and produces isotopes next to other **s**table isotopes: it occurs in He-fusing stars;
	+ the **r**-process involves **r**apid addition of neutrons and produces neutron-**r**ich isotopes (to the **r**ight of the s-process path) by β-decay: it occurs in supernovae;
	+ the **p**-process involves loss of neutrons (or addition of protons) and produces neutron-**p**oor isotopes: it also occurs in supernovae.

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| ***A*** | **process** | **in** | **notes** |
| 2 (H) | BBN | early universe | destroyed in stars |
| 3 (He) | BBN | early universe | some cosmic-ray production too |
| 4 (He) | BBN and H fusion | early universe; MS and RGB stars | most of it (~90%) comes from early universe |
| 5-11 (Li, Be, B) | spallation | space | apart from 7Li, which is made by BBN |
| 12 (C) | He fusion | horizontal-branch and AGB stars | also other α-process isotopes such as 16O, 20Ne, 24Mg, in diminishing quantities |
| 14 (N) | CNO | MS stars of >1.1 solar masses, RGB stars | by-product of hydrogen fusion |
| 16-56 | fusion | massive stars (>8× solar mass) | either directly from fusion, e.g. neon and magnesium from carbon fusion, or as a result of secondary reactions |
| ~56 (iron peak) | thermonuclear | supernovae, mostly type Ia | produced at very high temperatures where elements are made democratically, so the most stable isotopes win |
| 56-209 | s-process | He-fusing stars (HB and AGB) | can only add one neutron at a time, so can only make isotopes from a pre-existing *stable* isotope with atomic mass *A* – 1 |
| >56 | r-process | supernovae | stable isotopes produced by β-decay, so stops at the first (lowest *Z*) stable isotope for given *A* |
| any | p-process | supernovae | high-energy photons knock neutrons out of pre-existing nuclei; makes neutron-poor isotopes  |
| 56-105 | rp-process | neutron star accretion | makes neutron-poor isotopes by adding protons; probably more important than p-process for lighter neutron-poor isotopes |

 Abbreviations: BBN = big bang nucleosynthesis, MS = main sequence, RGB = red giant branch (fusing H in shell around He core), HB = horizontal branch (fusing He in core), AGB = asymptotic giant branch (red giants that fuse He around a carbon core)

1. In fact, deuterium fusion is even easier, and turns on earlier – but the natural abundance of deuterium is very small, so the deuterium-fusing stage is very short and generates little energy. It is usually neglected in considering stellar evolution, but is used as a convenient yardstick to separate brown dwarfs (which never fuse 1H, but do fuse 2H) from gas giant planets (which never fuse anything). The corresponding mass is about 13 times the mass of Jupiter. [↑](#footnote-ref-1)
2. from Seeger, Fowler and Clayton, *ApJS* **11** (1965) 121. [↑](#footnote-ref-2)
3. not covered in lectures, so not examinable! [↑](#footnote-ref-3)