On the Origin of the Chemical Elements

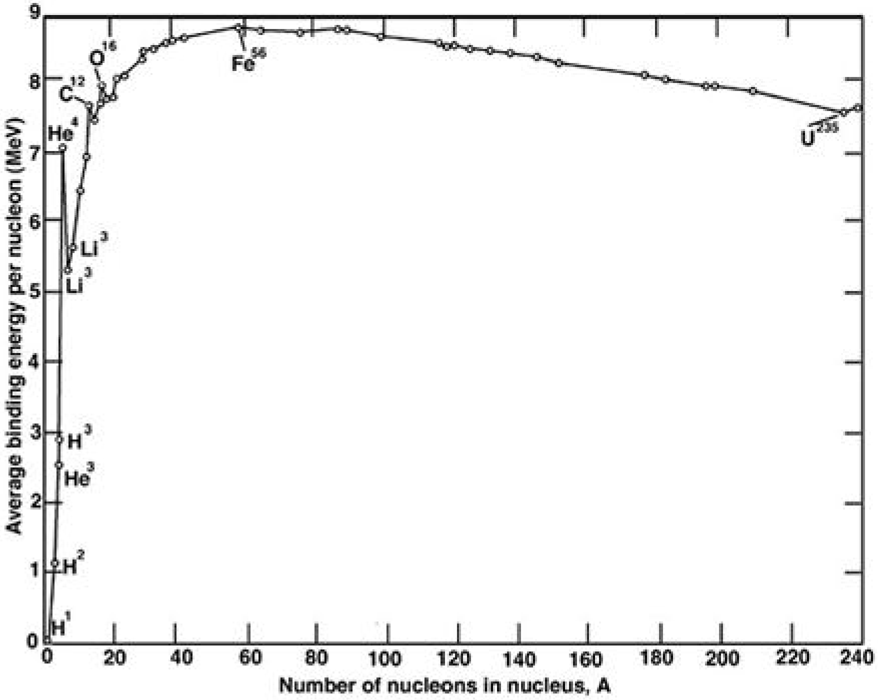
The Big Bang

At the beginning of the universe it is unknown what occurred exactly, however, cosmology has been able to give insight into the very first baby steps of the universe, during which the building blocks for all the chemical elements came about. Initially conditions were hot, approximately 10^{12}K (Seeds & Backman 2015), and protons came into existence for only short time periods before being annihilated again by their antimatter pairs. After two minutes, temperatures were cool enough to allow deuterium to exist; after 3 minutes reactions were able to form helium. From these few components small amounts of lithium and beryllium were also able to form through nuclear fusion (Seeds & Backman 2015). After roughly 30 minutes reactions decline as energy levels are too low and energy is too dissipated to form any further stable atomic nuclei through fusion processes. The creation of new chemical elements continues many millions of years later deep in the belly of red giant stars.

Fusion

The process of nuclear fusion in which two nuclei are fused together, overcoming coulombic repulsion to reach the distance scales at which the strong nuclear force can begin acting, is the process responsible for the formation of elements from hydrogen through to iron. Why the process stops here can be seen from the graph of binding curve energy (Figure 1) (Splung 2017). Elements heavier than iron have less binding energy per nucleon and so are no longer viable to be produced easily through nuclear fusion.

Figure 1: Graph of Nuclear Binding Energy



Proton-proton fusion

Hundreds of millions of years after the big-bang the distribution of hydrogen and helium gas from the Big Bang began to clump together under the influence of gravity (The StarChild Team 2003). This provided the formation of the first stars and the cumulative gravitational pressure necessary to allow fusion reactions. At temperatures of around 1.5 x 10^7K in the centre of stars (such as our sun) reactions of matter to energy conversion and beta plus decay occur. A total of 6 protons lead to the formation of a ^{4}He nucleus with by-products of 2 protons, a positron, an electron neutrino and energy (HyperPhysics 2017). This process is outlined in Figure 2.

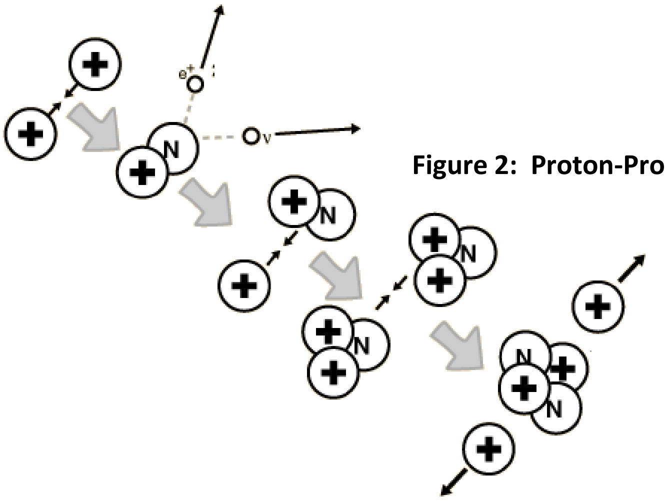


Figure 2: Proton-Proton Fusion chain

Eventually the hydrogen deposits in the centre of the star will be entirely converted to helium and the lack of thermal pressure outwards will cause the star to contract under gravity. This provides greater internal heat levels and allows the hydrogen around the core to be burnt in “hydrogen Shell burning". By providing an increase in thermal pressure outwards, the star expands and enters the Red Giant phase of its lifecycle where temperatures continue to rise. Once temperatures reach around 100 million K, helium fusion can then begin to take place.

Triple Alpha Process

In the later phases of red giants and red supergiants, helium fusion is able to occur and elements not seen since the big bang appear. In this process two helium nuclei (^{4}He) are brought close together and fuse to form beryllium (^{8}Be) with the release of a high energy gamma ray. This beryllium nucleus is then able to fuse with a helium nucleus to form Carbon (^{12}C) with the release of another high energy gamma ray (Dawson 2017).

CNO Cycle

When the internal temperature of a star is around 15 million K (such as in the star Sirius with around twice the mass of our sun) the carbon-nitrogen-oxygen cycle becomes the dominant form of fusion (Hyperphysics 2017). Protons are sequentially fused to a carbon nucleus (^{12}C) with the end result being the creation of an alpha particle (^{4}He) and a ^{12}C nucleus, at which point the process can be repeated. Initially ^{12}C fuses with a proton to form ^{13}N which then undergoes Beta plus decay. In this process a proton transmutes into a positron and a neutrino resulting in the formation of ^{13}C (Guide to the Nuclear Wallchart 2000). The fusion of two more protons creates ^{14}N and then ^{15}O which undergoes beta plus decay to produce ^{15}N. A proton then fuses to form ^{16}O which then emits an alpha particle to return to ^{12}C. At this stage the cycle can then begin again and continue to produce more helium through fusion.

Neutron Capture

In the formation of elements above iron, another process called "neutron capture" is required to overcome the peak in the binding energy curve. A neutron will collide with a nucleus, and due to its neutral charge is not electrostatically repelled as a proton would be. This brings the neutron close enough to the nucleus to bind and form a new element with an atomic mass one unit higher than before.

S-Process

In the slow process of neutron capture a seed nucleus gathers a neutron on average once every 1×10^{5} years (Guth 2002). Beginning with ^{56}Fe this process can form cobalt (^{59}Co), the first new element seen since fusion processes created elements such as iron. The iron nucleus slowly gathers neutrons until it becomes ^{59}Fe, an unstable isotope which then undergoes beta minus decay in which a neutron transmutes into a proton with the release of an electron and an antineutrino to form ^{59}Co (Guide to the Nuclear Wallchart 2000, Hyperphysics 2017). This process similarly continues slowly climbing the steps of nuclear stability, decaying and then climbing again to continue to produce new heavier elements. Due to the instability of much heavier nuclei the S-Process can only continue to produce elements up to Lead (^{208}Pb) and Bismuth (^{209}Bi) (HyperPhysics 2017, Guth 2002). Due to the slow nature of this process the half-life of these elements is too short and the time before a consecutive neutron capture is too long to allow for heavier elements to form.

The probability of a Neutron capture occurring is known as the "neutron capture cross section", determined by quantum mechanical effects of closed atomic shells (Hyperphysics 2017). It is interesting to note that it is for this reason there is a notable peak in the abundance of elements with neutron numbers such as 28, 50, 82 and 126 as these provide smaller neutron capture cross sections and as such have a smaller chance of progressing to become heavier elements.

Based on the neutron densities, temperatures and durations required for the s-process, it is probable the environments required for it to occur are those of Asymptotic giant branch stars, seen in an image taken by the Hubble space telescope (Figure 3) (Guth 2002, Franke 2002). These stars are old and mostly burnt out and feature degenerate Carbon-Oxygen cores. Reactions in the shells of these cores such as the fusion of Helium with Neon or Carbon produce neutrons as by-products, which can then go on to be used in neutron capture. Once formed, these new elements are convected to the surface of the star where they are released in solar flares or in a supernovae explosion.

Figure 3: Asymptotic giant branch (AGB) star

In order for elements heavier than Bismuth and Cobalt to form, a faster acting process is required **which** can capture neutrons before these elements are able to undergo atomic decay.

R-Process

The Rapid process occurs at a very fast rate as some heavier unstable nuclei have half-lives of only a few seconds and successive neutron captures must occur before the nuclei decays. Neutrons continue to be captured by nuclei unhindered until equilibrium is reached where neutrons are as easily removed by surrounding thermal photons as they are captured by the R-process (Guth 2002). The Alpha instability of Lead (^{208}Pb) can be overcome by the R-process, producing elements much heavier than those from the S-process, and forming the many stable Actinides which are significantly abundant in the universe. These elements, along with others hard to reach on the neutron capture path, can be created via Alpha Decay from a heavier element (Guth 2002).

Similarly to the S process, neutron capture is less likely at certain Neutron numbers; hence these elements form in higher abundance from the R-process. Due to the instability of heavy nuclei they quickly decay once the process ends and so the preferable neutron numbers for the R-Process lie slightly lower than those in the S-process.

There have been many postulations as to the environments in which Rapid Neutron capture can take place since it was proposed in 1957 (Guth 2002). The most widely accepted location is in the heated neutrino-driven wind released from the surface of a neutron star shortly after its formation. This environment provides the high neutron density and the other conditions required for the R-Process to take effect.

Summary

The chemical elements are produced in a variety of environments, conditions and time-scales within our universe, and no single process is responsible for the creation of all elements. The immense variety in the places of creation testifies to the remarkable origin of many a thing we often take as ordinary.

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