# The origin of the elements

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Rocks are made up of minerals, which are themselves made of chemicals. Silicon and oxygen are prominent in the minerals that make up almost 75% of the earth's crust. The major chemical constituents of the crust are Oxygen, silicon, aluminium, iron, calcium, sodium, potassium and magnesium. For the planet as a whole, there is a large increase in iron, larger magnesium and nickel in significant quantities. For the entire universe, hydrogen forms about 75%, helium almost 25%, with oxygen the third most abundant at 1% and all the rest only 1%. The question arises as to where did all the elements come from originally to form the 100 or so elements in the periodic table. Was it from stars or were they formed in the Big Bang 13.7 billion years ago.

## The nature of elements

The atomic nature of matter was made clear by Richard Feynman (1918-88), who said that everything was made of atoms. This contrasts with the views of Democritus (c470-380BC), who identified 4 elements – earth, air, fire and water. This was used to explain how salt dissolves in water and how fish travel through water. David Bernoalli (1700-82) used Newton's Laws of motion to explain the nature of gas, with atoms being extremely small in comparison with the space between them, eg through Boyle's Law. Ludwig Bolzmann (1844-1906) and James Clerk Maxwell (1831-79) worked on the mathematical theory of gases but this was only a theory with no observable evidence.

Albert Einstein (1879-1955) gave the first demonstration of the actual existence of atoms when he explained Robert Brown's discovery of Brownian motion in terms of atomic theory in one of 5 papers published in 1905 along with the theory of special relativity and the photoelectric effect, which form the basis of quantum mechanics. At 1/10 of 1 billionth of 1m, the size of the atom was defined as 1 angstrőm.

Heinrich Rohrer and Gerd Binning invented the scanning tunnelling electron microscope, which enabled atoms to be resolved and the question was how many different kinds of atoms were there. Antoine Lavoisier (1743-94) produced a table of elements in a 1789 publication, only 23 of which are now recognised. Today, 118 elements have been identified, of which 94 occur naturally on earth. John Dalton noted how elements combine in different proportions.

## Key evidence was structure of the atom

Patterns to the relationship between different elements were recognised in the 19$^{th}$ century. Dimitry Mendeleyev (1834-1907) formulated the periodic table in 1869. The later discovery of 3 elements that he had predicted (Gallium, Scandium and Germanium) gave the clue that there must be some internal structure. Spectrometry was also a clue with each element having its characteristic frequency. The growing discovery of radiation with the work of Rontgen (1896) and Henri Becquerel's discovery of fluorescence was taken further by Marie and Pierre Curie, who discovered thorium and coined the word radioactivity. The work of Ernest Rutherford (1871-1937), J. Thompson and others led to more understanding of the internal structure of atoms with a positive nucleus surrounded by negative electrons (1911). The atom itself was mostly empty space, the nucleus in the atom being equivalent to a molehill in the middle of a football field.

Nuclei can have up to 250 neutrons and protons, with hydrogen having only a single proton. The clue to the origin of atoms is the origin of the nucleus. The atomic structure is not necessarily stable, especially in the heavier elements as in radioactivity. E=MC2 quantifies the energy released as the nucleus splits, with mass converted to energy, which was the basis of the mid-20$^{th}$ century exploitation of nuclear fission using the chain reaction in the atomic bomb and nuclear power stations. The question is how the heavy nuclei formed.

In 1868, Norman Lockyer, the founder of the Science Museum, who also launched *Nature*, used a spectrograph to look at the sun and discovered a new element – helium, the only element to be discovered outside the earth and the second most common in the universe.  Einstein and Arthur Eldington (1882-1944) looked at the source of the sun's energy.  They examined the possibility of it being radioactivity but the heavier elements are not present in the sun.  Instead there are large amounts of hydrogen and helium and the process is the opposite of fission, namely fusion, in which hydrogen is fused into helium, converting hydrogen with its one proton to helium with 2 protons and 2 neutrons.  This is the same as the alpha particle discovered by Rutherford as a key ingredient in radioactivity.  Eldington showed that, even though the sun is very hot, it is not hot enough to fuse the higher elements in the periodic table.

## The key is in the life cycle of stars

This relates not to how they burn in their lifetime but in their dying stages when the star runs out of primary fuel (hydrogen).  How they die depends on their mass and they become highly unstable with catastrophic collapse leading to supernova explosions.  Fred Hoyle said that a star becoming a supernova is the key to the formation of the heavier elements.  There are 2 major forces acting within stars, nuclear fusion blowing the star apart and gravity holding it together.  The hydrogen-burning star converts t a helium-burning star with a hydrogen-burning shield forming the stellar envelope.  Gravitational forces increase and the star starts to collapse inwards and temperature rises dramatically.  The heavier elements can then start to form and the star becomes a red giant.  When the fuel is exhausted, inward collapse leads to simultaneous conversion of up to 10% of the mass into energy in a supernova.

The temperature conditions required did occur at the time of the Big Bang but only for about 10 minutes.  Much longer is required to synthesise elements and a red giant can last up to 100 million years.  There is still a major problem, however, in that this only works up to as far as iron, the mid-point of the periodic table.  There is a sticking point between fusion and fission.  Hoyle suggested that the lighter elements formed through the α process with neutron capture at very high temperature in the red giant phase.  Margaret and Geoffrey Burbridge, Willy Fowler and Hoyle identified several different processes involved in neutron capture with long time scales required.  In a 104-page 1957 publication they identified 7 element-building processes – hydrogen-burning, triple α, α process, s-process, r-process, proton capture and equilibrium.  However, this could not explain the origin of lithium, which was created at the Big Bang like hydrogen and helium.

## Conclusion

At the Big Bang, there were only 4 elements formed – hydrogen, helium, lithium and probably beryllium (possibly be high-energy cosmic ray collisions).  It then probably took about 1 billion years before the first supernova explosion and the formation of other elements.