The genesis of elements

Introduction

The periodic table is continually enriched with new elements synthesised by nuclear reactions in laboratories, but only 90 of all the elements occur naturally. Those are found between atomic numbers 1 to 92, which is from 1H to 92U, excluding the elements technetium (43Tc) and promethium (61Pm). The latter two are made artificially, even though technetium has been recently discovered in stars.

All the elements are made from two fundamental building blocks, the protons and the neutrons, given the term nucleons. These are packed together into nuclei, with each element containing a different ratio of protons and neutrons in its nucleus. The nucleons can only be produced or annihilated at very high energies, and this occurred at the beginning of the universe.

“ What happened the first moments of the creation of the universe and how were the elements synthesised?” are the questions around which this report is circulated. Using astrophysics to discuss the universe creation is beyond the purpose of this report, and therefore most of the physical equations are excluded. All the terms are explained in simple scientific terms.

The areas discussed are how the universe began and how the elements were formed in this universe creation timeline, including any relevant nuclear reaction equations and theories that lead to the creation of the chemical elements as we know them at present. [1, 2]

The Big Bang and the origin of the chemical elements

The most widely accepted theory in cosmology is currently the Big Bang Theory, which was based on Einstein’s General Theory of Relativity (E= mc2). According to this, the universe was once concentrated in a small primeval nucleus of extremely high temperature and infinite density.

For some reason, that hot, dense state began to expand homogeneously and cool down at an incredibly fast rate. This sudden expansion into space, distributing radiation and matter everywhere uniformly, gave rise to the birth of the universe and it is known with the misleading title ‘ Big Bang’ (even though it was not an explosion but an expansion). The reason that caused this sudden expansion is not known yet, and scientists are still trying to give an answer to this big cosmology question with many research projects taking place in this field for the past few decades. It is beyond modern science to define what happened before the Big Bang since time and space came into being at that moment. According to this theory the universe is about 15 billion years old.

But which are the evidence that this ‘ Big Bang’ actually occurred? [1, 5, 6, 7, 8, 9]

Universe’s expansion

In 1929, Edwin Hubble discovered that the universe is expanding and that the galaxies that make up the universe are moving away from our galaxy with velocities proportional to their distance from us. Hubble’s law describes this expansion, stating that the farther a galaxy is from us, the greater its radial velocity of recession.

Hubble’s equations as follows [9]:

v (radial velocity) = H (Hubble constant) x d (distance)

In simple terms this means that the most distant galaxy is moving away from us at the fastest rate and the nearest at the slowest.

This, however, does not mean we are at the centre of the universe, since every observer in the universe sees all objects moving away from them with velocity proportional to the distance. So although the universe is expanding, it looks the same from every single galaxy.

Hubble’s conclusions resulted from observing the velocities via the redshift, which is the Doppler Effect applied to light waves. Each galaxy has a set of emissions and absorptions seen in their spectra and their characteristic frequencies are known. The characteristic lines from galaxies’ spectra turn out to move towards the red end of the spectrum, which means the galaxies are receding from us. This effect is known as the ‘ redshift’. If the galaxies were moving towards us the light waves would be crowded and the frequency would be raised. Since the blue light is of high frequency, a shift towards the blue side of the spectrum would be obtained, giving a ‘ blueshift’. But this does not occur, and the galaxies are all redshifted.

The proportional relationship between speed and distance indicates that in the past all the matter must have been concentrated at a point of extraordinary high density, from which it expanded to its present form. Hubble’s discovery provides one of the evidence for the Big Bang Theory. [6, 9, 11]

Cosmic Background Radiation

In 1965, Penzias and Wilson were investigating the radio noise found at wavelengths between a few millimetres and a few centimetres, by means of a special low-noise radioantenna. Once all the known sources of noise were identified, a remaining signal of radiation was left as an annoying excess noise. This signal was coming from all directions and the noise did not change in intensity with the direction of the antenna in the sky or the time of day and season. This radiation was identified to be Cosmic Background Radiation.

The radiation that Penzias and Wilson discovered was seen as the dying remnants of the Big Bang, and was probably formed due to photon production from matter-antimatter annihilation. Once the photon background was produced, it cooled with the expansion of the universe leaving behind this background radiation. This radiation contains more energy than the rest of the universe (stars and galaxies).

In the universe's early life, when it was very hot, radiation could not travel very far without being absorbed and emitted by some particles. This constant exchange of energy maintained a state of thermal equilibrium and therefore a thermal spectrum can now be obtained.

In 1989, Cosmic Background Explorer (COBE) satellite was launched which took measurements from above the earth's atmosphere, obtaining more accurate results for this radiation than Penzias and Wilson. The shape of the spectrum of thermal radiation that was observed at the temperature of 2. 73K was very similar to that of a blackbody's spectrum at the same temperature. The cosmic microwave spectrum shows that this radiation was generated in equilibrium conditions since it has a thermal shape. The radiation is also known as the ‘ 3K radiation’ or the Cosmic (comes from all directions) Blackbody (because of its spectral shape) Microwave (since its spectrum peaks at cm to mm wavelengths) Radiation – CBM.

In 2001 the Wilkinson Microwave Anisotropy Probe (WMAP) was launched by NASA, designed to determine the geometry, content and evolution of the universe and to make fundamental measurements of cosmology. WMAP successfully produced a full-sky map of the temperature anisotropy of the cosmic microwave background radiation, and it still continues to collect data from space.

The results from the different measurements of the cosmic background radiation taken through years are shown in the figure following.

Furthermore, the measured uniformity of the radiation confirmed some assumptions about some of the universe’s properties: its homogeneity (it looks the same at each point) and its isotropy (it looks the same in all directions).

To summarise, two evidences supporting the Big Bang Theory have already been discussed:

1. The Big Bang Theory explains Hubble’s observation that the universe is expanding, since it must have started its expansion from a hot and dense state in its early life.

2. It accounts for the existence of the cosmic background radiation observed by Penzias and Wilson, and confirms the assumptions that the universe is homogeneous and isotropic. The third evidence for the theory is that it accounts for the origin and the abundances of the light elements that exist in the universe. [6, 7, 9, 12, 14]

The timeline of the ‘ Big Bang’

Before the Big Bang the universe was compressed into a hot and dense nucleus. When the Big Bang occurred, the universe began to decompress rapidly. The modern science has not yet defined what happened earlier than Planck’s time which is at 10-43s after the Big Bang. At that time the four forces of nature were unified in a single super force (also referred to as Wald), being equally powerful.

The four forces are divided in the next two categories:

1. Forces between particles (operate over large distance):
    - Electromagnetic
    - Gravity
2. Forces in subatomic domain

(operate over very short distances):

- Strong nuclear force (it holds the nuclei of atoms together)
- Weak nuclear force (it crops up in radioactive decay and helps fission)

The forces’ strength is as follows: Strong > Electromagnetic > Weak > Gravity

In the ‘ primeval fireball’ formed after the Big Bang, the photons’ energy was so high that they can collide to form particles (creation of matter from light and formation of matter and antimatter in pairs. This is seen from the Einstein’s equation, E= mc2, which doesn’t say that this relationship is irreversible. So matter can become energy or energy can become matter! [5, 9, 10]

Some important terms, which are mentioned on the above timeline, are very briefly explained below [9, 10]:

- Quarks are the elementary particles that make up the protons, neutrons etc. A proton is made out of three quarks: 2 up and 1 down quark. Neutron is made out of 2 downs and 1 up.
- The antimatter has the same properties as the regular matter except that it has the opposite electrical charge.
- Inflation is the early phase of the exponential growth of the universe.
- Baryons are particles made out of 3 quarks. Out of those particles only protons and neutrons are stable; therefore the baryonic matter in the universe is considered to be made mostly out of them. The electrons are often included in the term baryons even though they are not made out of three quarks. The universe has neutral charge, i. e. 1 electron for every proton.
- Radiation: what we see in the universe comes from electromagnetic radiation. The light is made up from individual particles, the photons, ?. These protons spread at the speed of light, and (mostly the high energy ones) can interact with baryons and electrons; for example they ionise an atom by taking off an electron.

- Neutrinos are extremely weak interacting, massless particles produced in radioactive decay

The particles that were present in this cosmic nucleosynthesis are given in the following table:

In general, the universe is made out of the following [10]:

- Baryons (p, n, e)
- Radiation (photons)
- Neutrinos
- Dark Matter and Energy

Nuclear Processes taking place during the element formation

The light elements of the periodic table were produced during the beginning of the life of universe, whereas the heavier elements were produced later by thermonuclear reactions that power the stars.

The early universe could be viewed as a type of thermonuclear reactor. However, the abundances of the light elements produced soon after the Big Bang, have changed at present due to the nuclear processes in stars and other subsequent events in the interstellar medium.

Some of the reactions taking place during the life of the universe until now are shown on the following table.

Element Abundances

The abundance of the elements is the third evidence supporting the Hot Big Bang theory as seen earlier. These abundances are obtained from detailed spectroscopic analysis of samples taken from earth, meteorites, comets, moon, planets etc.

The chemical element abundances can be recorded in three different ways [16]:

1. Mass fraction: the mass of a constituent of a mixture over the total mass of all the constituents in the mixture à w = a / (a+b+c+…)
2. Volume fraction: the volume of a constituent of a mixture over the sum of the volumes of all constituents before mixing. For gases, the volume fraction is similar to the mole fraction à ?
3. Mole fraction: the number of moles of a constituent over the total amount of all constituents in the mixture à x

The graph has some certain features and trends which are seen below [1, 2]:

1. There is an approximately exponential decrease from H until A~100 (atomic mass number) or Z~42 (atomic number). Then, gradual decrease is observed.
    - For higher A, the rarity of synthesis increases showing that the stellar evolution (which builds the heavier elements) is not very common.
2. A peak is seen between Z= 23-28, i. e. for elements V, Cr, Mn, Fe, Co, Ni. At the maximum of the peak lies iron, and it is seen that Fe is 103 times more abundant than expected compared to its neighbouring elements.
    - The e-process (equilibrium). Iron lies on the maximum energy that can be released in stellar nucleosynthesis with the element

  burning processes. After this, the elements form mostly by neutron capture.

3. The elements D, Li, Be, B are rare compared to their neighbouring H, He, C, N which are highly abundant.
    - Their production is insufficient. Also they are consumed at very high temperatures in the stellar interiors. These elements are mostly made by stellar spallation.
4. Light nuclei up to Z~21 having their A divisible by 4 are more abundant than their neighbours. This was observed by G. Oddo in 1914.
    - These elements are alpha particle nuclei (e. g. O16, Ne20…Ca40, Ti48). It is seen that the He-burning and alpha-process are more efficient than the H-burning and s-process in these regions.
5. Double peaks can be seen at A = 80, 130, 196 (peaks due to neutron capture with r process) with A = 90, 138, 208 (due to neutron capture with the s process)
    - Magic numbers at N = 50, 82, 126 for progenitors and stable nuclei
6. Atoms with even atomic mass number, A, are more abundant that those with odd A, therefore the alternate peaks (up and down) are seen in the graph.
7. Heavy atoms tend to be neutron rich. Proton rich heavy nuclei are rare
    - This is because the proton- rich nuclei are produced in the p-process which is rare compared to the r- and s- processes.

The r and s peaks seen in the following smoothed curve correspond to the elements formed by the slow and rapid neutron capture processes. Some elements require the neutron capture to be slow enough so that intervening beta decays can occur. However, some other elements need neutron capture to happen very fast to be able to form through some short-lived nuclei. [18]

Big Bang Nucleosynthesis

The Big Bang Nucleosynthesis (BBN) occurred a few brief moments after the beginning of the universe, way before the stars existed. The light element formation happened via nuclear fusion reactions (a process by which smaller nuclei are joined into larger ones), which raged throughout the universe. It is also known as Cosmic or Primordial Nucleosynthesis.

For nuclear reactions to occur, some conditions should be present, which were both satisfied in the early universe:

1. The temperature and density should be high enough, so that the kinetic energy of nucleons can overcome the coulomb barrier
2. The particles must come close enough for the attractive nature of the strong nuclear force to overcome the repulsion of the electromagnetic force between the positive charges of the particles (protons).

As seen earlier, the universe was born by expansion from a hot, dense state in which its constituents were elementary particles. Atomic nuclei, except from the proton, began to form through nuclear fusion reactions, which could not take place until the temperature was low enough for them to occur. When the universe was about 1 second old, protons became available for fusion, and a proton and neutron can be combined to form a deuteron.

However, the deuteron was destroyed by photodissociation (break up of a nucleus by high energy gamma rays) before the more stable helium was formed. At this stage fusion could not proceed further until the universe was cooled further.

At about 100s after the Big Bang, the temperature had fallen to 109K and fewer deuterons were destroyed, allowing 4He to form, along with all the isotopes of hydrogen and helium below 4. No considerable amounts of elements above nucleus 4 were formed since there are no stable nuclei of atomic number 5 and 8. However, traces of 7Li and 7Be were formed.

At 1000s, the temperature had fallen too low for particles to have enough energy to overcome the coulomb barrier. Therefore, the fusion reactions stopped occurring and the abundances of the elements were ‘ frozen’. Most matter existed as rarefied gas for a few hundred million years until it was slowly drawn towards a star, where more reactions could take place, due to higher temperatures.

The only nucleus formed in a considerable amount was 4He, with some traces of lighter nuclei. Most of the material continued to be 1H.

Light element formation

Deuteron formation through fusion of a proton with a neutron gives out a photon of high energy (gamma ray). Most of the energy is carried away with this gamma ray, allowing the proton and neutron to bind. Otherwise, they would bounce off each other. The reversible reaction is also true, so a gamma ray can destroy the deuteron.

n + p à d + γ

When there is not anymore sufficient energy and collisions to form many deuterons, they start combining to form helium nuclei:

d + d à 4He + γ

However, some two step processes can occur between the proton, neutrons and deuterons to form the helium and hydrogen isotopes, 3He and 3H, as a between step. These two step processes are:

p + d à 3He + γ

n + 3He à 4He + γ

and

n + d à 3H + γ

p + 3H à 4He + γ

These processes can happen in the forward or backward way, until they reach equilibrium.

Neutron decay

In the early universe, the temperature was high enough for free protons and neutron to exist in thermal equilibrium at high energies. The free neutrons would travel long distances before colliding with other baryons, having a great chance of decaying into protons.

n + ve ßà p + e- + 0. 8MeV (ve is e- neutrino)[ref. 2]

When the thermal energy drops below 0. 8MeV it is hard for backward reaction to occur and therefore more neutrons decay into protons, setting the ratio of n: p to 1: 5. However, as soon as the energy falls more (about 0. 1MeV) the neutrons manage to form nuclei and become stable, with the ratio now being n: p to 1: 7 due to further reduction of the number of neutrons by decay that occurred in the time that it took for the energy to fall.

As seen, the only elements produced in significant abundance are 1H and 4He. 4He is formed since it is the most stable of the light elements and 1H is present since there are not enough neutrons to react with the protons (1: 7 ratio of neutrons to protons) and a large amount of protons are left over.

In universe’s primordial composition 4He is found to be about 25% (mass fraction). Since 4He is four times heavier than 1H, it implies that there is one helium nucleus for every twelve hydrogen ones. Other elements abundances are (compared to 1H abundance): D = 10-4, 3He = 10-5, 7Li = 10-10 [ref. 2]

The mole fraction of the elements is H 88. 6% and 4He 11. 3%. Since H and He account for 99. 9% of the atoms in the universe, it is concluded that nucleosynthesis of heavier elements has not yet gone very far. [ref. 4]

At present, the observed abundances of the elements are successfully reproduced by the Big Bang Theory (providing an evidence for the theory). However, the present composition of the universe is slightly altered from its primeval composition, because of the nuclear reactions occurring in stars.

Stellar Nucleosynthesis

Stellar nucleosynthesis is the fusion process that powers the stars, forming heavier elements out of the lighter ones. The main reactions taking place during this process are summarised in the table below, and then discussed more broadly.

Hydrogen burning

Hydrogen burning is the fusion of four hydrogen atoms to form a helium one. This happens through two different routes: [ref. 6]

Proton-proton chain. This is the primary energy producing process in most stars, especially in low mass stars like our Sun, and is as follows)

p + p à d + e+ + ve

p + d à 3He + γ

3He + 3He à 4He + p + p

The fusion of two protons to form a deuteron (the nucleus of a deuterium atom with 1p & 1n)

3He is an isotope of helium with 2 p and 1 n

4He is the most common isotope of helium, having 2p and 2n.

In the 1st step takes a very long time to occur (5×109 years), since it involves the weak nuclear force and there is a very small cross section. This is the reason for the long life of stars. The 2nd step involves the electromagnetic interaction and occurs in about 1 second, whereas the 3rd step involves the strong nuclear force, taking about 3×105 years.

CNO cycle. It is another method for burning of hydrogen, using carbon, nitrogen and oxygen as catalysts. These get consumed so as to help the process occur, but are afterwards reformed.

p + 12C à 13N + γ

13N à13C + e+ + ve

p + 13C à 14N + γ

p + 14N à 15O + γ

15O à 15N + e+ + ve

p + 15N à 12C + 4He

Nitrogen nucleus decays

Oxygen nucleus decays

Helium Burning (triple-alpha reaction)

Hydrogen burning releases 90% of the total energy available from fusion. The rest is coming half from the helium burning and the other half from other nucleus burnings up to 56Ni or 56Fe. However, since 5Li and 8Be are unstable, fusion after He can continue only at high density.

During the triple-alpha process three 4He nuclei fuse to form 12C. Then, helium and carbon react so as to form oxygen.

Some reactions are:

4He + 4He ßà 8Be An almost 100% reversible process since 8Be is highly unstable.

4He + 8Be ßà 12C* An excited state of 12C is formed and almost all decays back to He and Be.

12C* à 12C + e+ + e- However, about 0. 2% decays into a stable carbon nucleus.

When the 8Be barrier has been passed and the triple-alpha process forms carbon, the following also can occur:

4He + 12C à 16O + γ

4He + 16O à 20Ne + γ

Carbon Burning

The carbon burning follows when the star has run out of helium fuel. This can give three different products.

12C + 12C à

20Ne + 4He

23Mg + n

23Na + p

Oxygen burning etc.

Oxygen burning: 16O + 16O à 28Si + 4He

Neon Burning: 4He + 20Ne à 24Mg + γ

A 28Si can dissociate into 7 4He and react in silicon burning.

Silicon Burning: 28Si + 74He à 56Ni

(which can then ?-decay to 56Fe during or after a type II supernova)

From the above reactions protons, neutrons and alpha particles are released, which are then available for additional captures so as to form further isotopes of the elements.

The mass barriers in the element formation

In 1939 Bethe observed that ” no elements heavier than helium can be built up to any appreciable extent”, since there are no stable elements of mass 5 nucleus.

No reasonable ways of formation of elements could be given, since none of them would work:

- The addition of a neutron or a proton onto helium can not occur to form a mass 5 nucleus (unstable)
- The direct formation of 8Be out of two 4He is not possible due to the fact that 8Be is very unstable, with negative binding energy
- The formation of 12C out of three helium nuclei would not work either.

However, at sufficiently high temperature and density 4He can bind to form 8Be and therefore the mass 4 barrier can be passed. This beryllium formed, even though very unstable and at low quantities in the star interiors, it is enough to form 12C when another helium nucleus is added to it (Salpeter, 1952). Once the unstable mass 5 and 8 barriers are overcome, more elements can be formed.

Beyond the Iron Peak & Explosive Nucleosynthesis

The normal nuclear fusion reactions occurring in the star interiors can only form elements up to iron, 56Fe. They do not produce any elements beyond the iron peak since this would require energy rather than yielding energy. Beyond the iron peak, elements can be formed mainly by neutron captures. After 83Bi, no more stable isotopes can be formed. Neutrons are produced by some of the processes seen earlier, and one of the most favoured one is:

13C + 4He à 16O + n

In stars, mass loss processes, where a return back to the interstellar medium material occurs which is however altered from when it formed the star, are very common. These can be mild and form planetary nebulas, or can be violent and catastrophic explosions, known as novae and supernovae. During the latter processes, heavy elements are form rapidly before or after the explosion with neutron captures.

The two main types of neutron capture synthesising the heavy elements have been briefly discussed earlier (see p. 13) and they are the following:

1. S-process (Slow neutron capture)
2. R-process (Rapid neutron capture)

An unstable species has to decay before capturing another neutron, and therefore the s-process produces the less neutron rich compounds, since the process is slow enough, it allows beta decay by electron emission and the isotopes are stable before a lot of neutrons have been added.

However, during the r-process the neutrons are added rapidly and the nuclei do not have enough time to decay, allowing more neutrons to be added until they can not accept any more. This process forms the more neutron rich elements.

Other processes

The proton rich isotopes of the heavy elements are formed by the p-process, i. e. proton captures.

The elements 2H, 3He, 6Li, 7Li, 9Be, 10B and 11B, as well as some less neutron rich isotopes are not produced in significant amounts form the Big Bang and are less abundant than their neighbours. They are mostly formed during spallation reactions (fragmentation), during which more abundant elements (like C, N and O) are broken up in reactions between cosmic rays and the interstellar gas.

The cosmic rays consist of small subatomic particles (mainly p and He nuclei) which travel through our atmosphere from space at the speed of light. They are created in supernovae and some star interactions. The particles in the cosmic rays are accelerated by the galaxy’s magnetic field and fly towards every direction.

During their journey around the galaxy, the heavier particles of the cosmic rays collide with the atoms in the interstellar matter (mostly 1H and 4He), causing fragmentation, producing those lighter elements.

Nova

Some stars in the galaxy for binary systems, in which there are two stars revolving around each other. If their masses are different the bigger star will evolve faster and at some point their atmospheres combine, causing instabilities to form, resulting to an outburst of energy and matter as an explosion. This increases the luminosity of the stars and a nova is seen. During this procedure, heavy elements are synthesised.

Supernova

A supernova is a catastrophic stellar explosion during which so much energy is released that all the billions of stars can be outshined by it. It occurs when an evolving star runs out of nuclear fuel, and the core is so unstable that it collapses rapidly (in less than a second!). Just before or during this explosion, thousands of nuclear reactions (neutron captures) occur in a very short time, and form heavy elements.

The remains of the supernova spread out into space and can be used in the formation of new stars or can be captured by other evolving stars.

Conclusion

In this report some of the well known up to date discoveries of cosmology were discussed. However, the universe is so infinite and mysterious that many questions about its creation and the element formation remain unanswered and plenty of areas are still in dark.

NASA is currently the largest organisation performing investigation evolving around important cosmological questions, with its program Beyond Einstein. The satellites COBE and WMPA try to find an answer to what powered the Big Bang, whereas other missions wish to discover what the mysterious dark energy causing the expansion of the universe is. Fascinating findings about our universe and the genesis of elements are awaiting to be brought to light in the years to come.

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