THE ORIGINS OF ELEMENTS

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This article explores the origin of chemical elements as a process occurring inside stars, as well as in terms of what they mean to people.

It is an obvious fact that different substances make up the world as we know it. We look at the world through our senses and use our powers of deduction and inference (dependent largely on existing technology and robustness of intellectual structures) to aid in the discovery of new substances and categorise known ones in ever more suitable ways. Given the robust engineering capacities that humans display, it is clear, even from antiquity, that we could also make new kinds of substances by a suitable combination or distillation of existing ones, i.e. cooking a dish, mixing medicines and beverages, constructing buildings and tools, and so on. To make ever more complex substances and systems with properties that we desire, the following question must have been considered over the ages, "What are the basic substances out of which all other substances are made?"

Different civilizations have attempted to answer this question, and all of them seem to have postulated the existence of 'elements'. Believed to be created when the universe itself was created, elements have been thought of as being the unique and fundamental building blocks out of which all other existing structures are made. The Indians and Greeks thought that the world was made up of five elements which were Ether, Air, Water, Fire and Earth; the Chinese postulated that wood, metal, earth, water and fire made up all the substances of the world, and so on.

Atoms, on the other hand, were thought to be indivisible particles of the elements. For example, Kanada, founder of the Vaisheshika philosophy in 6th century BC, thought that the world was composed of atoms, which were of four basic kinds corresponding to the four elements – earth, water, fire and air. Each of these different kinds of atoms had other qualities assigned to them; and there were complex rules governing how these atoms could combine to produce all the substances seen on Earth. Similarly, the Buddhist, Jain, Islamic and Greek schools of thought also constructed the concept of atoms as representing elements, and being the origin of all matter, but their descriptions and qualities varied (see 'The Atom in the History of Human Thought' by Bernard Pulman[3] for a comprehensive account). All schools, however, agreed that atoms were eternal, indestructible and indivisible; and, importantly, atoms of any one kind were all identical.

This makes it evident that elements and atoms were inextricably linked in the ancient world – this is so even in the modern world. Today, we know of 92 naturally occurring elements, but can also artificially produce many more, with atomic numbers greater than 92. This is possible only because the relationship between atoms and elements is robust enough to allow such creation. So, according to modern scientific wisdom, how were these naturally occurring elements formed? The most widely accepted theory for the origin of the universe, which is somewhat similar to some of the theories propounded in the ancient world, is called the Big Bang theory. This event, occurring about 14 billion years ago, is believed to have created a large quantity of the primordial element hydrogen (which is made of one proton and a corresponding electron) along with very small quantities of helium, and trace amounts of other elements and isotopes. This is quite exciting, given that the Big Bang theory has arisen almost entirely out of observations made of the cosmos and experiments carried out in the laboratory.

Since old theories on the relationship between elements and atoms have not been able to withstand the scrutiny of modern scientific rigor, we will look afresh at the questions, 'How is an element defined?' and, 'What are atoms and how are they related to elements?' We begin our journey into the origin of elements by starting with the first of these questions.

Defining an element

Historically, elements have been defined in a variety of ways. For example, one, now 'obsolete', definition states that: *"An element is a substance that cannot be decomposed into simpler substances"*. This was possibly the first useful definition of an element, because it allowed one element to be experimentally distinguished from another. If a substance could be broken down into two or more new elements, which when recombined formed the original substance, the original substance was definitely not an element. Of course, it is impossible to use this definition to conclusively prove that a substance **is** actually an element because a substance which couldn't be decomposed using existing technology in one century could be decomposed in the next, when more advanced technologies became available.

Look at another, also obsolete, but more useful definition: *"An element is a substance composed of identical atoms".* This definition was one of the cornerstones of the (John Dalton's) atomic theory, but it was made obsolete by the discovery of **isotopes.** This discovery also made the previous definition of elements as non-decomposable substances untenable because an element

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18
1	H 1																	He 2
2	Li 3	Be 4											B 5	C 6	N 7	O 8	F 9	Ne 10
3	Na 11	Mg 12											Al 13	Si 14	P 15	S 16	Cl 17	Ar 18
4	K 19	Ca 20	Sc 21	Ti 22	V 23	Cr 24	Mn 25	Fe 26	Co 27	Ni 28	Cu 29	Zn 30	Ga 31	Ge 32	As 33	Se 34	Br 35	Kr 36
5	Rb 37	Sr 38	Y 39	Zr 40	Nb 41	Mo 42	Tc 43	Ru 44	Rh 45	Pd 46	Ag 47	Cd 48	In 49	Sn 50	Sb 51	Te 52	I 53	Xe 54
6	Cs 55	Ba 56	*	Hf 72	Ta 73	W 74	Re 75	Os 76	Ir 77	Pt 78	Au 79	Hg 80	Tl 81	Pb 82	Bi 83	Po 84	At 85	Rn 86
7	Fr 87	Ra 88	**	Rf 104	Db 105	Sg 106	Bh 107	Hs 108	Mt 109	Ds 110	Rg 111	Cn 112	Nh 113	Fl 114	Mc 115	Lv 116	Ts 117	Og 118
8	Uue 119																	
* lanthanoids			La 57	Ce 58	Pr 59	Nd 60	Pm 61	Sm 62	Eu 63	Gd 64	Tb 65	Dy 66	Ho 67	Er 68	Tm 69	Yb 70	Lu 71	
** actinoids			Ac 89	Th 90	Pa 91	U 92	Np 93	Pu 94	Am 95	Cm 96	Bk 97	Cf 98	Es 99	Fm 100	Md 101	No 102	Lr 103	

Fig. 1. The periodic table with all known elements.

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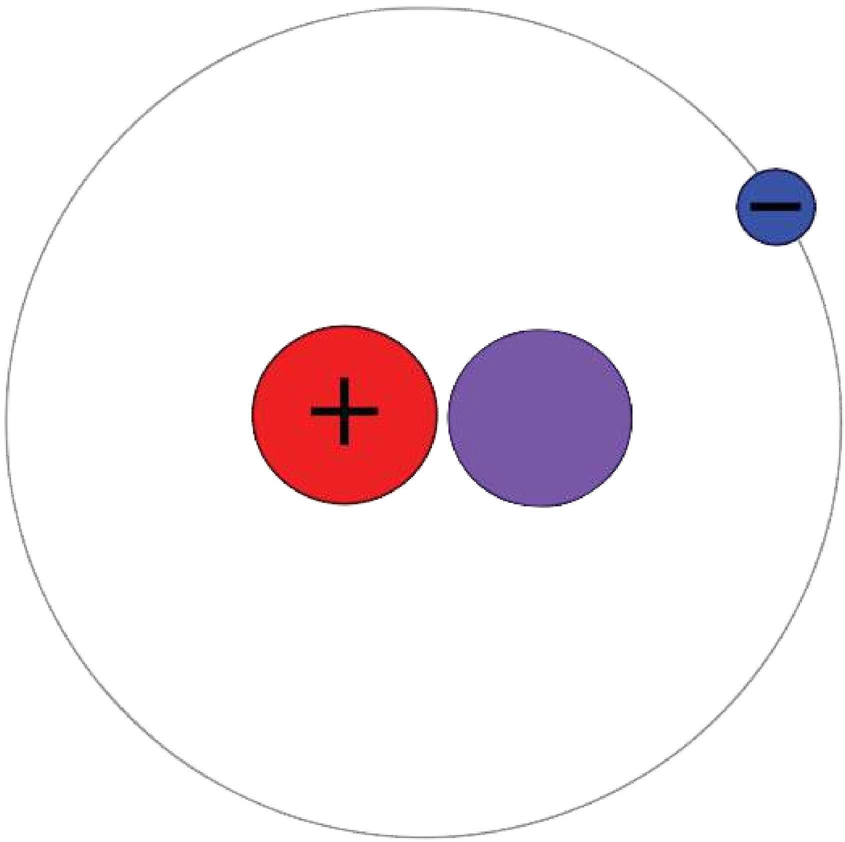

Fig. 2. A deuterium atom.

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can be decomposed into its isotopes, which have slightly different properties than those of the original element. This means that a given element's atoms can exist in different forms, contradicting Dalton's definition. Further, recombining its isotopes gives back the original sample, and so, by the previous definition, any element that consists of more than one isotope cannot be a true element. One striking example of this is seen in the existence of heavy water. Normal water has the usual form of hydrogen, with one proton in its nucleus; while heavy water has Deuterium, which is an isotope of hydrogen with one extra neutron present in it. This makes molecules of heavy water significantly heavier (one mole of heavy water can be around 2 grams heavier than one mole of normal water) – its freezing point is about 4^{0}C, and it is about 11% more dense. Heavy water has unusual nuclear and biological properties and is extensively used in nuclear reactors as a neutron moderator, i.e. to absorb neutrons. Isn't it amazing that the mere presence of an isotope can cause such a difference in properties?!

The modern era of chemistry probably started around 1789, when the 'father of chemistry', Antoine-Laurent de Lavoisier (1743–1794), attempted to classify elements. Lavoisier defined a chemical element as a substance that could not be further divided by any known method of **chemical analysis**. This was a very precise definition – remarkable because in retrospect it seems as if by restricting this definition to objects that were 'indivisible by chemical analysis', Lavoisier was suggesting that other methods, that came to be known about 150 years later, could succeed in splitting an element or making it (see Box 1).

Let us now look at the second question 'What are atoms and how are they related to elements?' Many amazing scientific discoveries in the 19th and 20th centuries, including advances in nuclear physics, astrophysics and so on, have clearly shown that all the different types of elements are made up of atoms. We also know that atoms are made up of essentially three stable particles – positively charged protons, neutrons with no net charge, and negatively charged electrons. The atoms of any element have a specific number of protons and neutrons that together form a small nucleus, with electrons orbiting around this central core. Keeping these three particles in mind, we can now arrive at a rigorous, unambiguous definition of an 'element' in terms of its atoms:

'An element is composed of atoms of one kind, all of which have the same number of protons (called its atomic number)'.

This definition makes it clear that a single free neutron, or other sub-atomic particles like neutrinos, pions, kaons, photons, and so on, cannot be thought of as elements.

Box 1. Experimental Deduction: Getting to know an element as an element. Why is it definitely not a compound or a mixture?

If you put two graphite rods (you could use thick pencil leads) into a glass of tap water, and connect these rods to an 18V battery, you'll see bubbles arising at both electrodes. The gases given off at these two electrodes can be easily collected into test tubes. Now we know, from textbooks and other sources, that these two gases are elements i.e. hydrogen and oxygen - but how does one prove that experimentally?

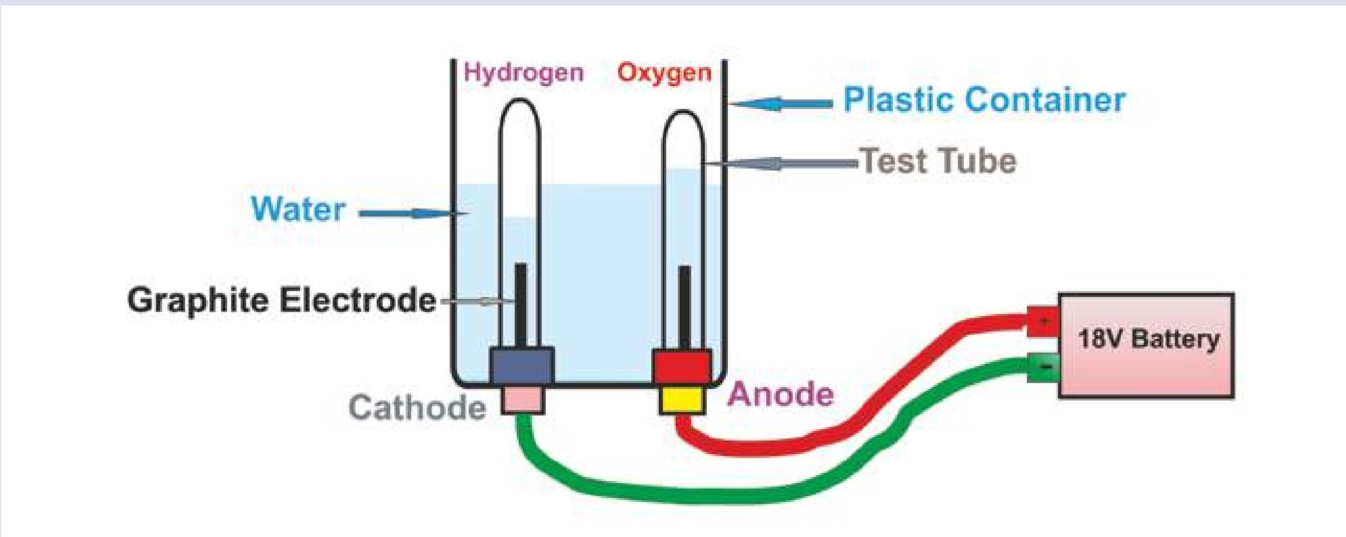

Fig. 3. The electrolysis of water: Oxygen and hydrogen gases collect in the test tubes.

Take oxygen for example. Let us imagine at first that it is actually made up of a mixture of two or more gases. Assuming that we can use all known gas separation techniques, we ought to be able to get these gases by **at least one** method. This will prove that oxygen is actually a mixture of gases. In the real world, however, we have only managed to separate the different isotopes of oxygen, all of which are very similar to each other in their physical and chemical properties.

One could, however, argue that our inability to separate oxygen into two significantly different gases is because we don't yet have the technology to do so. So we could hypothesize that the **chemical properties** of oxygen might be able to reveal the presence of many different gaseous components that are probably all similar in weight to each other, which is why they could not be separated by our separation techniques in the first place. One way of testing this hypothesis would involve reactions between oxygen and specified quantities of pure alkali metals (like sodium and potassium) for example. We avoid using transition elements as they can have different oxidation states, forming different sorts of compounds when reacted with the same substance. If we get two or more compounds **in any one** given reaction that we can clearly distinguish by sight, smell, touch or other chemical properties, it will prove our hypothesis. Another way we can test this hypothesis is to get oxygen from other sources, like by heating mercury oxide or some nitrates. If this reacts with the hydrogen obtained from splitting of water, after discarding the oxygen produced during the split, then we should get water as a result. If we do, **(and we actually do)** then it shows that the simplest explanation is that oxygen is **not a mixture of gases**. Whew! That is a lot of work just to show that a given substance is not a mixture!

However, our proof of oxygen's elemental nature is not yet conclusive. What if we consider the possibility that oxygen is actually a compound, rather than a mixture? The situation, then, becomes much more complicated. Firstly, because we may not yet have discovered the tools to split this compound apart chemically, and till someone does so, oxygen will continue to be considered an element. Once we do, and we use these tools to split oxygen into its components, these components will be regarded as elements if they cannot be further divided by any known chemical means. This has never been done as of now, and so we "know" that oxygen is an element and not a compound. Look at the flow chart that indicates a possible scheme of investigation when you encounter a substance that is new to you

It is interesting (and amusing) to note that Lavoisier included **all entities** he could not split using chemical means in his list of elements. This included **light, heat,** and metal oxides. Metal oxides could be broken down only when the use of electric current became wide spread in the nineteenth century. Light and heat, of course, are not substances, and so are not classified as elements now.

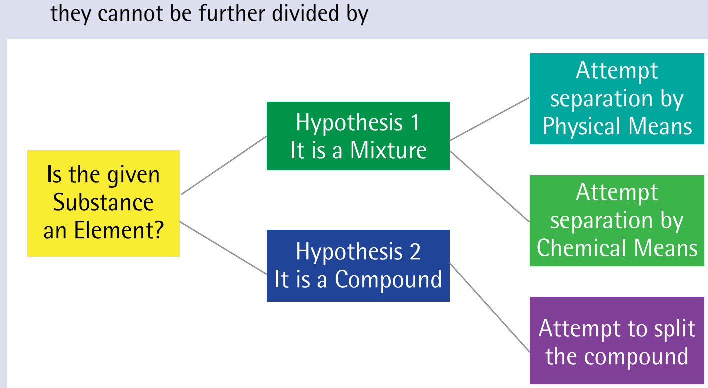

Fig. 4. Flow chart showing a scheme of investigation to show that a substance is an element.

Box 2. Are atoms real?

We have seen that any discussion on the origin of elements ought to begin with the notion of atoms – since elements are composed of atoms. But, are atoms real? Intriguingly, even long after they were conceived of (and after the birth of the modern science of chemistry), no one could actually see atoms in any way. In fact, it is only since late last century that we have come close to actually seeing atoms (see https://www.youtube.com/watch?v=ipzFnGRfsfE for an illuminating idea of the history of atoms and how they can be seen and manipulated).

In spite of this, the idea of atoms has been of immense importance. As the famous physicist Prof. Feynman wrote, *"If, in some cataclysm, all of scientific knowledge were to be destroyed, and only one sentence passed on to the next generations of creatures, what statement would contain the most information in the fewest words? I believe it is the* ***atomic hypothesis*** *(or the atomic* ***fact****, or whatever you wish to call it)* ***that all things are made of atoms – little particles that move around in perpetual motion, attracting each other when they are a little distance apart, but repelling upon being squeezed into one another.*** *In that one sentence, you will see, there is an* ***enormous*** *amount of information about the world, if just a little imagination and thinking are applied."*

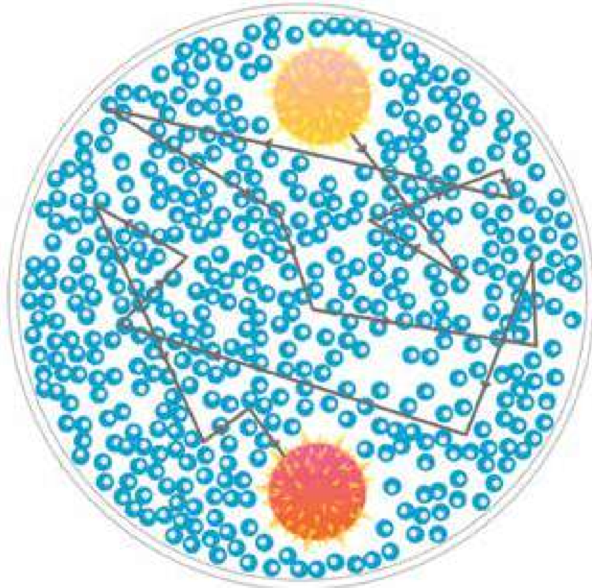

Fig. 5. The random motion of pollen is a result of the Brownian motion of atoms in water.

Experiment: 'Seeing' atoms indirectly through Brownian motion.

Put some pollen from a grass flower into a drop of water and observe using a microscope. If the size of the pollen is right (neither too heavy nor too light), you will see it move or jiggle in a **random manner** as opposed to showing continuous smooth motion. This random movement is called "Brownian Motion", after Robert Brown who discovered (but could not explain) it in 1827.

In a path-breaking paper, published in 1905, Einstein showed that this random motion unequivocally proved the existence of atoms. That Einstein received the Nobel Prize in Physics in 1921 for this discovery indicates how significant it was perceived to be.

In this experiment, the random motion of pollen actually **proves** that the drop of water is made up of atoms. How does it do that? If the drop of water were continuous, the suspended pollen grains could only bob and move smoothly in different directions as the water jiggled and moved about. But their random motion indicates that each pollen grain is actually being hit randomly. This random hitting can only be possible if the water is made up of atoms which are doing the hitting as they move around.

A harder experiment to conduct is to shine a bright light through some smoke particles captured in a glass cell and observe this through a microscope. Amidst swirling masses of smoke, one may occasionally spot smoke particles, which look like bright spots of light, showing Brownian motion.

See https://en.wikipedia.org/wiki/Brownian_motion for an accurate motion picture of Brownian motion.

Observations of atoms

Let us now consider the meaning of constructing an atomic theory. Do we need it at all? What are the benefits of doing so? But, first, let's begin by considering much simpler questions – are atoms real? If yes, can they be seen (see Box 2)?

Now that the setting is clear and we are sure about the reality of atoms even though they cannot be directly seen, we move onto how people envision the creation of all the elements out of the primordial element, hydrogen, which was created during the Big Bang.

Dynamics within a cloud of gaseous hydrogen

As the universe cooled down after being created, hydrogen atoms condensed into massive clouds held together mainly due to gravitational attraction (see the article on the 'Origins of the solar system' in the same issue, for a detailed account of how these clouds condense). Notice that although a cloud of gas has no walls for the gas molecules to bump against, it does have pressure, volume and temperature – all of which change as the cloud is compressed (see Box 3). Thus while these quantities may or may not have been the same everywhere within a cloud, a more condensed cloud definitely had greater internal pressure and temperature.

Amazing things happen when a cloud of hydrogen has enough internal-gravity to begin contracting (see Box 4). Note that we are thinking of a gas cloud with an

Box 3. Experiment: Squeezing a gas

You will need a 20ml syringe for this experiment. Use some araldite to plug the hole where the needle fits. Before closing this hole, pull the piston all the way up making sure that there is enough air inside. After the araldite dries, try to squeeze the piston of the syringe to the maximum extent and make a note of your observations. Clearly, the air seems to push back. How does it do that?

What is happening here is that the air molecules bump against the walls of the container, and as the volume of the syringe reduces, the frequency of bumping increases. At every position within the piston, the pressure applied by the air matches yours, and if you relax, the piston comes back to its original position.

When this experiment is done using a bigger piston-cylinder system like a cycle pump, the air within the pump definitely gets warmer, i.e. its temperature increases.

enormous amount of mass. It is so large that it can condense to ignite nuclear reactions and produce a star. Some of these clouds are much smaller, and stop condensing after a point as they do not possess enough gravitational potential energy, but we will not discuss these clouds here.

When the temperature at the core of a contracting gas cloud reaches a few million degrees centigrade, the atoms in it cease to exist and become just a dense soup of separately moving electrons and protons. When two protons in this state collide against each other, they are able to overcome their strong electrostatic repulsion (both are positively charged), and come close enough to exert nuclear forces of attraction. This happens because of a phenomenon that we know as quantum tunnelling. Quantum tunnelling brings two protons close enough to bind even at relatively low temperatures – it was realised in the 1920s itself that the temperature at the core of a star, which is a few million degrees centigrade, is about a **1000 times smaller** than what is actually required to bring two protons close enough to bind. What is interesting is that we came to this realisation even before the neutron was discovered (which was in 1932). At that time, the possibility that elements with larger atomic weights were formed by fusion was pure conjecture, with no plausible evidence as to how it could take place.

When protons come close enough to each other to be able to **quantum mechanically tunnel** into each other, the nuclear forces i.e. the strong and weak forces, come into play and the whole game immediately changes. The protons can now change into neutrons; other protons can join in to form larger nuclei, and so on. The energy given off in these nuclear reactions is immeasurably larger than the heat radiation energy that was given off till now. A star, as we know it, is now actually born, and generates energy by nuclear fusion. This slows its contraction, with the star beginning to

Box 4. Stretch of reason: the dynamics inside a cloud

What are the things that can possibly happen inside a condensing cloud of gas? I've listed some of my questions about its fate below. You could add your own questions to this list.

- When a cloud of gas condenses, why does it get hotter? We should keep in mind that the standard gas laws (PV = nRT and so on) that hold for ideal gases are applicable to much of this contraction.
- What happens to the contraction when it gets hotter?
- What quantity of gas is needed for condensation to occur due to internal gravity?
- Does the temperature inside the core of the gas increase as it condenses?

Regarding questions one and two, the gas gets hotter simply because its molecules are confined to a smaller space, much like in the case of a gas in a cycle pump which is compressed and not allowed to escape. On Earth, the contraction of a gas stops once its temperature rises to a certain level, usually because of the walls surrounding the gas. In contrast, in a massive gas cloud, contraction produces warming which stops it from contracting any further. However, this warming ensures that heat in the gas cloud is radiated away from its surface. This cools the gas, and once it has cooled sufficiently, the contraction and clumping begin with renewed vigour, and the cloud becomes smaller. **This is clearly a runaway effect – this cycle of events continues endlessly, stopping only if the amount of matter in the cloud is small.**

There are several answers to the third question. One of them gives us an idea of how stars are formed. Usually atoms cannot get too close to each other. Therefore, squeezing a solid, liquid or a gas gets progressively harder beyond a certain point. For a gas to condense due to its **own gravity** there needs to be a lot of it; given that gravity is the weakest force in the universe. Also, according to **Pauli's exclusion principle**, which states that one just cannot put two electrons or protons or neutrons on top of each other, a cloud can be gravitationally compressed only if its mass exceeds a certain limit of about 4×10^{32} grams. Thus, the greater the mass of a gas cloud, the hotter the stars formed from it. For the record, our sun has a mass of about 2×10^{33} grams, which is obviously greater than the minimum mass required for condensation to occur.

For the last question, it turns out that the temperature at the core of the gas cloud does increase, and its value depends on the mass of the cloud. This is reasonable because the contraction would be faster for a gas cloud with higher mass, and so the gas ought to get hotter. Connecting this to the answers of the first and second questions, we can deduce that the core of the gas cloud should just keep getting progressively hotter. How hot can it become? In fact, once it reaches a few million degrees centigrade, **nuclear reactions begin**, i.e. the energy of the protons begins to gradually overcome the repulsive electromagnetic force between the positively charged protons. As we will see later, this means that the internal temperature of a gas cloud can increase by much more.

Box 5. The mysterious Quantum Mechanics & Quantum Tunnelling

What is quantum mechanics? To explain it simply, you need to imagine a system with a limited number of states of existence. To understand this, imagine a particle put inside a "box" which is somewhat penetrable (if the particle has enough kinetic energy). The "states" of this particle are clearly that of being anywhere inside the box and those of being outside it. An example of a state could be the position of the particle at, say, a point in the middle of the box at a particular time and moving along a given direction with some speed. This is different from a state where the particle can be 10cm outside of the box at a particular time and going with the same speed along some other direction. Clearly, the particle does keep changing states as its position and velocity keep changing.

Now, imagine that all of these states can occur, each with some **probability.** If we can somehow conceive of a **superposition of states**, where instead of the electron or particle being in any one state, it can potentially be in a **mix of all their possible states** (how it is mixed is decided using mathematical rules and cannot be stated easily in ordinary language), then you would have a model of a quantum mechanical system. The last thing we need to add is that **when we make a measurement**, the particle or electron **can only be** in some specific state. For the particle in the box, the states it can be in are either somewhere inside or somewhere outside the box.

Now comes the amazing part. Even if we started out with the particle having less energy than that required to penetrate the box, there is a slight chance that it can jump out, or, in other words, it can still **tunnel through to the outside**. The rules that govern the superposition of states somehow allow for this possibility, and every once in a while the particle does just that. This has been observed experimentally in various situations and is uniquely a quantum phenomenon. There is no classical analogue to this effect.

It was in 1929 that George Gamow (1904–1968m), Ronald Gurney (1898–1953) and Edward Condon (1902–1974) discovered the phenomenon of quantum tunnelling. It would be hard to overestimate the importance of the tunnelling phenomenon in many disciplines, especially astrophysics. This one discovery essentially kick-started the entire field of nuclear astrophysics. The tunnelling phenomenon is one of the crucial factors required for the existence of life in the cosmos. It provides both the energy and a suitably long time-scale for its release in stars. What is interesting is that for several years before this discovery, Condon, who eventually explained how nuclear reactions can occur in stars, had believed that mass annihilation was the source of stellar energy and explained their long life. However, no reason was found to explain why mass annihilation should generate energy at the rate it does inside the Sun. Tunnelling gives a much better explanation for both the quantity of energy produced and how quickly it is produced. This tunnelling effect is also the phenomena behind the workings of the ever-present solid-state devices, the diode and transistor, which are literally the backbone of the electronics industry.

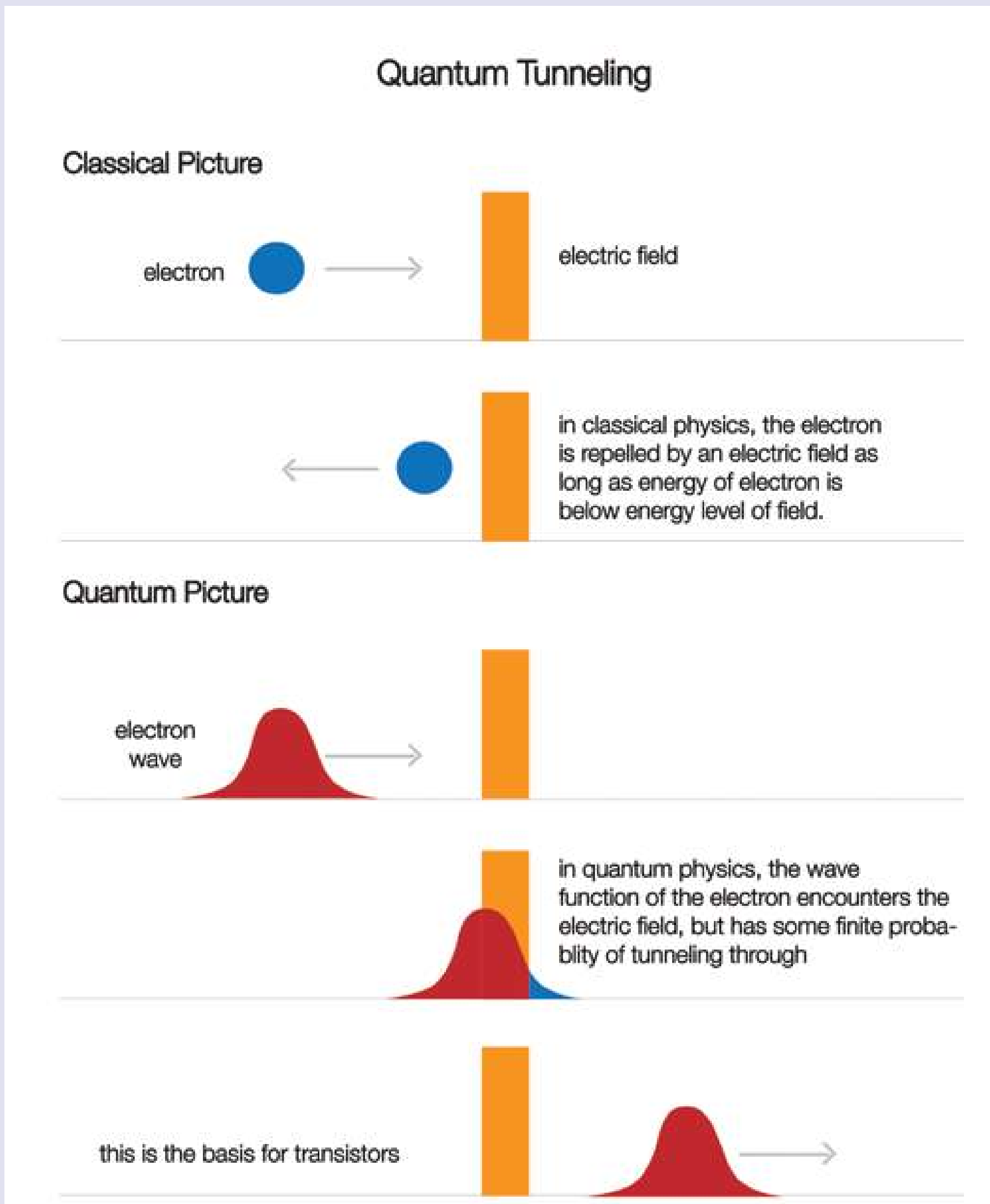

Fig. 6. Quantum Tunnelling.

Credits: Dr. James Shombert, University of Oregon.

generate heat which is radiated away from its surface. These two processes of energy generation and radiation ensure that the star remains a certain size for a long time.

The temperature within stars is sufficiently low to allow nuclear reactions to proceed slowly enough to provide energy over the long time scales needed for the evolution of planets, and indeed, life itself. If the temperature at the core of stars had been higher, the reactions would have proceeded faster, the energy generated would have been greater, and their lifetimes would have been shorter.

Creation of the heavier elements

Before we get into the details of the creation of heavier elements, let us just take a quick look at the notation for the nuclei of the elements that will be used from this point onwards.

We use the notation $^{Z}_{A}S$ to denote an atom S, with an atomic number (or number of protons in the nucleus) of A, and a mass number (number of protons plus the number of neutrons) of Z. We will normally omit the atomic number as it can be rather cumbersome, and stick with ^{Z}S when convenient. If you have access to a periodic table, and know the symbol for an atom, you can always find its atomic number. For example, ^{8}Be would be the nucleus of the Beryllium atom with an atomic **mass** of 8 (its atomic number is 4).

Going back to the events happening within stars, there are two basic nuclear reactions that produce helium from hydrogen. The first, called the proton-proton chain reaction, accounts for about 94% of the energy produced in an ordinary star (see Fig. 7).

In these reactions, ^{1}H stands for the **hydrogen** nucleus which is just a single proton, ^{2}H stands for the Deuterium nucleus which is made up of one proton and a neutron bound together, **e^{+}** is the positron (experimentally discovered in 1932) or anti particle of an electron, ν_e is the electron neutrino (existence postulated in 1930 and experimentally discovered only in 1956), **^{3}He** is an isotope of the Helium nucleus consisting of two protons and one neutron,**^{4}He** is the standard Helium nucleus which consists of two protons and two neutrons, and γ is the radiant energy released.

First, notice that the pp chain is actually a **cycle** – one that starts off with two protons interacting, and ends with a helium nucleus and two more protons. The very first reaction of this chain, which shows two protons interacting to give a Deuterium nucleus (with a positron and neutrino), is the **deciding factor** for the entire chain. The time scale for its occurrence is around a billion years. That means that it can take **over a billion years** for a given

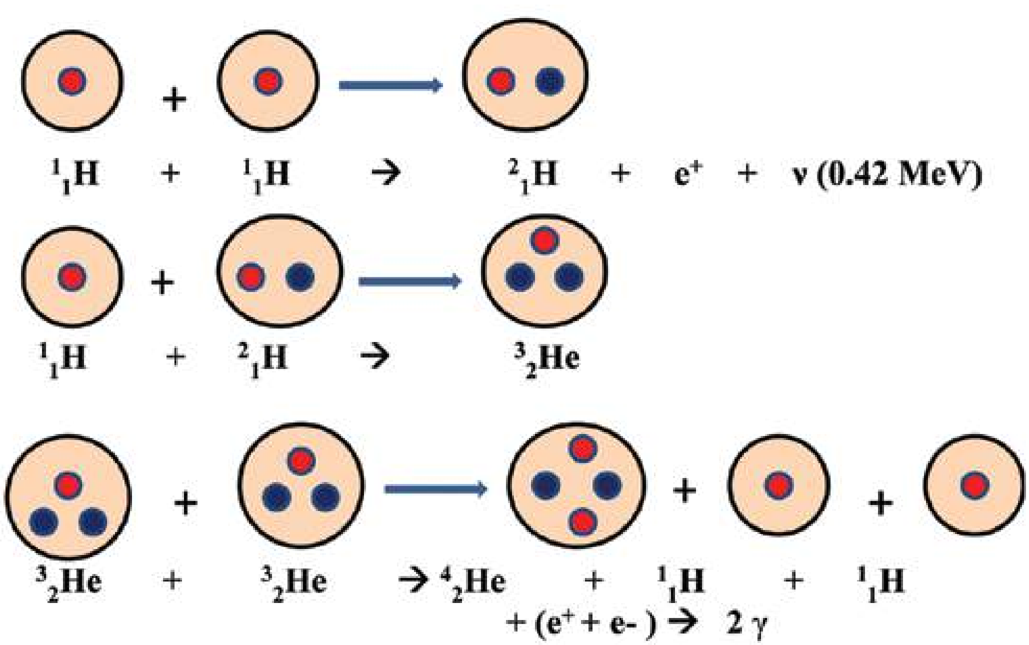

Fig. 7. The proton-proton chain (or pp chain) reaction.

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pair of protons to combine to form a Deuterium, even under the conditions of pressure and temperature found at the core of the sun. In most collisions between protons, they just come together and break up again. The chances of fusion occurring remain really small, because **weak nuclear forces** decide this reaction. The other reactions in the chain are comparatively fast because they are controlled by the **strong nuclear force**, which is much more powerful than the weak force.

The other important reaction to generate helium and, hence, energy in the Sun, is that of the CNO cycle. As the name suggests, this reaction involves the presence of the elements carbon, nitrogen and oxygen, but we will not describe this here.

Let us now consider reactions in which helium is burnt to form the heavier elements. These reactions do not happen to a significant extent in the Sun or similar-sized stars, which still predominantly burn hydrogen.

Going back to the dynamics within a gas cloud, we know that once hydrogen is converted to helium, and the extra heat generated is radiated off, the star cools down a bit, and then slowly starts to contract again. This contraction raises the temperature of the core of the star to about a hundred million degrees centigrade. At these temperatures, helium nuclei fuse to produce heavier elements.

The first reaction in this Helium burning is:

$$^{4}He + {}^{4}He \longrightarrow {}^{8}Be$$

This reaction is **endothermic**, i.e. it needs energy to form. However, the next crucial stage in Helium burning, involving the conversion of ^{8}Be to ^{12}C, is **exothermic**

$$^{8}Be + {}^{4}He \longrightarrow {}^{12}C + \gamma$$

The combination of these two reactions results in to the formation of one carbon nucleus from three helium nuclei. The net reaction releases energy, as the second reaction releases more energy than is used up in the first. However, this reaction is highly temperature sensitive, implying that as a fuel, **helium is much more explosive** in a nuclear reaction than hydrogen. Once ^{12}C is formed, further reactions forming oxygen and neon nuclei begin occurring:

$$^{12}C + {}^{4}He \longrightarrow {}^{16}O + \gamma$$

$$^{12}O + {}^{4}He \longrightarrow {}^{20}Ne + \gamma$$

These processes – similar to that of Helium burning – lead to the burning of heavier elements such as carbon, neon, oxygen, silicon, etc. Such reactions become more probable only at temperatures of a **billion degrees** or more. Most of these reactions are fairly complex, and can proceed through very many **channels**, i.e. can give more than one sort of product based on chance (recall Box 5). As an example, consider the reaction of two carbon atoms, which can produce either magnesium, or sodium, or neon, or oxygen:

$$^{12}C + {}^{12}C \longrightarrow {}^{24}Mg + \gamma$$

$$\longrightarrow {}^{23}Mg + n$$

$$\longrightarrow {}^{23}Na + p$$

$$\longrightarrow {}^{20}Ne + {}^{4}He$$

$$\longrightarrow {}^{16}O + 2\,{}^{4}He$$

The relative probabilities for each of these channels are very different, and depend on the temperature at the core of the star. Similarly, we can have different reactions involving oxygen nuclei, with the reactions ending up with ^{28}Si, ^{31}S, and ^{31}P.

At these very high temperatures, some of the radiation produced can actually break the newly created nuclei apart into smaller nuclei, a process aptly named **photo-disintegration.** The existence of such reactions complicates matters at these high temperatures. For example, the reaction:
$^{20}Ne + \gamma \longrightarrow {}^{16}O + {}^{4}He$, can produce helium by the photo-disintegration of neon. Such a helium nucleus will again combine in a sequence of reactions to give a pool of ^{16}O, ^{24}Mg, and ^{28}Si.

When the temperature in a star's core is higher than three billion degrees, several complex sequences of nuclear reactions and photo-disintegration can occur. These processes gradually build up heavier nuclei, such as ^{27}Al and ^{24}Mg, working all the way up to ^{56}Fe. The formation of nuclei with masses lower than ^{56}Fe release energy, but those of nuclei with masses higher than ^{56}Fe require energy to make.

But, how are these heavier elements synthesised? One set of such reactions relies on the capture of neutrons by nuclei. This is a process that is not

Box 6. A short time-line of Deuterium (^{2}H) formation

Around the 1930's, nuclear physics was coming up with crucial results, and plenty of important isotopes and elements were being discovered. Two scientists – Robert d'Escourt Atkinson and Charles Critchfield, played key roles in developing our understanding of the proton-proton chain reaction.

1919: The astrophysicist Eddington suggested that the **synthesis** of hydrogen to Helium might be the source of energy in the Sun, but he had no idea how this could work. People thought that the Helium nucleus contained 4 protons and 2 electrons, so as to have a net positive charge of two (recall that the neutron was discovered only in 1932). Also, no nuclei with atomic masses of 2 or 3 were known to exist in nature. Hence, the only way Eddington's hypothetical synthesis could happen would be for 4 protons and 2 electrons to come together simultaneously, release energy, and then stay together as a Helium nucleus. This was known to be a hopelessly complicated and extremely rare process.

1931: "The situation was", as Atkinson remarked, "that so much observational data had accumulated that it was no longer possible to **construct an arbitrary hypothesis without producing a contradiction**." At this point of time, many nuclear experiments were being carried out, and it was also recognised that hydrogen was the **first and probably only** chemical element to have existed at the beginning of the universe. The difficulty lay in finding how fusion could start with just pure hydrogen. All the scenarios that researchers came up with assumed the **pre-existence of elements heavier than hydrogen**, but without any explanation for how these heavy elements could have been formed.

1936: Atkinson re-examined his scenarios from 1931 in view of the recent discoveries of the neutron, Deuterium (^2H), and the positron. It was believed that nuclear reactions with neutrons do not face the problem of repulsion with protons (neutrons have a net charge of zero) and hence can operate at any temperature. The question was whether neutrons could be produced in sufficient amounts in stars. Checking all possible neutron production reactions seen in laboratory conditions revealed that such reactions were very slow, producing insignificant quantities of neutrons. For example, the reaction $^1H + e \rightarrow n$, namely, the absorption of an electron by a proton resulting in a neutron was not seen at all. The only alternative left, and suggested by Atkinson, was to generate neutrons by first producing plenty of Deuterium (^2H) via the reaction: $^1H + {}^1H \rightarrow 2\ {}^2H + e^+$, and then splitting the Deuterium. In this way, Atkinson discovered the first reaction of the pp chain. However, Atkinson expected this reaction to produce Deuterium, and from it, neutrons. He also expected it to be easy to see and measure the rate of this reaction in the laboratory. In this, he was mistaken, because **this is the most famous nuclear reaction in stars** – one that cannot be measured in the laboratory because of its extremely low yield, i.e. it hardly ever happens. Also, it is only after the difficult process of formation of Deuterium occurs, that the road to other, faster, nuclear fusion reactions opens.

Fig. 8. Robert d'Escourt Atkinson and Charles Critchfield played key roles in developing our understanding of the proton-proton chain reaction.

1938: Charles Critchfield (1911–1994) was a Ph.D student at George Washington University, working under the guidance of the scientists Teller and Gamow. The subject of his thesis, suggested by Gamow, was to calculate how quickly the first pp reaction happens in stars. When Critchfield finished the calculation, Gamow suggested that he should present the calculation to the 'high priest' of nuclear physics, a scientist named Hans Bethe, and try to get his approval. Bethe found the calculation to be correct, and so in 1938 Bethe and Critchfield published the calculation. The authors gave no credit to Atkinson, although it was Atkinson who had come up with the idea of the pp reaction.

This was how the first reaction of the pp chain was found. Much of this investigation was done in laboratories, and checked with observations of the energy output of the sun to ensure accuracy.

affected by the strong repulsion that exists among positively charged nuclei. So a nucleus with an atomic mass of Z and atomic number A will change to one of Z + 1 when it absorbs a neutron, and this can continue till the resulting nucleus decays by emitting an electron to give a new element with atomic number A + 1. In this way, elements higher than iron are also synthesised. Note that elements not found in nature are also produced in a similar manner in the laboratory i.e. through the absorption of neutrons.

Conclusion

We've looked at the story of how elements are generated in stars in brief here. As stars grow older and turn into supernovae, they explode and seed the cosmos with the elements that they have created. These elements often end up in gas clouds which can condense to form new stars and planets that can harbour life.

Much of this story could not have been discovered if nuclear physics had not developed to the point of being able to generate reactions by throwing particles at each other and observing what new nuclei form, how they decay through their collisions and noting the probabilities with which these reactions occur. New channels, new ways of looking at radioactivity, and understanding the stability of nuclei have been crucial to deciphering how stars cook up elements. With many, many questions still remaining unanswered, this remains a thriving field of study offering plenty of surprises.

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