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COSMOLOGY

(the origin and evolution of the universe; cosmic coincidences and the anthropic principle; conditions for extra-terrestrial intelligent civilizations; Is there anything esle besides this Universe?; the universe has a purpose; the primary condition of the universe; the fabric of the universe; are there other universes?; universe with life or nothing? etc.)

LIFE IN THE UNIVERSE

(the origin and evolution of life in the universe —how did life begin?; irreducible complexity and intelligent design; extraterrestrial life — are we alone in the universe?; define „life" in the context of the limits of the substance (matter) and life (energy); What is life made of? etc.)

ANTHROPOLOGY

(humankind's past, present and future; mind and consciousness; free will and human behavior; death and after it; is it possible for the evolution to explain human nature and the moral character of its acts, or is it something else needed, other than science can explain on its own? are `God`, `faith`or conscienceness only a function of your brain or are them something more than that? etc.)

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The Unique Hoyle State of the Carbon Atom

Steinar THORVALDSEN
Dept. of Education
University of Tromsø, N-9037 Tromsø, Norway
steinar.thorvaldsen@uit.no

***Abstract*: The famous astronomer Fred Hoyle (1915-2001) started his research career as an atheist. Hoyle's most important contribution to astrophysics is the theory of nucleosynthesis, i.e. the idea that chemical elements such as carbon can form in stars on the basis of hydrogen and helium. Essentially here was his prediction that the carbon core has a state with a specific energy which is precisely adapted to the basic fusion process. This result was one of the most important breakthroughs in modern astrophysics, and the so called Hoyle state has become a cornerstone for state-of-the-art nuclear theory. The calculations he made, eventually revealed a fine-tuning of the universe. Hoyle's work in this area supported the anthropic principle that the universe was fine-tuned so that intelligent life would be possible. It is said that what really made him conclude that creation demanded intelligence, were his calculations of the special properties of the carbon atom. This shook his atheism fundamentally [1, p. 57]. In this paper we describe this discovery.**

Keywords: Nucleosynthesis; Anthropic principle

I. Introduction

The universe is made up of a variety of chemical elements such as hydrogen, carbon, oxygen, nitrogen and iron (Fig. 1). A chemical element is a substance in which all atoms have the same number of protons in the nucleus. In addition, any neutrons determine the isotope of the element we are dealing with. If we change the number of protons, we get a completely different chemical element, but if we change the neutrons we obtain another variant (isotope) of the same element. The classical Big-Bang model explained prevalence of the light elements hydrogen and helium in the universe, but not the incidence of heavier atoms.

In this context helium cores are often called *alpha particles* (α). For a long time science lacked a mechanism that could form anything but the very light chemical elements. This was one of cosmology's puzzles. Hoyle's important contribution to astrophysics was achieved in this area, and it is often called the *nucleosynthesis*, i.e. the theory of how chemical elements such as carbon can form in stars on the basis of hydrogen and helium. Crucial in his prediction was the existence of a new state in the carbon atom with a specific energy that is precisely adapted to the basic fusion processes of the nuclei. This process is essential because it links to the carbon in the universe, which is a prerequisite for the existence of all carbon based life. Hoyle predicted that the nuclear reactions that could produce carbon in sufficient quantities required a specific and statistically improbable energy level in the carbon nucleus. He inferred that the so-called *triple-alpha reaction* had to work through an unknown process.

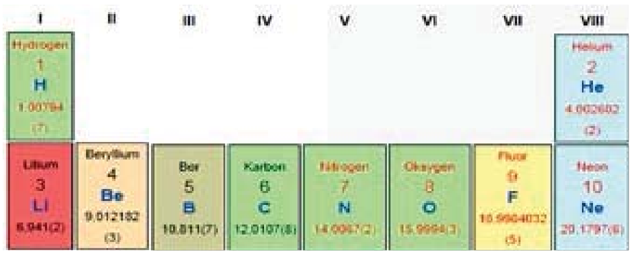

Figure 1. First part of the periodic table of the chemical elements.

II. Tripple- Alpha

The common carbon consists of 6 protons and 6 neutrons, and helium has two of each. One might imagine that three helium nuclei could collide simultaneously, and form a carbon core. But this is impossible in practice, the probability that three helium nuclei would be in exactly the same place at the same time, while moving in exactly the right speed to merge, is vanishingly small.

Another possibility is that two helium particles at very high temperatures melt into one beryllium atom, which in turn merges with a third helium nucleus to form carbon (see Fig. 2). This will give a total of 12 core particles. The first problem here is that beryllium core will be extremely unstable and typically cleave again almost instantly. It would barely be conceivable that a new helium nucleus may be combined with beryllium during its brief existence. Moreover, there is another major obstacle:

The sum of the masses of helium and beryllium nucleus is in fact *larger* than the mass of the carbon nucleus. The total energy of the whole particle would be higher than the ground state of carbon. So if helium and beryllium merged together and formed carbon, the mass difference has to be emitted in the form of energy, because energy and mass are equivalent ($E = mc^2$). This takes extra time, precisely what initially was lacking. Consequently, it is highly unlikely that a new particle is formed in this way, in the same way as two plus two does not make three.

In physics a system (atom, molecule, core) is called *excited* if it interacts with other particles or electromagnetic radiation (photons) and is brought from its usual lowest energy state (ground state) into a state with higher energy. The excited system will return to the ground state by emitting energy in the form of photons. If the system is supplied with enough energy, it may also be broken to pieces.

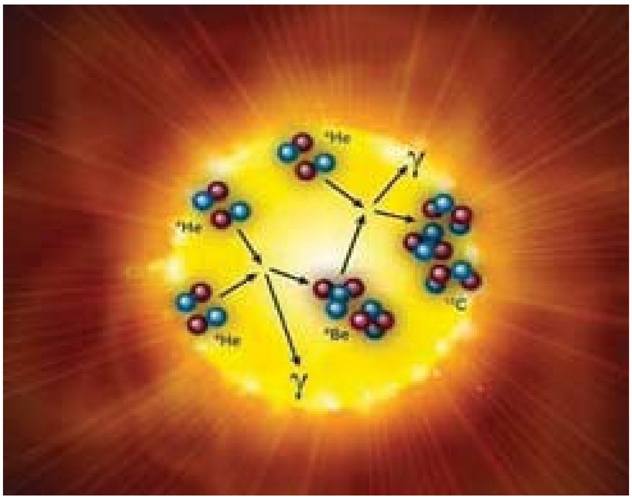

Figure 2. The triple-alpha reaction, where three helium nuclei (He) forms carbon (C), is hiding a big secret. Gamma (γ) means emission of energy. Illustration from Epelbaum, et al. [6].

III. Triple- marvel

At this point Hoyle made a bold prediction. To solve the problem he assumed that carbon can exist in a new energy state (*excited* state), which until then was unknown. His prediction was that there had to be an energy state with mass exactly equal to the sum of the masses of beryllium and helium. This condition would be a new carbon state making it possible to form carbon within the short time window. The carbon could then transform to its normal ground state. The energy sent out by the internal transition was estimated at 7.65 million electron volts (MeV). From this he calculated the required values for the energy levels of the carbon nucleus. Hoyle described his ideas like this:

Salpeter's publication [in 1952] of the 3α process freed me to take a fresh look at the carbon production problem. I found difficulty in generating enough carbon, because the carbon kept slipping away into oxygen as it was produced. A theoretically possible way around this difficulty was greatly to speed-up the carbon synthesis by a rather precisely tuned resonance which would need to be about 7.65MeV above ground-level in the carbon-12 nucleus. [2, p. 449]

Hoyle's theoretical predictions were later confirmed by laboratory tests. This is considered one of the greatest scientific triumphs of the 1950s, and the paper which he wrote together with Geoffrey & Margaret Burbidge and Fowler is just called the B^2FH article by the authors' initials [3; 4].

In practice, the Hoyle state nuclei almost always decay back into beryllium and a helium particle. But in around 0.04 percent of the cases, these inflated carbons relax into their stable, ground state configuration, giving off the extra energy as an emission of gamma rays as shown in Fig. 3. The new carbon-12 nuclei that are formed subsequently populate the periodic table. Some stay as they are, while others merge with another helium particle to become oxygen. A fraction of the oxygen nuclei are stripped of a proton, transforming into nitrogen, and so on.

The internal energy levels that exist for carbon nuclei are very interesting. The excited state is what we call a *resonance*, and it is precisely so that it supports the process that gives ordinary carbon as its result! A resonance means that the particles vibrate in phase towards and out from the center of the nucleus. When beryllium and helium then collide, they will hang together a while before they fly apart again. While hanging together they will with a certain probability emit energy in the form of radiation, while the carbon goes down to the stable ground state. If the excited state had not been like this, the reaction *Be + He => C + energy* had to be made in one step, without the ability to "rest" in the resonance condition. This would have made production of carbon highly unlikely. In order to achieve the stable ground state, there must be such a resonance. The probabilities for these conditions to be so that stable carbon was not possible are infinitely greater.

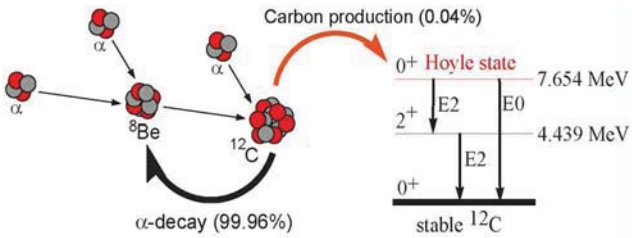

Figure 3. The triple-alpha process. Two helium nuclei (α-particles) fuse together and form a beryllium atom, and then a third α-particle merge rapidly to create what equals the Hoyle state of the carbon nucleus, where a certain amount is proceeding to stable carbon in its ground state. In the right part of the figure the three states of the carbon atom are represented, where the Hoyle state and the ground state has spin 0. The spin is conserved in this type of reactions, so the state in the middle does not matter as it has spin 2. This process marks the start of the generation of the basic atoms necessary in biology.

IV. Bent arm formation

The unstable state of the carbon atom is now called the *Hoyle state*, and proved to be a natural so called eigenstate of the carbon atom, with virtually the exactly same energy as the combined mass of beryllium and helium. The special properties of the Hoyle state (both its energy level and resonance) allow it to function as a helping hand in the production of stable carbon. The process works through this gateway.

Several research groups are currently at work to determine the detailed picture of the carbon nucleus. Both the ground state of carbon, and the excited Hoyle state, are highly complex 12-body problems to determine the motion of these 12 core particles that mutually affect each other. This is difficult to calculate even with today's supercomputers. Recently a German/American research team has announced calculations revealing the configuration of these two important conditions, as shown in Fig. 4 [5; 6]. The ground state has a compact triangular formation of the helium nuclei, while the Hoyle state shows the three helium nuclei in the form of a "bent arm". The results are still uncertain, and others [7] have found solutions similar to an oblate (flattened sphere). The calculations which the supercomputers had to perform, would typically have taken more than 200 years on a regular laptop.

Next to carbon, oxygen plays a vital role for life on earth, and similar internal details of the oxygen nucleus play a critical role. Oxygen has 16 core particles and may be formed by combining carbon and helium nuclei. If the resonance level of the carbon atom was 4 percent lower (a few hundred keV) [8], there would be essentially no carbon. Was that level in the oxygen atom only 0.5 percent higher, virtually all of the carbon would have been converted to oxygen. These are quite small margins, as also pointed out by Hoyle in 1965 [9, p. 160].

Moreover, some of the oxygen nuclei may be stripped of a proton and converted to nitrogen. Without carbon, oxygen and nitrogen, the carbon based life characterizing our planet was not possible. The Hoyle state is the bridge that opens up the way to life giving chemical elements, and the carbon atom is very special since it can form a variety of chemical compounds, particular within organic chemistry.

The Hoyle state also enables the creation of matter in the universe to take place in one initial act. This is well known from the biblical account of creation in which the creation of matter is described by one phrase.

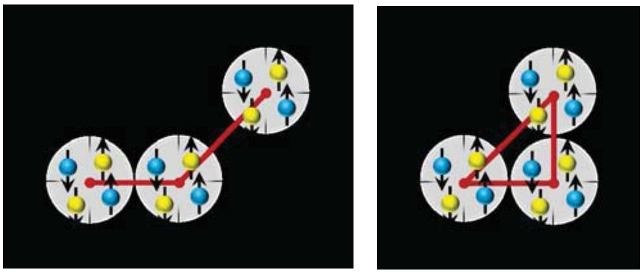

Figure 4. The Hoyle state (left) of carbon shows three helium clusters distributed as a "bent arm" [6]. It is energetic with about 7.65 million electron volts extra energy, but emits energy in the form of radiation when it goes to the ground state. The ground state (right) of carbon shows a configuration with three helium clusters distributed on the vertices of a compact triangle shape. The isosceles right triangle, rather than an equilateral triangle, is just an artifact of the lattice spacing used in the paper. The protons are blue and neutrons are yellow. Research is still going on how the carbon nuclei may be configured.

V. Hoyle's design inference

The unique energy levels required to produce carbon and oxygen, are, as we have seen, statistically highly unlikely. In 1959 Hoyle addressed the remarkable discovery in the University Church, Cambridge:

> *I do not believe that any scientist who examined the evidence would fail to draw the inference that the laws of nuclear physics have been deliberately designed with regard to the consequences they produce inside the stars. If this is so, then my apparently random quirks have become part of a deep-laid scheme. If not then we are back again at a monstrous sequence of accidents [10, p.57-58].*

Some years later Hoyle restated and fortified the conclusion:

> *Would you not say to yourself, "Some super-calculating intellect must have designed the properties of the carbon atom, otherwise the chance of my finding such an atom through the blind forces of nature would be utterly minuscule… The numbers one calculates from the facts seem to me to so overwhelming as to put this conclusion almost beyond question" [11, p.16].*

He estimated the chance of things coming out appropriately at about 1 part in 1000 [12, p. 140], and compared it with tuning a radio:

> *Oxygen and carbon are like two radio receivers, each tuned to a particular wavelength. Unless the receivers are right, with the two dials set at the appropriate wavelengths, far more oxygen are produced than carbon. But, as it happens, the tunings are indeed correct, so that oxygen and carbon atoms are produced in the Universe in appropriate balanced amounts. The problem is to decide whether these apparently coincidental tunings are really accidental or not, and therefore whether or not life is accidental. No scientist likes to ask such a question, but it has to be asked for all that. Could it be that the tunings are intelligently deliberate? [13, p. 218-219].*

VI. Discussion and Conclusion

Carbon is the fourth most common atom in our galaxy, after hydrogen, helium and oxygen. There are few nuclei that have captured human imagination more than carbon-12. Its synthesis is a key to the origins of organic life and the organic chemistry. The gateway through which carbon synthesis proceeds is dominated by the presence of the excited Hoyle state at 7.65MeV. Hoyle's argument for the existence of a resonance state in carbon-12, at this specific energy level, was a brilliant prediction based on astrophysical reasoning, and one that deserves a prominent place in the history of astrophysics [14, 15]. In a bright moment he saw that carbon production was just possible because there was an enhancement effect in the form of a resonance at just the right energy level to permit what would otherwise have been a forbidden process. If the nuclear forces had been only a little different, there would have been no proper resonance and no carbon-based life.

Hoyle described the energy levels of both carbon-12 and oxygen-16 as a "put-up job" apparently designed to produce the two elements in the right ratio:

A common sense interpretation of the facts suggests that a superintellect has monkeyed with physics, as well as chemistry and biology, and that there are no blind forces worth speaking about in nature. [11, p. 16]

The overall configuration of quantitative properties of these elements is so unlikely that it made Hoyle to expect “a supercalculating Intellect.” For Hoyle the figures spoke so clear that this conclusion was virtually self-evident.

His work in this area supported what in the 1970s was called the “anthropic principle” [16] that our universe was and is finely tuned to make intelligent life possible. Hoyle also spoke of the prediction as “an early application of what is known nowadays as the anthropic principle” [17, p. 266]. While Hoyle did not think anthropically when he made his discovery in the 1950s, his writings 30 years later showed him looking in the rear-view mirror to understand it as an anticipation of the anthropic principle.

The question as to if Hoyle in any way applied the anthropic principle or not in relation to his original prediction, has been the subject of some recent study [15]. Some measurements published in 1940 indicated the existence of an exited state of the carbon atom, although subsequent measurements had failed to confirm its existence. However, nothing indicates that Hoyle was aware of these earlier measurements when making his prediction and discovery.

And even if the existence of the Hoyle-state was not predicted anthropically, the existence of such a state at the right energy (within a few hundred keV), and with the right properties, is really amazing. This fact may just be a happy accident of nature, or it may carry a deeper meaning of intelligence and design. Hoyle himself was clearly in favor of the second position.

Acknowledgment

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