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Carbon Based Life - Its Quantum Physics Origins

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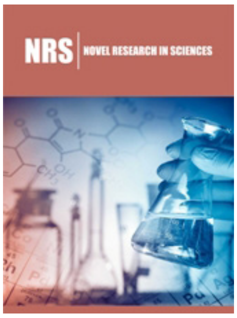

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Abstract

This work comments, in a detailed and physically conceptual way, The role of Carbon as the fundamental ingredient in the origin of life. Emphasis is given to two quantum effects that made it possible for carbon to have this unique primacy - one at the atomic level and the other at the nuclear level. The seemingly improbable ${}^{8}\mathrm{Be} + {}^{4}\mathrm{He} \rightarrow {}^{12}\mathrm{C}$ nuclear reaction is commented on and discussed in detail.

Introduction

The creation of Carbon (${}^{12}C$) in nucleosynthesis is part of the plot of an authentic "Cosmic Epic", successful thanks to an "improbable quantum attunement" between the energy levels of the protagonists ${}^{4}He$ and ${}^{8}Be$ (here addressed).

In a completely different and Earth-bound scenario, Carbon-based life emerged from Quantum Mechanics, being ultimately molecular (see e.g. *Quantum aspects of life* [1]).

This manuscript discusses two *quantum aspects* of matter, one at the *atomic level* (Carbon electrons orbitals) and the other at the *nuclear level* (triple alpha resonance), which were pivotal in the adoption of Carbon as the ingredient element for the constitution of life.

Attempts to imagine life forms based on chemical elements other than Carbon are reported in tortuously byzantine theoretical exercises, particularly in science fiction literature, where Silicon is its favorite element. This is because it is the most abundant element in the Earth's crust. However, it is very simple demonstrate that this Silicon-based life form cannot evolve spontaneously from its emergence [1].

Why are All Living Things Carbon-Based?

Carbon is very suitable to form complex molecular structures essential for life functioning. This characteristic is due to the fact that some configurations of its electron orbitals are *Quantum Mechanically* more favorable in terms of energy, resulting in greater stability. In fact, of its six electrons four are located in its outer shell, significantly increasing the possibilities of forming molecular structures. As a consequence, Carbon can easily form very long stable and complex molecules like the DNA, which is capable of storing enormous amounts of biological information allowing organisms to develop, replicate and evolve. Actually, only Carbon-based life can spontaneously develop from a very simple event, like the fertilization of an egg by a spermatozoon.

All these findings lead to the obvious conclusion that life flourished, at least on this planet, thanks to an abundant production of Carbon.

Big Bang Nucleosynthesis – Abundant Carbon Production

Before the Big Bang (which occurred 13.7 billion years ago) space was filled with Hydrogen, Helium and traces of Lithium, and the first stars appeared 100 million years after the Big Bang. **This is when the first Carbon atoms were produced.**

Thus, Carbon and Oxygen were **not created in the Big Bang** but rather much later in stars. All of the Carbon and Oxygen were produced via thermonuclear *fusion reactions* in the interior of stars, which consume their Hydrogen, Helium, and Lithium to produce heavier elements [2-4].

Big Bang nucleosynthesis was the creation of elements heavier than Hydrogen, mainly Helium. After this cataclysmic cosmic event occurred, the Universe was populated only with **protons** and **neutrons**. Free neutrons have a half-life of about 10 minutes, but right after the Big Bang temperatures and pressures have become high enough to create **Helium** and **Beryllium**.

Nuclear fusion reactions

The leading nuclear fusion reactions are

$$^{4}\text{He} + {}^{4}\text{He} \rightarrow {}^{8}\text{Be} \quad (1)$$

Where two Helium nuclei (alpha particles) fuse into Beryllium, and

$$^{8}\text{Be} + {}^{4}\text{He} \rightarrow {}^{12}\text{C} \quad (2)$$

These reactions occur in the interior of stars. They basically consist of adding Helium nuclei (alpha particles) to existing nuclei. For instance, if Carbon fuses with another Helium nucleus we have Oxygen production, that is

$$^{12}\text{C} + {}^{4}\text{He} \rightarrow {}^{16}\text{O} \quad (3)$$

Helium nuclei are very stable and, as a general rule, those nuclei formed by multiples of ^{4}He will also be stable, such as Carbon (3 x ^{4}He), Oxygen (4 x ^{4}He), etc., where Beryllium (2 x ^{4}He) is an exception to this rule.

Actually, this radionuclide (^{8}Be) is an *unbound resonance* with respect to alpha emission; it is a resonance having a width of 6eV, decaying into two alpha particles (^{4}He) with a half-life of ≈ 8.2×10^{-17} seconds (on the order of 10^{-16} seconds, an unimaginably short time for a Physics layman).

In the context of Nuclear Physics, an *unbound resonance* refers to a state where a nucleus, as ^{8}Be, does not have a bound state, by existing transiently (momentarily) as a resonance before decaying into other particles, two alpha particles (^{4}He) in this case. The "unbound" aspect indicates that the particles are not held together by the nuclear force in a permanent manner.

In simpler terms, ^{8}Be can be thought of as a *transient* arrangement of two alpha particles that briefly forms before splitting apart again after an elapsed time on the order of 10^{-16} seconds (see above), as it is energetically more favorable for alpha particles to exist separately rather than bound together in the form of ^{8}Be.

The Triple-Alpha Resonance

However, in 1954 the legendary astronomer Fred Hoyle [5] postulated the existence of a triple-alpha resonance in carbon-12 enhancing, therefore, the creation of carbon-12 despite the extremely short half-life of beryllium-8. Hoyle deduced that the conditions prevailing in the stellar interior were ideal for a "resonance" between 4He, 8Be and 12C (The triple-alpha resonance). The existence of this resonance (the Hoyle state) was confirmed experimentally shortly thereafter [6,7].

In the dense and hot environment of a star's core, there is a chance that a third alpha particle will collide with the ^{8}B nucleus before it decays. This can form the ^{12}C Hoyle state, an excited state produced via the 7.7MeV resonant triple-alpha process [6,7].

In simplified terms, the three helium (^{4}He) nuclei participating in the formation of Carbon (^{12}C), first produce Beryllium (^{8}Be) using two of them. Then, the third and remaining ^{4}He would have only 10^{-17} seconds (see above) to complete the fusion with ^{8}Be and produce ^{12}C. But the apparently unpromising collision of this third ^{4}He with the "fragile" ^{8}Be would only accelerate its disintegration. Thus, nucleosynthesis would be interrupted at the 8Be formation stage – in the words of Gribbin and Rees [8] we would be facing the "Beryllium bottling", and without Carbon we would not be here to tell this story.

The existence of this *Hoyle state* is essential for the nucleosynthesis of carbon in helium-burning stars. In fact, although unstable, the *Hoyle state* has a higher probability of decaying into the *stable ground state* of ^{12}C, thus creating carbon. The process occurs predominantly in red giant stars, which are rich in helium and have the necessary conditions of temperature and pressure to facilitate these reactions.

Because it is responsible for the formation of ^{12}C, despite the extremely short half-life of ^{8}Be, the triple-alpha process is essential for life, as well as being a fascinating phenomenon in astrophysics.

Fine-tuning between 4Hr and 8Be energy levels

The triple-alpha resonance is feasible because in the last step of this process ($^{8}\text{Be} + {}^{4}\text{He} \rightarrow {}^{12}\text{C}$) there was a fine-tuning between ^{4}He and ^{8}Be energy levels, resulting in a fruitful production of ^{12}C created with an energy exactly equal to that of one of its natural levels (the 7.6 MeV level).

In fact, as a general Quantum Mechanic rule, a $A + B \rightarrow C$ fusion reaction will occur only if the new nucleus, C, is created in one of its naturally existing states. This correspondence of the energies to one of the appropriate levels of the new nucleus (the 7.6 MeV ^{12}C level) is called "resonance". So, with that, all the necessary carbon was produced.

The Role Played by the Fine Structure Constant

The Fine Structure Constant (α) is given by

$$\alpha = \text{k.e.2(hc)}^{-1} \quad (4)$$

Where k is the electrostatic constant in the vacuum, e is the electron charge and c the speed of light. α is a dimensionless constant characterizing the strength of the electromagnetic interaction between elementary charged particles – see more in [9].

The α constant is also related to the maximum positive charge of an atomic nucleus that allows a stable electron orbit, which is relevant for elements up to Feynmanian.

Additionally, the *Fine Structure Constant* is part of the composition of energy levels. For example, the Hydrogen atomic levels E_n are given by [10]

$$E_n = \left(B/n^2\right)\alpha, \text{ or } E_n = q_n.\alpha \qquad (5)$$

Where $q_n = \left(B/n^2\right) \equiv$ constant (for a given n)

The *Fine Structure Constant* also has deeper implications in physics. For instance, if α were much larger than it is, the electromagnetic force would be much stronger than the nuclear force, which would prevent the existence of stable atomic nuclei. On the other hand, if α were much smaller than it is, the electromagnetic force would be much weaker than the nuclear force, which would cause all the protons and electrons to fuse into neutrons.

The Primordial Soup

If we rethink cosmogenesis, from the "primordial soup" of quarks and gluons to the Big Bang, when the universal physical constants originated from the complete randomness of processes, as pedagogically described by Stephen Hawking in his work "A Brief History of Time" [11], We could conjecture that almost everything that exists could exist because these physical constants have the values we know and measure.

Thus, for example, (1) if the fine-structure constant differed by about one percent from its actual value, the structure of stars would be drastically different. (2) Also, the consequent minute variations in nuclear forces could have prevented the formation of the resonance that led to abundant carbon production (see above Section 4.1: *Fine-tuning between 4He and 8Be energy levels*). In this case, carbon, a decisive biological element, essential to the evolution of life, would exist as the scarcest of the elements in the universe.

The origin of the values exhibited by the fundamental constants of Physics, among them the Fine Structure Constant, from the chaotic explosion that was the Big Bang, is a topic of great interest and research in theoretical physics, and several theories try to explain why these constants have the values we observe. However, to date, there is no definitive answer to this question. This circumstance reinforces that it all occurred due to a fantastically improbable fine-tuning between 3 alpha particles (see Section 4. *The triple-alpha resonance*).

Final Remarks

As discussed above, the formation of primordial Carbon is associated with two remarkable Quantum Mechanical effects – one at the atomic level and the other at the *nuclear level*. Therefore,

Atomic level quantum effect

The circumstance that four of the six electrons in carbon are located in its outer shell confers great stability, as well as greatly increasing the possibilities of forming molecular structures as complex as a DNA molecule.

Nuclear level quantum effect

The triple-alpha resonance in ^{12}C occurred thanks to a fantastic fine tuning between 3 alpha particles, populating the 7.6 MeV level naturally existing in ^{12}C.

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