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Who Discovered the Hoyle Level?

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Abstract

The prediction of Hoyle that the nucleus of ^{12}C must have a resonance at 7.62MeV was the trigger to the Anthropic Principle. We review the history of the discovery of this level and investigate to what extent this was a genuine prediction.

Keywords: anthropic principle - nuclear physics - stellar evolution.

1 Who Is Who

Three dominant personalities were involved in the present story: Sir Fred Hoyle FRS (1915-2001), who was one of the greatest astrophysicists in the second half of the twentieth century with major contributions to Stellar structure (nuclear astrophysics - synthesis of the elements) and to Cosmology - (Steady state theory dubbed the name Big Bang) as well as planetary formation. William A. Fowler (1911-1995), who can be considered as the father of nuclear astrophysics and Edwin Salpeter (1924-2008) top theoretical astrophysicist, who has numerous seminal contributions in many astrophysical fields as well as in physics.

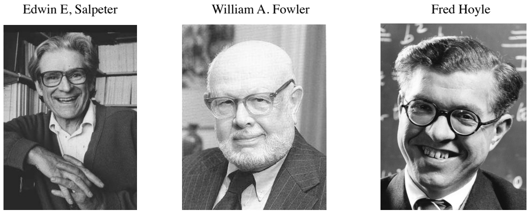

Figure 1: The dominant personalities involved in this story: The discovery of the triple α process.

2 What Is the Hoyle Level

The synthesis of helium into carbon in stars proceeds via resonant reaction, namely the three α particles fuse into an excited energy level in the ^{12}C nucleus. The rate of the reaction was calculated before the existence of this level was known and was found to be very low compared to the rate of destruction of ^{12}C by collisions with α particles. As a consequence, it was impossible to predict the evolution off the main sequence towards the Red-Giant branch and the calculation implied that all the ^{12}C is converted into ^{16}O. But stars do evolve and we know that somehow carbon is synthesized. In view of the impass, Hoyle predicted therefore, that ^{12}C has an energy level just at the right place and the reaction of carbon synthesis proceeds via this resonance level. The level was then discovered in the laboratory. This chain of events: prediction the existence of a nuclear level from astrophysical constraints, wa s considered as a big victory for astrophysics and the level was named the Hoyle level.

3 What Is the Anthropic Principle

The Anthropic Principle is a philosophical hypothesis that measures of the physical Universe must be compatible with the existence of conscious life that observes it. The phrase "Anthropic Principle" appeared first in Brandon Carter's contribution to the 1973 Krakow symposium honoring Copernicus's 500th birthday. Carter argued as well, that humans do not occupy a privileged position in the Universe. The trigger to the idea that life as we know it, and the cosmos around us, "are tuned", emerged from Hoyle's prediction of the existence of a special energy level in the nucleus of ^{12}C. If such a level did not exist, argued Hoyle, life could not have develop in the cosmos, more accurately, ^{12}C based life could not emerge. Was it really so amazing? Was it a full prediction?

The basic astrophysical problem emerged when Hoyle and Schwarzschild calculated, in the early nineteen-fifties, the evolution of stars off the main sequence into the red-giant using reaction rates known at the beginning of the nineteen fifties and got that as soon as ^{12}C is synthesized from helium, it absorbs another α particle and becomes ^{16}O leaving no carbon. The reaction forming ^{12}C was much slower than the reaction that destroys it. If so, argued Hoyle, life should not exist! Alternatively, as ^{12}C does exist in our universe, there must be a resonance in this nucleus that accelerates the formation of carbon by many orders of magnitude. This was 'reverse engineering' at its best. You know what should happen and find out how can it be.

Could ^{12}C be synthesized elsewhere? The only known alternative was the Big-Bang. But Hoyle argued that all elements were synthesized in stars. On the other hand, Gamow argued that all elements were synthesized in the Big Bang. However, the various models of Big-Bang nucleosynthesis failed to produce elements like ^{12}C and higher (in atomic weight), and left stars as the only cosmic site for synthesis of ^{12}C and heavier nuclei.

4 The Nuclear Barrier

Two nuclear barriers exist in the synthesis of the elements from hydrogen up (see fig. 2). The barriers are the non existence of a stable A=5 and A=8 nuclei as shown in the figure. This means that the synthesis of the elements, if started from hydrogen, must jump over these nuclei.

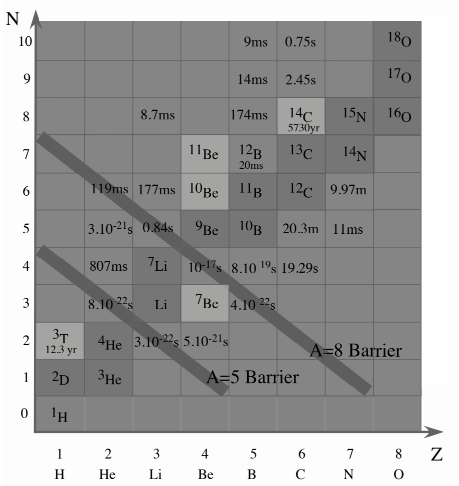

Figure 2: The nuclear barriers at A=5 and A=8, namely the non existence of stable nuclei with these number of protons and neutrons.

Many attempts and suggestions to overcome the barriers were suggested. We mention here only Bethe's attempt, namely a three body reactions. Bethe knew from Eddington's stellar models what are the central temperatures and densities in stars and soon realized that a 3-body reaction is much too rare under such conditions. We note that Eddington's results were derived without reference to what is the energy source of stars (which he did not know but hypothesized, already in 1919, that it must be the fusion of hydrogen into helium). In fig. 3 we show the structure of all nuclei with N+Z=8. The instability of the A=8 nucleus implied that any fusion reaction leading to this nucleus will not create it. The so formed nucleus may live a short time but eventually it decays.

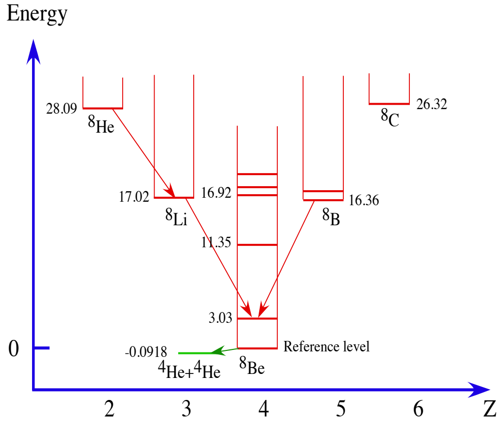

Figure 3: The relative energies of the ground states of the N+Z=8 nuclei. The numbers are the energies in MeV relative to the ground state of ^{8}Be, which has the lowest ground state energy of all A=8 nuclei. However, the state of two free α's has still lower energy. Hence, there is no stable nucleus with A=8.

5 Why Nuclear Physicists Were Interested in the Problem?

The fundamental problem in nuclear physics at the beginning of the nineteen thirties was the nuclear structure. It was already known that the α particle is the most bound nucleus as it has the highest binding energy per nucleon. Similarly, nuclei like ^{12}C,^{16}O,^{20}Ne etc have a higher binding energy than their neighboring nuclei. The question was therefore, are these so called α nuclei composed of α particles or of just an equal number of protons and neutrons, as shown in fig. 4. In particular, is the excited state of ^{12}C a three body state? Consequently, attempts to find the energy level structure of the excited ^{12}C were

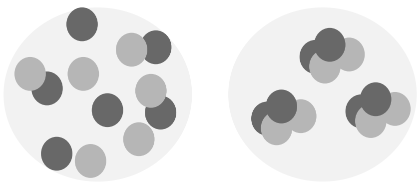

Figure 4: The two possible options for the structure of the carbon nucleus. On the left we see 12 nucleons moving independently of each other and on the right we see groups of 4 nucleons moving as a bound unit.

carried out long before any astrophysical interest in the problem arose. Actually, even before Bethe discovered how the CN cycle powers the Sun (today we know that the CNO cycle contributes about 4% of the total energy produced by the Sun and the *pp* chain contributes the rest.)

6 The History of the Discovery of the ^{12}C Nuclear Levels

Already in 1933 Lewis et et al. experimented with the reaction:^{14}N+^{2}D $\rightarrow$ ^{12}C+^{4}He. The nucleus of ^{12}C so formed has significantly more energy than the ground state as it forms in an excited state. The decay of the excited state to the ground is performed by one or more emissions of γ photons. In principle, if you measure the energy of the $\gamma's$ you can easily figure out the energies of the energy levels in the newly formed nucleus. Lewis et et al. did not measure any $\gamma's$ as they did not have the equipment, they however, discovered the emitted α particles. As they did not detect all particles emitted in the reaction they found that the emitted α particles have about half the energy difference and it was not known where the other half was lost.

Lawrence et al (1935) repeated the experiment, again without any device to measure $\gamma's$. However, they measured the energies of the $\alpha's$ and found two groups of α particles having different energies, and so were able to infer that ^{12}C has two energy levels: at 3.8MeV and 4.7MeV. Actually, the interpretation of the experiment was not complete. As shown in fig. 5, there are two possibilities to interpret this experiment.

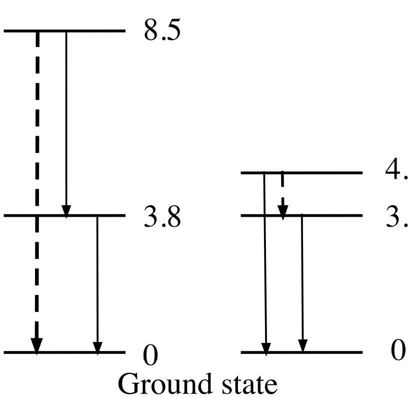

Figure 5: The interpretation of Lawrence et al. result. One alternative can be two levels at 3.8 and 8.5MeV with allows transitions between these two levels and forbidden transition directly from the 8.5Mev level to the ground state. The other alternative is two levels with allowed direct transition to the ground state and forbidden transition between the levels. Lawrence et al assumed the latter case but as we will see that in reality it was the first alternative.

Crane and Lauritsen observed γ's from the reaction: ^{11}B+^{2}D $\rightarrow$ ^{12}C+p. These experiments which were carried out in the early 1930th made it clear that ^{12}C has excited states but their energy was not known to better than $\pm 1 MeV$.

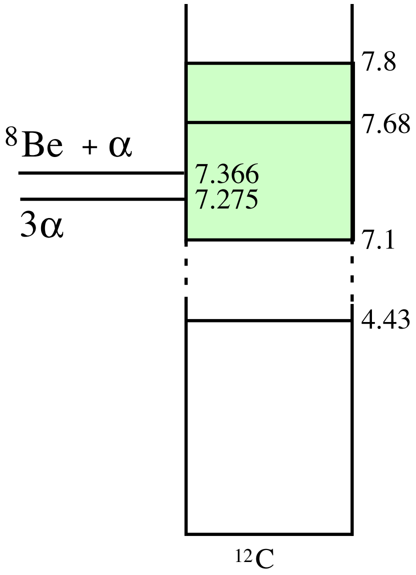

Figure 6: The structure of the ^{12}C nucleus as known in 1940. The level at 7.68MeV can decay into a ^{8}Be$+\alpha$ or 3α. The green color spans the range where the various experiments gave an indication of an energy level. All energies are in MeV.

In 1940 Gaerttner & Pardue of the Kellogg laboratory at Caltech investigated the reaction ^{14}N+^{2}D $\rightarrow$ ^{12}C+α and discovered that on top of the emitted α particles also γs with energies 1.9,3.1,4.0,5.3 & 7.0 MeV were emitted. It became clear already at this epoch that there exists a level at $\sim$ 7.2MeV but it is weakly coupled to the ground state, namely the transition to the ground state was too weak to be observed! Hence, only an upper limit to the rate of transition could be found. The implication was that indeed, if the reaction product goes to excite this level in ^{12}C, then extremely few ^{12}C nuclei would decay from this state to the ground state. It appeared therefore, that from stellar nucleosynthesis this is not likely to be the way ^{12}C forms. But this question of transition probability was not yet raised.

In the same year Holloway and Moore (1940) repeated the experiment ^{14}N+^{2}D $\rightarrow$ ^{12}C+^{4}He and confirmed the existence of the levels at 4.37 & 7.62MeV and suggested that in most cases the (excited) ^{12}C* disintegrates by emitting an α particle. They wrote that: *The corresponding excited state of* ^{12}C *would be unstable against* α *emission, but it is still easily conceivable that such a state could not actually emit an* α *because* *of selection rules.* Clearly, in the first case this is not the way to form carbon while if carbon is formed in this way we can claim that astrophysical situation implies that the channel in which ^{12}C* disintegrates by emitting an α may exist but along with the decay to the ground state.

As for our particular reaction, what Holloway and Moore argued was that in the reaction ^{8}Be+$\alpha \leftrightarrow^{12}$ C+γ the compound nucleus disintegrates mostly into the incoming channel.

Terrell (1950) examined the ^{9}Be+$\alpha \rightarrow$ ^{12}C+n and found no evidence for excited states in ^{12}C. In the same year Johnson (1952) investigated the ^{11}B+^{2}D $\rightarrow$ ^{12}C+n reaction and found the 4.4 & 9.6MeV levels but not the one around 7MeV. It should be realized that these experiments are very difficult and tricky and hence no wonder that it took such a long time to find the accurate structure of the nucleus of ^{12}C.

In 1950 Hornyak et al. summarized the known data of the ^{12}C nuclear structure as depicted in fig. 6. The 7.86MeV level is shown but very weak, namely only rare transitions into it, and hence a problem to experimentalists. Lauritsen and Fowler were co-authors on this paper.

In 1951 Miller & Cameron followed the motion of ^{8}Be nuclei in nuclear emulsion and observed their decay. They found a lifetime of $5 \pm 1 \times 10^{-14} sec$. This lifetime is 10^{6} times longer than the two α's mutual crossing time. This was the paper that put an end to a long line of papers that claimed alternatively that ^{8}Be is unstable and unstable. Miller & Cameron succeeded to watch the motion of the ^{8}Be nucleus in emulsion and see its decay. We mentioned above that α-like nuclei are expected to be more bound than their neighbors. Here we have a nucleus composed of just two α nuclei and it is unstable!

7 The Wrong Solution

Some people claim that Salpeter, who discovered the basis for the triple alpha process, must share the credit with Öpik. Öpik, according to this claim, solved the problem of the helium fusion to carbon already in 1951. The trouble was, so goes the claim, that Öpik published his paper in the Proc. Royal Irish Acad. 1951. A seldom visited by astrophysicists journal.

But Öpik's paper is wrong and not identical with that of Salpeter. Öpik, who had many important and very original contributions, apparently did not read the nuclear literature or ignored it, because he ignored the fact the ^{8}Be is unstable, a fact known already in 1951.

So Öpik assumed a 3 body collision. The $\alpha + \alpha$ penetration takes about $0.8 \times 10^{-20} sec$ and the third α must collide within this time. Clearly, the lifetime of ^{8}Be as assumed by Öpik, is off by a factor of 10^{6}. This factor enters into the rate. Moreover, despite the fact that the energy level in the ^{8}Be continuum was already known, Öpik overlooked it. Öpik assumed that He burning lasts $10^{14} sec$. The question then was at what temperature would helium burning last this time and with his wrong reaction rate Öpik derived that helium burning takes place at 6×10^{8}K. This is known today as far off and it implies a discrepancy between the formation of ^{8}Be via two $\alpha' s$ and the formation of ^{12}C, as we will shortly see. Öpik's paper did not attract the astrophysical community and from its publication in 1951 till 2009 Öpik's paper was cited just once, and it was by Salpeter...

In 1972 Marshal Wrubel wrote a review on Ernst Öpik's contributions to Red Giants and did not mention his contribution to the 3α process.

The uncertainty in the energy levels prevailed in 1950. Guier and Roberts looked at: ^{9}Be+$\alpha \rightarrow$ ^{12}C $+n$ and claimed the level is at 7.8MeV. The experiment was repeated with Bertini joining the team, and no level was observed.

In 1952 Azjenberg & Lauritsen prepared a compilation of all the experiments and provided the following summary in fig. 7. Our particular level is well marked.

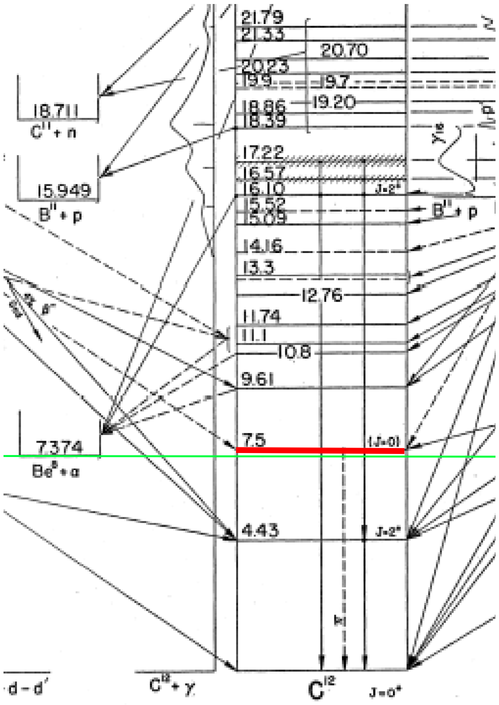

Figure 7: The structure of the ^{12}C nucleus as summarized in 1952. The energy level under discussion is marked in red and is at 7.5MeV. Note that the authors assigned the level $J = 0$, which is identical with that of the ground state. But $0 \rightarrow 0$ transitions are forbidden.

8 Salpeter Enters the Game

Salpeter entered the game in 1951 just after the publication of the Bethe-Salpeter equation. It was upon Fowler's request for help in the theory, that Bethe decided to send his distinguished young physicist Salpeter to the Kellogg laboratory at Caltech. Salpeter spent two summers in Caltech. On October 1951 Salpeter submitted his first paper to the ApJ: ^{12}C had no level around 7.6MeV. On October 1951 Ajzenberg & Lauritsen submitted a paper to Physical Review in which ^{12}C had a level at 7.5MeV with J=0 (no known parity). Two of the most important results for the triple alpha process were published at the same time by people from the same laboratory in two different journals and no citation was given to one another. They simply did not know of each other.

When Gamow considered in 1938 the possible energy source of MS stars he assumed, in an attempt to overcome the A=5 barrier, that: $2^4\text{He} \leftrightarrow {}^8\text{Be}$, namely the reaction is in a dynamic equilibrium and assumed ^{8}Be to be stable. Salpeter was unaware of this publication of Gamow but knew already that ^{8}Be is unstable.

So Salpeter, facing the same dilemma as Gamow, assumed that the two $\alpha's$ go into the *95KeV level* (which was known already to Salpeter) *in the continuum* and the so formed nucleus lives long enough (just $10^{-14}sec$ which were inferred from the width of the level) for a third α to collide and create a ^{12}C nucleus. Salpeter realized that $10^{-14}sec$ is orderes of magnitude longer than the two $\alpha's$ self-crossing time and hence his treatment was justified because ^{8}Be lives a long time before it decays and the assumption of equilibrium is fully justified. If so, there is no need for a cross section! Next, Salpeter assumed that the ^{12}C nucleus "somehow decays" in flight (no level in ^{12}C was known to certainly exists) into the ground state of ^{12}C.

Salpeter stressed that he assumed no resonances in $^{12}\text{C}, ^{16}\text{O}, ^{20}\text{Ne}, ^{24}\text{Mg}\ldots$. Salpeter felt uneasy about it and wrote that: *The nuclear γ-ray width for the formation of* ^{12}C *(but not the one for* ^{8}Be*) is required. This width has not yet been measured, and the position of resonance levels was not known accurately enough and an estimate of 0.1eV was used for this width. Hence the correct production rate could be smaller by a factor of as much as 10 or larger by as much as 1000.* Thus the reaction rate known in the literature was estimated ignoring the possible existence of unknown resonances.

Two comments: In 1954 Öpik wrote a paper about WD and the 3α. He wrote that: *the lifetime of the temporary nucleus* ^{8}Be *formed is assumed equal to* $\sim 8 \times 10^{-21}sec$ *being an estimate of the duration of penetration. The lifetime of true* ^{8}Be *is probably much shorter, about* $10^{-22}sec$ *... No resonance capture is assumed in this case.* Moreover, Öpik complained that Salpeter did not cite him and added: *His method of calculation is not quite clear from his brief note. It seems that the reaction* $2\alpha \rightarrow {}^8\text{Be}^*$ *he has treated in a manner similar to ours, where as in* $^8\text{Be}+^4\text{He} \rightarrow {}^{12}\text{C} + \gamma$ *he has postulated a resonance process. The outcome is a formula yielding* 1.4×10^{13} *times higher an energy generation with practically similar temperature as our formula.* How many errors can be written in a single sentence?

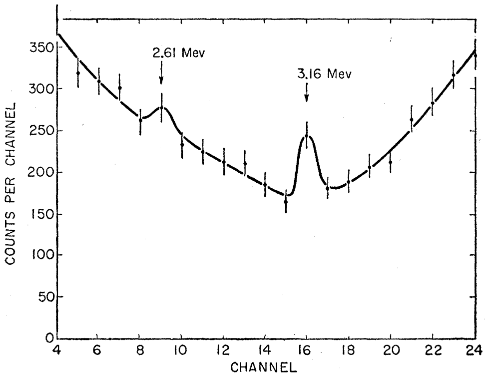

Figure 8: The very nice discovery of the energy levels by Beghian et al (1953).

In 1953 Beghian et al investigated the $^9\text{Be}+\alpha \rightarrow {}^{12}\text{C}+n$ reaction. They detected two groups of γ rays: at 3.16MeV and at 4.43MeV and concluded that: ^{12}C has two levels: at 4.43 & 7.59MeV (The first alternative is shown in fig. 5) . They did not find any γ rays with energies close to 7.5MeV. Hence they concluded that the probability of the 7.59MeV level to decay to the ground state is $< 1/2500$. Willy Fowler did not trust any of the previous measurements of the carbon level and searched for a way to carry out a trustful experiment.

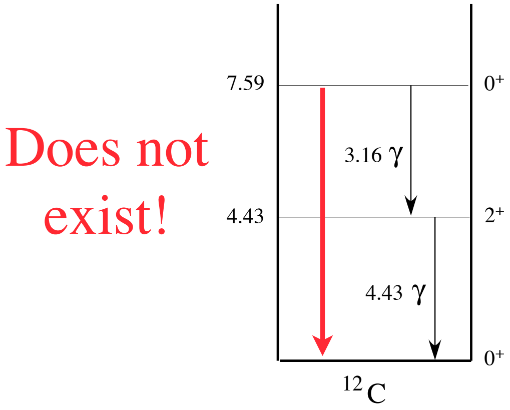

Figure 9: The structure of ^{12}C after Beghian et al discovery. The direct transition from the 7.59MeV to the ground state is forbidden.

The symmetry of the ^{12}C ground state leads to a $J = 0^+$ state. The state at question appears to have also $J = 0^+$. Angular momentum conservation do not allow the 0^+ state to decay into the ground state which is also 0^+. Hence, if eventually the decay of this state leads to the ground state, there must be another intermediate level below the 7.59MeV one with the proper spin, to which this level can decay. Hoyle never mentioned these requirements nor allowed and forbidden transitions. He tacitly assumed that the 7.69MeV level 'somehow' decays to the ground state.

9 1953 Kellogg Phase I

When Martin Schwarzschild and Fred Hoyle tried to evolve main sequence stars off the main sequence and derive the Red Giant, the modeling failed and they could not get the Red Giant branch. Beside the failure to derive the branch, there was a problem with the composition. The rate of $^{12}\mathrm{C} + \alpha$ (carbon conversion into ^{16}O) was much greater than the rate of carbon formation and hence no carbon was left after helium burning. The model moved from helium to oxygen leaving no carbon.

Hence, Hoyle argued that there should be a level at about 7.6MeV which accelerates the reaction and leads to the formation of carbon (relative to its destruction). Hoyle spoke only on the energy of the level and he knew at what energy in ^{12}C it should be because he assumed it takes place via $^8\mathrm{Be} + \alpha$. This is exactly the level we discuss here.

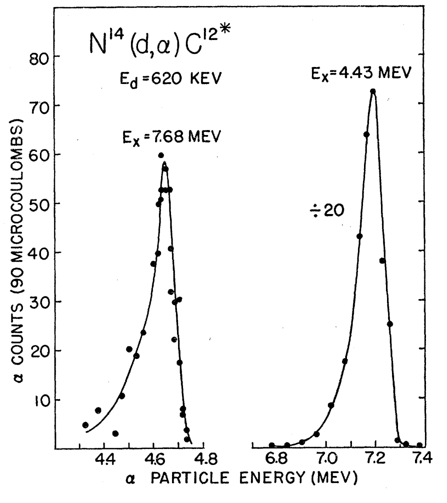

Figure 8.15: *Dunbar's et al. 1953 result. A beautiful manifestation of the predicted* 7.68MeV *level.*

Figure 10: The structure of ^{12}C after Dunbar et al discovery.

When Hoyle came to Kellogg in the first time he convinced Ward Whaling to look for this level and indeed Whaling went to the lab and found the level exactly where Hoyle claimed it must be. The level was rediscovered!

Hoyle spoke about the energy of the missing in calculation level and did not discuss any spin, selection rules etc. The abstract was presented in the American Physical Society meeting in Albuquerque, NM, Sep 2-7, 1953. The paper was presented in the session on nuclear physics not astrophysics. It was a victory for Hoyle in particular in front of skeptical Fowler.

10 How Did Hoyle Predict the Nuclear Level in ^{12}C

Hoyle assumed the that κ defined as:

$$\kappa = A\frac{Rate(^{12}\mathrm{C} + \alpha \rightarrow ^{16}\mathrm{O} + \gamma)}{Rate(3\alpha \rightarrow \gamma)} = \frac{destruction}{formation}$$

is given and calculated the resulting mass fraction of ^{12}C after the burning of helium into carbon. Hoyle obtained in this way the results shown in fig. 11. It is easily seen that $\kappa \gg 1$ (the destruction is much faster than formation) yields no carbon at the end of helium burning.

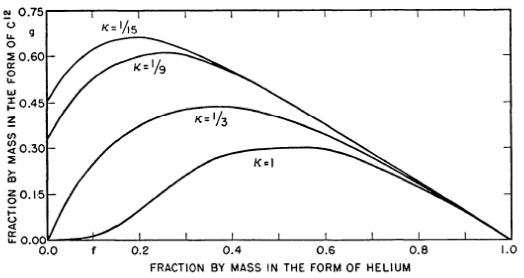

Figure 11: The argument by Hoyle that the resonance must exist.

The paper by Hoyle, Dunbar et al had the title: *A state in* ^{12}C *Predicted from Astrophysical Evidence.* The abstract also admitted that: *A level had previously been reported at 7.5MeV, based on Ajzenberg and Lauritsen 1952.* . on the other hand, the decay mode of the level - a crucial point - was not discussed at all. Beghian discovery of the 7.59MeV level was overlooked.

But Hoyles victory was not complete - his friends did not accept the idea. Could Hoyle invert the process and learn nuclear physics from the stars? Cook, Fowler, T. Lauritsen and C.C. Lauritsen 1957 argued that:Experimental evidence on the character of the 7.7MeV state is not entirely clear. It seems well established that the state does not radiate directly to the ground state but rather cascades via the 4.43MeV state. The authors added that: one must (a) make sure that the level can be formed by $^8\mathrm{Be} + \alpha$. The spins should agree. (b) It must have a finite probability to decay to the ground state.

Note: the direct reaction cannot be investigated in the lab because the rate is very slow. Consequently, the ^{12}C level must be populated indirectly.

Cooks et al. had a sever technical problems: On one hand: It was established that there is no direct way to the ground state. On the other hand no one observed that the compound ^{12}C nucleus disintegrates into ^{8}Be* + α. There were conflicting estimates of the probability to emit an α. Uebergang and independently Steffen, got that the excited ^{12}C nucleus emits α at about << 50% of the cases while Bent et al and independently Hornyak got that it emits an α in >> 97% of the cases.

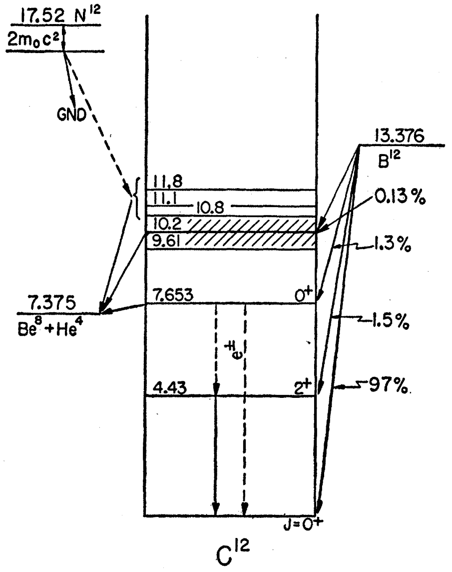

Figure 12: The final experiment by Cook et al. 1957: creates the nucleus ^{12}B and follow its decay into the 7.653MeV level (only 1.3%).

To overcome the problems Cook et al 1957 created the radioactive nucleus ^{12}B which decays into ^{12}C. Most of the decay goes into the ground state and only 1.3% decays into the investigated level.

11 1957 Salpeter Finishes the Job

Remaining problems: What is the spin of the 7.68MeV state? Fregeau & Hofstadter (1955) using electrons scattering from the nucleus (an experiment for which Hofstadter got the Nobel prize 1961), claimed that J=0+ is not inconsistent with experiment. So Salpeter assumed $J = 0^+$ or 2^+. The latter yields a result which is about 1000 smaller than the first one.

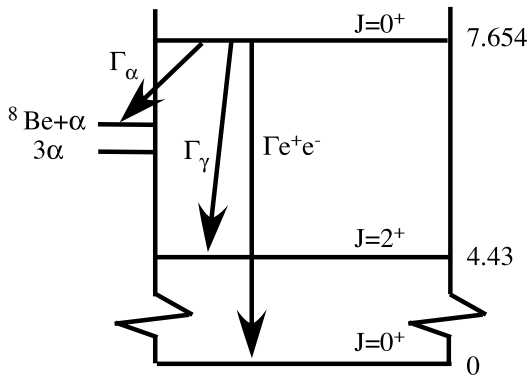

Figure 13: The part of the energy schemes of the ^{12}C nucleus relevant to the 3α reactions as was finally assumed by Salpeter in his final paper in 1957

The structure of ^{12}C as assumed by Salpeter in 1957, is given in fig. 13. Γ_α is the probability of decay emitting an α particle, Γ_γ is the probability of decay emitting a γ photon and $\Gamma_{e^\pm}$ is the probability to decay by emitting an electron-positron pair. This is a rare mode of decay and of no importance to our story here. This was the structure of ^{12}C after Salpeter obtained the improved results of Cook et al 1957.

Salpeter made some critical assumptions: The disintegration channel ^{12}C* decaying back into ^{8}Be + α is the dominant channel and all other possibilities are very small leakages. Consequently, Salpeter assumed a *dynamic equilibrium*, namely

$$^{12}\mathrm{C}^* \leftrightarrow {}^8\,\mathrm{Be} + \alpha.$$

If so, the concentration of ^{12}C is determined from the equilibrium (small sensitivity to the energy of the level) and all the uncertainty is in the small leakage to the other channels. In particular, the is no need for a cross section,to evaluate the rate. The reaction is in a statistical equilibrium.

On January 1955 Salpeter presented the results in the New York meeting of the Physical Society. By now he became aware of the Ajzenberg & Lauritsen old result and cited it.

Fowler won the 1983 Nobel prize (with Chandrasekhar) for contributions to nuclear astrophysics, but Fowler's Nobel speech was one long discussion about . . . Hoyles contributions. As for Salpeter, Fowler commented that he ignored the 7.68MeV state - which is a very wrong claim. He ignored it when it was unknown to him. Fowler was a great experimental nuclear physicists but without knowledge in statistical mechanics and he did not like that 'the nuclear physics' was eliminated from the problem.

Hoyle and Salpeter shared the 1997 Crafoord prize[1] in particular for the physics of the triple α reaction. The process is called today the Salpeter process and the energy level is called the Hoyle level.

Fight for priority: Salpeter informed Hayakawa et al. about the probability that the 7.68MeV state decays into the 4.43MeV state. Hayakawa et al hurried and submitted their paper to Progress of Theoretical Physics Japan in July 1956 in which they made just this claim. The journal published on November 1956.

Salpeter published his work only in 1957. Surprisingly the japanese authors claimed that: *This (meaning theirs) rate is* 10^6 *times greater than given by Salpeter 1952. Such a great difference is due mainly due to the fact that he did not take into account the* ^{12}C *resonance.* They did not mention that it was Salpeter who told them about his work and the ^{12}C level.....

12 Is This the Entire Story?

Is this the entire story? No! What about the structure of ^{16}O? Following Hoyle, we treated the reaction

$$^{12}\mathrm{C} + \alpha^{16} \to \mathrm{O} + \gamma$$

as well established. However, this is not the case. In 1974 Dyer and Barnes from CalTech attempted to measure the ^{12}C+α reaction. The next attempt was carried out in 1982 when Kettner et al. from Münster measured the reaction and discovered that it is 3 to 5 times faster then what Dyer and Barnes from Caltech found. As a consequence, the most abundant specie at the end of helium burning was found to be ^{16}O and not ^{20}Ne as the formation of ^{16}O is faster than its destruction.

Langanke and Koonin (1983) criticized the analysis and the conclusions of the experimenters and repeated the very long theoretical analysis of the experimental data. However, they could not resolve the discrepancy between the Caltech data (Dryer and Barnes) and the Münster data (Kettner et al.) and fitted each experiment separately. Thus, the Münster data was 1.5 time higher than that of Caltech, which in turn was 3 times higher than what stellar modelers used. As Lankange and Koonin wrote, such higher values , as those found in Münster and Caltech, lead to ^{16}O rather than ^{12}C, as the final product of helium burning, and in this way cast a shadow on Hoyles argument. In fig. 15 we show a comparison between two recent experimental result and a theoretical fit. The red arrow shows the energy range in stars where this reaction takes place. So far this experimental discrepancy is not sett led.

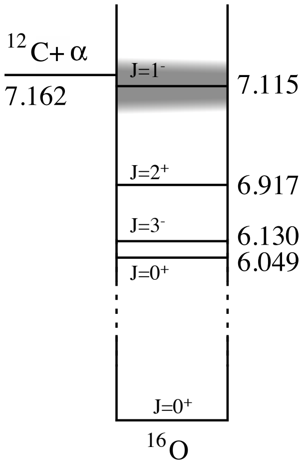

Figure 14: The structure of ^{16}O based on Ajzenberg & Lauritsen 1952. The partial width of the relevant level at 7.115MeV is not known because it is a very difficult measurement. The uncertainty in the level is marked by the grey zone around the level. The difficulty stems from the fact that the level lies just below the continuum and hence extremely difficult to feed in.

The next question is where carbon is synthesized? Or what happens if the carbon level were at another energy? would carbon still be formed? The answer is

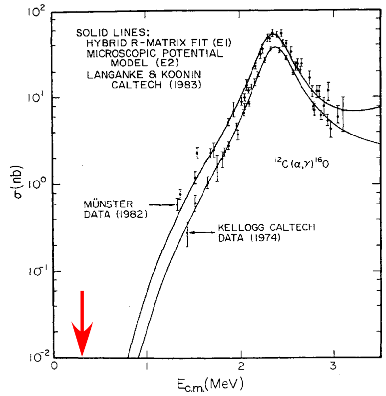

Figure 15: The measured capture probability (in units of nano-barns) by the Munster (1982) and the Kellogg(1974) laboratories. The arrow marks the energy range at which the reaction takes place in stars. The continuous lines are the theoretical fit by Langanke & Koonin 1983 and it includes the effect of the resonance.

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[1] The Crafoord Prize in astronomy and mathematics, biosciences, geosciences or polyarthritis research is awarded by the Royal Swedish Academy of Sciences annually according to a rotating scheme. The prize sum of SEK 4 million makes the Crafoord one of the worlds largest scientific prizes.

given in fig. 16 for low mass stars and fig. 17 for high mass stars. We see that 'moving' the level quite significantly changes the dominant stellar mass at which carbon is formed but not in a way that would required a revision of our ideas.

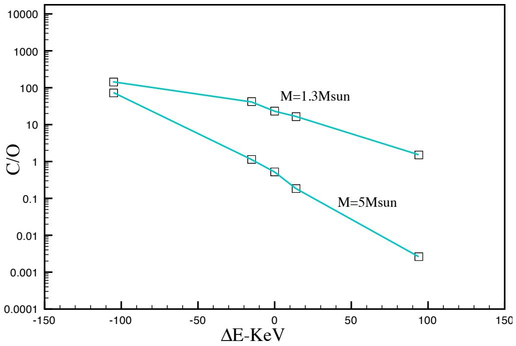

Figure 16: The C/O ratio obtained in the evolution of low mass stars ($1.3M_\odot$ and $5.0M_\odot$) upon a hypothetical change in the location of the resonance in ^{12}C.

We did not discuss the possible decay of the excited nucleus $^{12}C^*$ to 3α. We can, however, repeat Hoyle's argument and argue that the observations imply that this decay, though possible energetically and should take place, is very rare and hence neglected.

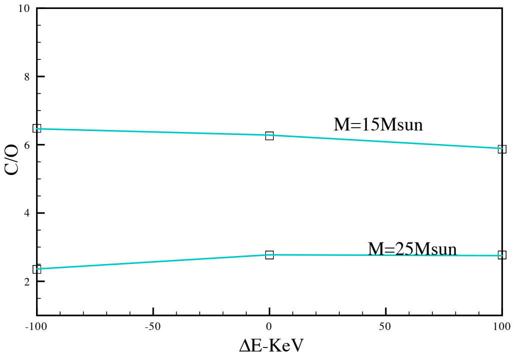

Figure 17: The C/O ratio obtained in the evolution of high mass stars ($15M_\odot$ and $25M_\odot$) upon a hypothetical change in the location of the resonance in ^{12}C.

13 In Retrospect

In 1985 Arnet and Thielemann questioned the logic of Hoyles original argument as the synthesized carbon may be fused into heavier nuclei or locked in WDs. Hence, we should re-think how carbon is synthesized and it is not clear that any remnant of the Anthropic Principle will prevail. However, Hoyle's reverse engineering methodology is right: If we see carbon in Nature, there should be a way to synthesize it!

Today, the principle has its own life and the origin which triggered it is mostly forgotten. In any case the old justification that lead to its inception is not that valid.

The story is told in more detail in Shaviv (2011).

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DISCUSSION

TZUMI HACHISU: Is the carbon-burning C/O ratio still uncertain?

GIORA SHAVIV: The reduced width of the ^{16}O level is still unknown and there are only guess on its value. Sp any C/O ratio between 1/4 - to -3/4 is to my mind plausible.

In 2002 Kunz et al. carried out an extensive theoretical analysis based primarily on Kunzs experimental PhD thesis. The result of Kunz et differs significantly from Caughlan & Fowler known tables at low temperature which are the relevant temperatures for quiet helium burning. However, it is not the last word on the subject.