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Physics in Perspective

# The History and Impact of the CNO Cycles in Nuclear Astrophysics

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The carbon cycle, or Bethe-Weizsäcker cycle, plays an important role in astrophysics as one of the most important energy sources for quiescent and explosive hydrogen burning in stars. This paper presents the intellectual and historical background of the idea of the correlation between stellar energy production and the synthesis of the chemical elements in stars on the example of this cycle. In particular, it addresses the contributions of Carl Friedrich von Weizsäcker and Hans Bethe, who provided the first predictions of the carbon cycle. Further, the experimental verification of the predicted process as it developed over the following decades is discussed, as well as the extension of the initial carbon cycle to the carbon-nitrogen-oxygen (CNO) multi-cycles and the hot CNO cycles. This development emerged from the detailed experimental studies of the associated nuclear reactions over more than seven decades. Finally, the impact of the experimental and theoretical results on our present understanding of hydrogen burning in different stellar environments is presented, as well as the impact on our understanding of the chemical evolution of our universe.

*Key words:* Carl Friedrich von Weizsäcker; Hans Bethe; Carbon cycle; CNO cycle.

## Introduction

The energy source of the sun and all other stars became a topic of great interests in the physics community in the second half of the nineteenth century. The theory of thermodynamics had been developed and looked for new applications and the question "what makes the stars burn" required a satisfying answer.[1] Chemical or combustion energy, such as burning coal, was quickly dismissed; meteoritic bombardment—which drove the heating of the early earth in the Hadean period—also was unsustainable. It would translate into a growing mass of the sun in contradiction of observation.[2] Also, the release of gravitational energy through a continuous contraction of the sun as proposed first by Herman von Helmholtz and William Thomson was not sufficient, since it required the sun to be rather young, in contradiction with geological research indicating an old earth.[3] In the beginning of the twentieth century, with the discovery of radioactivity, new ideas of

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subatomic sources of energy added to the discussion. As early as the late nineteenth century, the discovery of long-lived radioisotopes was seen as confirmation of a finite universe and as an indicator of a correlation between the macroscopic world of our universe and the microscopic world of atoms.[4] The observation of radioactive decay and the associated release of the decay heat led to speculations of our sun being a gigantic radioactive source.[5] Yet this thought was not generally accepted, in particular since no spectral lines from actinide elements could be discovered in the solar spectrum.[6] The problem remained present to such an extent that Niels Bohr started to formulate doubts about fundamental physical principles such as the conservation of energy in the subatomic world.[7] However, with the discovery of neutrons, the predictions of neutrinos, and the observation of nuclear reactions and the associated release of energy, the idea of radioactive decay as subatomic energy source was quickly replaced by the idea of nuclear reactions powering the sun. Predictions were handicapped by uncertainties in nuclear masses and only gradually the present interpretation of solar burning as a fusion process of four hydrogen nuclei to one helium nucleus emerged.

Still, there was debate until the 1950s on the primary source; the first one was the so-called *pp*-chains that are based on sequentially adding protons to proton in a reaction sequence that eventually produces helium. The second source was the CNO cycle, which is based on existing $^{12}C$ and $^{16}O$ catalyzing material facilitating the same fusion process by converting carbon to nitrogen and nitrogen to oxygen until finally emitting an alpha particle—a $^{4}He$ nucleus—returning back to its original carbon stage. In this paper, I present in more detail the history of the process leading to the discovery, formulation, and interpretation of the carbon-nitrogen-oxygen or short CNO cycle, which plays an important role for our sun and has a crucial role in our understanding of the energy generation in stars after the onset of nucleosynthesis with the first generation of stars.

Research was driven by the question of the origin of energy in our sun and the question for the origin of the elements in our universe. Arthur Eddington (1882–1944) summarized the early thinking about the source of stellar energy and the origin of the elements in a 1920 *Nature* article,[8] in which he dismissed the still widely accepted Helmholtz-Kelvin theory of the sun generating its energy by gradual gravitational contraction.[9] Eddington equated this theory's scientific relevance with the theory of Archbishop James Ussher (1581–1656) regarding the age of sun and earth.[10] This may have been harsh, since gravitational contraction is a major energy source in astrophysical environments, but Eddington was right to require another energy source for stars during their long phases of quiescent burning. For this he was encouraged by the discovery of radioactivity and more so by the observation by Francis William Aston (1877–1945) and Ernest Rutherford (1871–1937) at the Cavendish Laboratory, that the mass of a helium atom is less than the mass of four single hydrogen atoms. He wrote in his paper:

> Sir Ernest Rutherford has recently been breaking down the atoms of oxygen and nitrogen, driving out an isotope of helium from them; and what is possible in the Cavendish Laboratory may not be too difficult in the sun. I think that the suspicion has been generally entertained that the stars are the crucibles in which the lighter atoms, which abound in the nebulae are compounded into more complex elements. In the stars matter has its preliminary brewing to prepare the greater variety of elements which are needed for a world of life. The radioactive elements must have been formed at no very distant date; and their synthesis, unlike the generation of helium from hydrogen, is endothermic. If combinations requiring the addition of energy can occur in the stars, combinations which liberate energy ought not to be impossible.
>
> We need not bind ourselves to the formation of helium from hydrogen as the sole reaction which supplies the energy, although it would seem that the further stages in building up the elements involve much less liberation, and sometimes even absorption, of energy.[11]

Yet, these were speculations, which needed, as Eddington himself admitted in the same paper, detailed modeling of the actual energy generating processes, requiring validation by observation and experiment: "The time when speculative theory and observational research may profitably go hand in hand is when the possibilities, or at any rate the probabilities, can be narrowed down by experiment, and the theory can indicate the tests by which the remaining wrong paths may be blocked up one by one."[12]

A few years later, Robert Atkinson (1898–1982) and Fritz Houtermans (1903–1966) took the first steps toward a quantitative theory of how nuclear energy is released. In 1929 they offered the first quantitative estimate for energy production in stars through nuclear reactions with hydrogen.[13] In this effort, they largely relied on the theory of the young Russian scientist George Gamow (1904–1968), who had introduced quantum mechanics into the solar energy debate by demonstrating that charged particles could tunnel with a certain probability through the Coulomb barrier.[14] During a visit to Cavendish Laboratory, Gamow convinced Rutherford and his young student Ernest Walton (1903–1995) to test and confirm his predictions. Although this first contribution by Gamow was motivated by purely quantum mechanical considerations, it was the fundamental idea that provided the basis for the field of nuclear astrophysics as we see it today. This work was one of his many contributions to nuclear astrophysics, a field in which Gamow can be considered as source and catalyst for many of the most critical thoughts and developments. Robert d'Escourt Atkinson and Fritz Houtermans used this formalism to perform the first calculation of the tunneling probability of charged particles through the Coulomb barrier. The tunneling probability determined the reaction probability, which in turn allowed a first estimate of the strength, or the cross section, of nuclear reaction processes in stars.

This was a first quantitative result with respect to the strength of a nuclear reaction. The approach allowed for the identification of dominant reactions, the determination of reaction flux, and the associated energy release in a stellar environment. At this point, the young and ambitious German physicist Carl Friedrich von Weizsäcker (1912–2007) provided an important contribution to the field. He developed, in the early 1930s, a relatively simple formula for predicting the masses of nuclei. It was the so-called droplet model, in which the nucleus was described in terms of different components contributing to its binding energy. He observed a correlation between the predicted binding energies and the observed abundances in the solar system. He saw this as direct evidence for a nuclear mechanism underlying the formation of the elements: "The abundance distribution might be correlated with the reactions that drive the energy production."[15] He was especially interested the role of neutrons, which he saw, after their discovery in 1932, as the key to the formation of the heavy elements above iron and he concluded: "If it is possible to identify a sufficiently probable process that provides free neutrons, one might be able to apply the current knowledge of physics towards a theory of building the elements in the stars."[16]

These ideas were the result of intense conversations Weizsäcker had, between 1932 and 1936, during regular and sometimes extended visits to the Institute of Theoretical Physics in Copenhagen, led by Niels Bohr (1885–1962). One of Weizsäcker's main discussion partners was the young astronomer Bengt Strömgren (1908–1987), who worked at the Copenhagen Observatory with research focusing on the theoretical interpretation of the Hertzsprung-Russell diagram and on the spectral analysis of elements in stellar atmospheres.[17] Strömgren was also interested in the question of energy generation and element synthesis in stars and developed a comprehensive theory of the conditions inside the stars.[18] This theory caught the interest of Weizsäcker who immediately recognized the fundamental connection between stellar energy release and nuclear reactions and binding energies.

## Energy Production in Stars

Weizsäcker was motivated by his exchange with Strömgren in Copenhagen and encouraged by further discussions with the astronomer Ludwig Biermann (1907–1986) from the Berlin observatory. Biermann had received his PhD in 1932 in Göttingen with a work on "Convection Zones in the Interior of the Stars" and was interested in questions of stellar evolution and energy production. Based on these conversations, Weizsäcker developed a first concept for the reaction mechanism, which released the necessary energy within the stars by the transformation of light to heavier elements.[19] Again, these ideas were based on the assumption of predominantly hydrogen-containing stars, as propagated by Eddington and Strömgren, but Weizsäcker added a new thought that led far beyond the Atkinson and Houtermans original idea of the conversion of hydrogen to helium by successive reactions. This new aspect was the possibility of catalytic reactions. These are only possible with the existence of certain catalyst elements in the stellar matter. Weizsäcker first proposed the possibility of helium-4 ($^{4}$He) acting as a catalyst element in a cyclic process, which was based on the existence of $^{4}$He in stars and the assumption of the existence of particle stable $^{5}$Li and $^{5}$He isotopes. He suggested that the process was initiated by the proton capture, $^{4}$He + $^{1}$H → $^{5}$Li, followed by the decay of $^{5}$Li to $^{5}$He. A second proton capture $^{5}$He + $^{1}$H → $^{4}$He + $^{2}$H would generate a deuterium $^{2}$H isotope, while leaving the initial $^{4}$He catalyst element. Free neutrons can be generated via the subsequent deuterium fusion $^{2}$H + $^{2}$H → $^{3}$He + $n$, which are then available, adding fresh $^{4}$He through a neutron-capture reaction $^{3}$He + $n$ → $^{4}$He and even more so, would provide the fuel for building the heavier elements beyond iron. The propagated cycle is initiated by proton capture at helium via which $^{5}$Li is generated, the mass of which was not known in 1937. However, it soon became known that $^{5}$Li is highly unstable and immediately disintegrates into the proton and alpha ($^{4}$He) channel, rather than decay to and equally unstable particle unstable $^{5}$He. This makes the process impossible, but the new idea of having elements acting as catalyst in cyclic nuclear processes was born.

### *Weizsäcker and the Carbon Cycle*

Only eighteen months later, in 1938, Weizsäcker published a second essay in which he largely rejected his previous hypothesis on the origin of heavy elements.[20] He seems to have already come to his new view during the winter of 1937–1938. In January 1938, he was the only physicist to attend a colloquium in Göttingen to discuss the chemical composition and structure of the stars. According to Hans Haffner (1912–1977), Weizsäcker had started to question the direct correlation of energy production and the development of the heavy elements during a workshop in Göttingen in winter 1938.[21] As a consequence, he had abandoned the question of element synthesis and focused on questions of energy generation. His ideas were also influenced by a visit with Gamow in the spring of 1938. Gamow had participated in the conference in Warsaw on “New Theories in Physics” and took the opportunity to visit his friend and colleague Weizsäcker in Berlin to discuss the latest physics developments.[22] Gamow told Weizsäcker about the new results and discussions in the United States, in particular about the Fourth Annual Conference on Theoretical Physics, which he had organized earlier that year to address questions about “Problems of Stellar Energy Sources.” At that conference, Strömgren had presented Weizsäcker’s work, but the claim of a possible long-lived $^{5}$Li and $^{5}$He nucleus was rejected by the community.[23] In subsequent, more detailed work in May 1938, Gamow also discussed the difficulties with the structural hypothesis in the production of natural heavy radioactive elements such as uranium and thorium.[24] This would require a considerably higher neutron flux than was provided by the Weizsäcker mechanism.

These questions were probably the main topic of the conversations between Gamow and Weizsäcker in Berlin and might have had a great influence on the content and direction of the second article.[25] In this paper, Weizsäcker himself points to new results that could not be explained within the framework of his original hypothesis. The first section of the article presents the arguments against his originally proposed idea, the second part concentrates on the question of the possible energy sources of stars. Weizsäcker pointed to the still unpublished work of Hans Bethe (1906–2005) on *pp* chains,[26] which Gamow had told him about, and then proceeded with the observation that other higher-mass elements exist in the interior of the star, which could facilitate alternative energy sources. He postulated carbon $^{12}$C as the most stable element in the mass range and proposed a reaction cycle of four proton capture reactions and two positron decays that would facilitate a catalytic fusion of four hydrogen nuclei to a helium nucleus:[27]

$$^{12}\mathrm{C} + {}^{1}\mathrm{H} \rightarrow {}^{13}\mathrm{N}, {}^{13}\mathrm{N} \rightarrow {}^{13}\mathrm{C} + \beta^{+}, {}^{13}\mathrm{C} + {}^{1}\mathrm{H} \rightarrow {}^{14}\mathrm{N},$$
$$^{14}\mathrm{N} + {}^{1}\mathrm{H} \rightarrow {}^{15}\mathrm{O}, {}^{15}\mathrm{O} \rightarrow {}^{15}\mathrm{N} + \beta^{+}, {}^{15}\mathrm{N} + {}^{1}\mathrm{H} \rightarrow {}^{12}\mathrm{C} + {}^{4}\mathrm{He}.$$

Each reaction takes place on the residues of the previous one. He also postulated the possibility of further cycles: “If the abundance of the carbon is eventually reduced by secondary reactions, an analogous oxygen cycle becomes available.”[28] In a footnote to the same article, Weizsäcker points out: “I learned from Mr. Gamow that Bethe recently has investigated the same cycle quantitatively.” He also notes that main sequence stars may already be “tuned to the carbon cycle,” referring again to the conversations with Gamow. [29]

These arguments clearly demonstrate that Weizsäcker recognized the importance of the carbon cycle at an early stage, but also indicate that he may not have come to this conclusion completely independently. The scientific exchange and discussions with Gamow on his visit to Berlin caused Weizsäcker to reconsider his initial idea and motivated him to accept the new hypothesis of the carbon cycle as an alternative catalytic process for stellar energy generation. Gamow served, so to speak, as a catalyst for the emergence of the new scientific idea. On the one hand, Gamow presented the ideas of Weizsäcker at the Washington conference and, on the other hand, he introduced the expanded concept of the carbon cycle by Bethe in Berlin. Weizsäcker's great contribution was to provide the first idea and qualitative formulation of element synthesis and the role of catalytic reactions in the framework of his *Aufbautheorie* (synthesis theory).[30]

Weizsäcker's work of 1938 was the last contribution he made in the field of nuclear astrophysics. He did not follow up with formulating the mathematical details necessary for a qualitative analysis of the carbon cycle, instead turning his attention to the question of planet formation as well as to the question of nuclear fission.[31] Later, as a member of the German Uranium Club, his interest focused on the question of energy production and possibly on the design of a German fission bomb.[32] Meanwhile, Bethe pursued the question of stellar energy production on the other side of the Atlantic, and delivered within a year the first quantitative analysis of the nuclear reaction processes taking place in the stars.

### *Bethe and the Carbon Cycle*

In order to understand Bethe's role in the formulation of the carbon cycle, one must take a closer look at the aforementioned 1938 Washington conference. The conference series had been organized by Gamow following the example of the conferences at the Bohr Institute in Copenhagen. It aimed at bringing together selected experts from various disciplines to discuss a common topic of interest. The fourth conference was devoted to the topic of energy generation in stars, and for this purpose Gamow had invited a number of illustrious scientists from the fields of nuclear physics, astronomy, and astrophysics. Thirty-four participants came to the meeting. Subrahmanyan Chandrasekhar (1910–1995) from the University of Chicago represented theoretical astrophysics. In his book, *An Introduction to the Study of Stellar Structure*, published for the first time in 1939, Chandrasekhar described Weizsäcker's *Aufbautheorie* in detail.[33] Strömgren was also present. In 1937, Strömgren had accepted a position at the Yerkes Observatory of the University of Chicago,[34] and he presented his ideas on stellar evolution and element synthesis that he had developed in Copenhagen. Among the nuclear physicists was Edward Teller (1908–2003), who in 1935 was appointed to George Washington University at the instigation of his friend Gamow.[35] Gamow placed particular emphasis on the participation of Bethe from Cornell University, who, despite his young years, was regarded as one of the most promising nuclear physics theorists of his time. In 1937, Bethe had published a comprehensive article on the theory of nuclear reactions in *Reviews of Modern Physics*, which provided the theoretical basis for the role of nuclear physics processes in stars (figure 1).[36]

Initially Bethe was not particularly interested in the question of energy generation in stars. He had participated in the previous meeting but refused to attend the meeting scheduled for 1938 because the topic appeared vague and far-fetched, but, with Gamow being a persuasive and insistent man, Bethe finally agreed.[37] Gamow himself later mocked Bethe in his autobiography, saying of Bethe that he, "on his arrival knew nothing about the interior of stars but everything about the interior of the nucleus."[38] This changed, however, with his participation in the conference, at which Bethe recognized the problem of stellar energy production as a nuclear physics problem. Inspired by the Weizsäcker idea of the catalytic and cyclic reactions that Gamow presented, he spontaneously presented a contribution by suggesting the carbon cycle as an alternative source of solar energy.[39]

Immediately after his departure by train back home to Cornell, Bethe began to convert the idea into a quantitative calculation of energy production in the carbon cycle. Gamow portrayed this episode in his popular science book on the development of the Sun in 1940: "But it should not be so difficult after all to

**Fig. 1.** Participants at the 1938 Washington Conference on *The Origin of the Elements*. Notable participants were George Gamow as organizer (front row fourth from left), Hans Bethe (left behind Gamow), Edward Teller, who was not particularly interested but was a local participant (center), Bengt Strömgren (last row, third from right), and the young Subrahmanyan Chandrasekhar (front row, second from right). With permission of the Donald E. Osterbrock Papers, UCSC Special Collection and Archives, The University Library, University of California, Santa Cruz

find the reaction which could just fit our old sun, thought Dr. Hans Bethe, returning home by train to Cornell from the Washington Conference on Theoretical Physics of 1938, at which he first learned about the importance of nuclear reactions for the production of solar energy; I must surely be able to figure it out before dinner!... And he had the correct answer at the very moment when the passing dining-car steward announced the first call for dinner."[40] Bethe himself was a bit more prosaic in his description of the situation: "I did not, contrary to legend, figure out the carbon cycle on the train home from Washington. I did, however, start thinking about energy production in massive stars upon my return to Ithaca."[41]

Indeed, in the following weeks, Bethe developed the quantitative concept of the carbon cycle shown in figure 2, after a representation in Gamow's 1940 book *The Birth and Death of the Sun*. Bethe estimated the cross sections of the nuclear reactions and determined the released energy based on the mass differences of the participating nuclei. This led him to a first estimate of the energy production rate seemingly in agreement with solar energy production. Bethe also worked with Charles Critchfield (1910–1994), a former student of Gamow and Teller, on calculating the energy production in light fusion processes suggested by

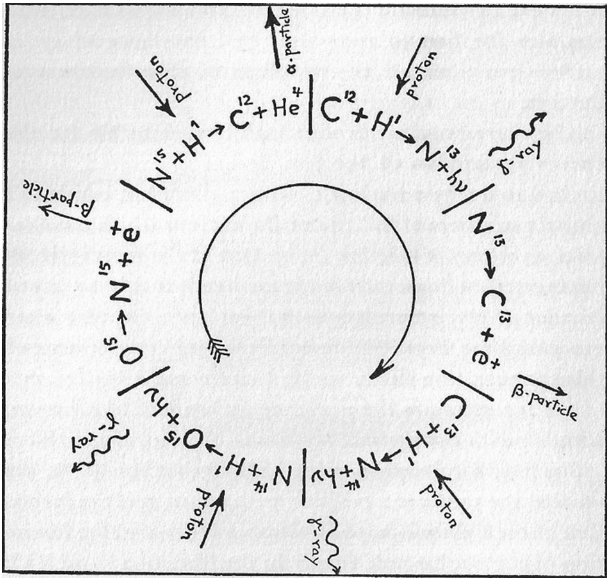


**Fig. 2.** The carbon cycle as presented by George Gamow. It displays a series of proton captures, starting on $^{12}$C located in the top, intersected by two $\beta$-decays of $^{13}$N and $^{15}$O, located at the right and left and side of the circle. The cycle is closed with the proton capture on $^{15}$N and the emission of one $^{4}$He nucleus from the $\alpha$-unbound excited compound state of $^{16}$O. Source: George Gamow, *The Birth and Death of the Sun* 1940, with permission of the Estate of George Gamow

Weizsäcker in his first article, such as the $p + p \rightarrow d + e + (\nu)$ reaction.[42] The probability for this weak interaction process, as estimated using the Fermi theory of weak interaction, is twenty-five orders of magnitudes smaller than the probability nuclear reactions based on the strong force. Bethe submitted both papers in the same year to *Physical Review* for publication. However, only the work on the *pp* chains was published because shortly afterwards Bethe withdrew his manuscript on the carbon cycle.[43] He later gave as reason that the subject was sufficiently interesting to get a prize from the New York Academy of Science for the best work on energy production in stars and he held back to get a scholarship for his student Robert Marshak (1916–1992).[44] After this was accomplished, he again submitted the work to *Physical Review* in September 1938, but it was only published in 1939.[45] This left Weizsäcker's paper as the first in the literature to refer to the carbon cycle, but Bethe received in 1967 the Nobel Prize in Physics for the work on the theory of nuclear reactions and their contributions to stellar energy generation, in particular the carbon cycle.

In his paper, Bethe provided a comprehensive quantitative analysis of all possible nuclear reactions that might take place inside stars. He rejected most of them because they led to the rapid degradation of the involved isotopes and therefore could not be a long-term source of energy. Only the reaction sequence initiated by the $p + p$ fusion, finally resulting in the formation of $^{4}$He, the so-called *pp* chains, as well as the carbon cycle, were able to generate the necessary energy production rate corresponding to the stellar luminosity. Bethe compared the energy production of both reaction mechanisms for various temperature conditions in the stellar interior and showed for the first time that the energy production of the stars at low temperature would be dominated by the *pp* chains and at higher temperatures by the carbon cycle. The point of intersection of the two energy production rates was in the range of the temperature expected from the interior of the sun, but the uncertainties in the estimated reaction rates made it impossible to determine which sequence served as the dominant solar energy source.

This question remained open for the time being because Bethe was appointed in 1941 as director of the theory department at the Manhattan Project in Los Alamos, thus turning his attention toward the possible application of nuclear fission in a nuclear bomb, like his German colleague Weizsäcker. The final answer to the question of stellar energy generation in the sun had to wait and was only delivered in the following decade, by experiment.

## Nuclear Physics of Stellar Reaction Sequences

The following will focus on the nuclear physics aspects of energy generation and the associated synthesis of the light elements. This development was complemented by ideas on stellar structure and stellar evolution, to these ideas and developments we refer the reader to some recent reviews summarizing these issues.[46] Before proceeding with the discussion of the historical developments on the carbon cycle and its significance for the astrophysics of the late twentieth century, the following section will present some aspects of sequential and cyclic reaction sequences and the underlying nuclear physics parameters that are critical for evaluating the reaction rates associated with these processes. These considerations are important for evaluating and comparing the role of the *pp*-chain and CNO cycles in stellar burning environments.

### *The pp Chains*

The fusion of two protons to deuterium is the initial reaction of the *pp* chains. In this process, a proton must be converted into a neutron. This process is based on the weak interaction and thus more than twenty orders of magnitude less likely to occur than reactions based on the strong interaction. For this reason, many of the leading physicists at the time, such as Gamow and Teller, did not believe that such a reaction could have a great influence. Also, the initial estimates by Bethe gave a significantly lower value for the reaction rate than is adopted today.[47]

Initially, the question of the subsequent reactions was not clear, since deuterium (D) could be further processed by a series of fusion reactions, or again broken down into a proton and a neutron because of its low binding energy. Energetically possible were a series of reactions: $D + p \rightarrow {}^{3}He + \gamma$; $D + p \rightarrow 2p + n$; $D + D \rightarrow {}^{3}He + n$; $D + D \rightarrow {}^{3}H + p$; $D + D \rightarrow {}^{4}He + \gamma$.[48] The question was, which of these reactions was the most probable? Only direct measurements of the different reaction channels could provide a reliable answer. It was not until 1952 that the student and young colleague of Bethe at Cornell University, Edwin (Ed) Salpeter (1924–2008) delivered the solution in two publications. He recalculated the $p + p$ fusion reaction, based on a new determination of the coupling constant taking into account a series of measurements on deuterium and helium-3. He formulated the concept of the *pp* chains, which convert four hydrogen nuclei via a sequence of light fusion and capture reactions to helium-4, releasing the binding energy of 26.7 MeV: $p + p \rightarrow D + \gamma$; $D + p \rightarrow {}^{3}He + \gamma$; and ${}^{3}He + {}^{3}He \rightarrow {}^{4}He + 2p$.[49] The most important result of this work was that the calculated reaction rate for the $p + p$ fusion was an order of magnitude higher than the original value estimated by Bethe and Critchfield, a result that identified the *pp* chains as the dominant energy source of low-mass stars such as our sun.[50]

## *The Carbon Cycle*

The function of the carbon cycle as a catalytic energy source depends on several conditions. First, the cycle must be capable of fusing four hydrogen nuclei into a helium nucleus. In this case, energy must be released that corresponds to the difference in mass between the initial nuclei and the final product. This energy release must be sufficient to contribute significantly to the stabilization of the star in the hydrogen-burning phase. Second, the individual reactions in the sequence must to be exothermic, that is they release and cannot consume energy during the reaction sequence, since the typical temperatures in the interior of the star are not sufficient to allow for endothermic reactions to occur. Third, the reactions must be sufficiently fast to allow continuous energy production over the typical lifetime of a star. The first two conditions were ensured, as predicted on the basis of the Weizsäcker mass model and confirmed by the direct mass measurements of the various nuclei involved.

The question now posed was the strength or probability of the different reactions in the stellar environment, the so-called reaction rate. This depends on the abundance and the energy distribution of the interaction nuclei as well as the reaction cross section. The reaction rate is inversely proportional to the time scale of the reaction process and determines the processing time of the cycle. The energy distribution of particles in a stellar burning environment is well described by a classical Maxwell-Boltzmann distribution, the elemental abundances are obtained by astronomical observation and stellar models, and the reaction cross sections depend on the quantum mechanics of the interaction probabilities. The formalism for the study of the different reaction components and mechanisms had already been developed by Bethe in a series of fundamental works on the dynamics of nuclear processes.[51] For reactions with charged particles, the Gamow tunnel effect through the Coulomb barrier played an essential role. The tunneling probability decreases exponentially with the energy, which leads to an extreme energy dependence of the cross section, which in turn is translated into an exponential dependence of the reaction rate on the temperature in the interior of stars. These theoretical ideas provided Bethe with the tools for estimating the reaction rates associated with the carbon cycle. The methodologies were, however, still very imprecise and the data on the various reaction contributions were too uncertain to allow for the calculation of the different reaction rates reliably. This can be seen, for example, in the comparison between the strengths of so-called $(p,\gamma)$ radiative capture reactions, where a proton is captured through electromagnetic interaction by a nucleus emitting $\gamma$ radiation and particle transfer reactions such as $(p,\alpha)$, where a proton is captured through strong interaction and an $\alpha$ particle is ejected from the newly formed nucleus. Bethe considered the latter to be a million times stronger than the electromagnetic counterpart. Today it is known that the difference ranges only between two to four orders of magnitude, depending on the details of the nuclear structure (Figure 3).

With regard to individual cross sections in the carbon cycle, these are determined by different reaction components. The first component is the so-called *direct capture process*, which decreases exponentially with energy. It depends on the quantum-mechanical probability in which a proton tunneling through the Coulomb barrier of a nucleus is captured by the nucleus with energy emission in the form of $\gamma$ radiation. The second component is a two-step process, the so-called *compound reaction* mechanism, in which an excited state in the intermediate or compound nucleus is populated and subsequently decays into another nuclear configuration. If such a state exists in the stellar energy range, the probability of the reaction may increase by many orders of magnitude depending on the specific structure of the state. This effect appears as resonance in the reaction cross section. Most of the reactions in the carbon cycle are determined by resonances. However, the characteristic properties of these resonances are difficult to calculate, and provide a further factor of uncertainty in the estimation of the overall cross section. The theoretical estimates therefore had to be tested in the nuclear physics experiment.

## Experimental Efforts

In 1940 Bethe published a comprehensive summary of the question of stellar energy generation in the *Astrophysical Journal* in which he presented the latest developments summarizing a series of recent experimental results.[52] For the first time, the cross sections of possible nuclear processes in stars were investigated experimentally in order to verify the predictions that were mostly based on the Gamow estimate of the tunneling probability of charged particles through the

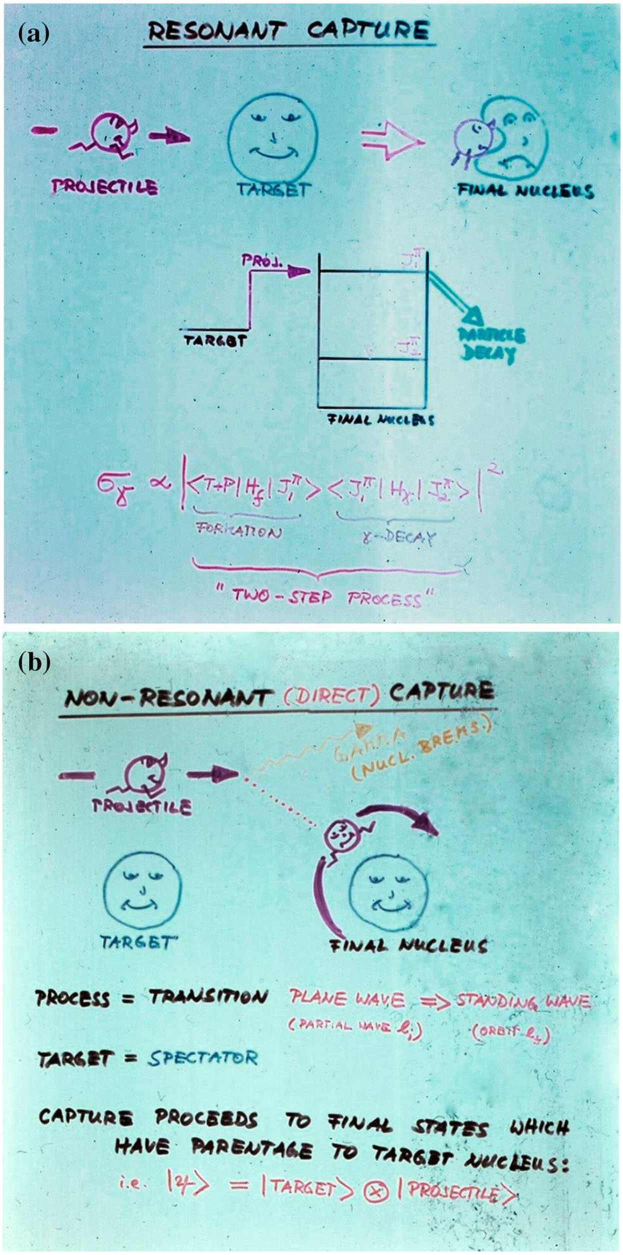


**Fig. 3.** Cartoon-style presentation of direct capture and resonance process by Claus Rolfs, following the concept of George Gamow in trying to visualize complex one step (direct) and two-step (compound) quantum mechanical reaction processes to students and the public. Source: Slide collection of the author

Coulomb barrier. For these measurements, accelerators were needed to bring the charged particles to the necessary energy and thereby initiate the reactions, so that the reaction products could be measured. From the number of the reaction products or the intensity of the emitted radiation, the cross section can be directly calculated. This kind of experiment requires, however, considerable effort in the development of accelerators and detectors.

*The First Experiments*

Accelerators were developed in the late 1920s and played an important role in the early development of nuclear physics, especially in the 1930s. The two most important types were the cyclotron developed by Ernest Lawrence (1901–1958) in Berkeley, and the electrostatic machine, patented by Robert J. van de Graaff (1901–1967) in Princeton and later built at MIT. This type of machine is traditionally named after him, the "Van de Graaff accelerator."[53] Stan Livingston (1905–1986) built a cyclotron at Cornell University in 1938 to test the predictions of Bethe. Bethe himself participated in this work.[54] Experiments were also carried out on the famous accelerator of Raymond Herb (1908–1996),[55] which had been built in 1935 at the University of Wisconsin. Tom Lauritsen (1915–1973) designed an electrostatic machine based on the Van de Graaff principle,[56] which allowed nuclear reactions to be measured over a wide energy range between 100 keV and 2 MeV. With the development of this machine, the focus of experimental activities shifted to the California Institute of Technology (Caltech).[57] Figure 4 shows the schematic structure of the Caltech accelerator. Charles Lauritsen (1892–1968) and his brother Tom Lauritsen together with the young William Fowler (1911–1995) took up the idea of the carbon cycle and started to systematically investigate all of the associated reactions—a project that was interrupted by the entry of the United States into World War II and the participation of the experimental nuclear physicists in the Manhattan project.[58] It was only in the late 1940s that the work of the Kellogg Laboratory was revived. The mathematical formalism used for extracting the reaction cross sections from the experimental data is described in an article by Fowler, Charles Lauritsen, and Tom Lauritsen (1948), which is still worthwhile reading.[59] The work describes in detail the detectors and techniques with which different types of radiation could be detected, which was of particular importance for the measurement of the reactions of the carbon cycle. Many of these techniques did not exist before the war and had only been developed during the Manhattan Project.[60]

The new experimental effort produced a flood of data and results on the different reactions and cross sections of the carbon cycle. Based on these results, the reaction rate predictions had to be revised frequently, sometimes by several orders of magnitude. In 1953 Fowler gave a first summary account of the state of the experiments and the effect of the experimental results on the role of the carbon cycle in stellar burning at the fifth Liège conference on "Les Processus

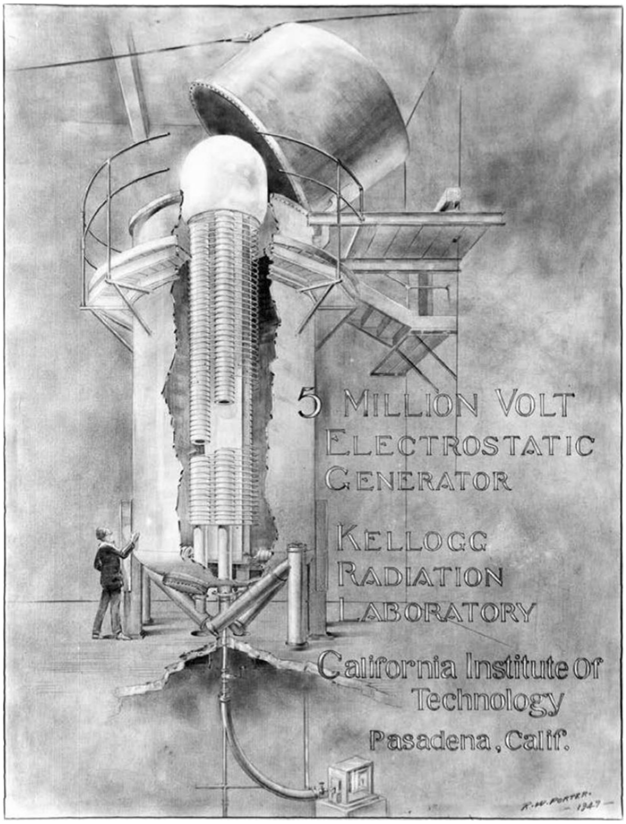


**Fig. 4.** Original design drawing of the electrostatic accelerator at the Kellogg Institute for Radiation Physics at Caltech in Pasadena, California. This machine was used for the first systematic study of the nuclear reactions in the carbon cycle. Source: Drawing by Russell Williams Porter (1871–1949) in 1947, reproduced with permission of the Caltech Archives

Nucléaires dans les Astres."[61] The results showed that wide resonances dominate most of the nuclear reactions involved in the carbon cycle, which are therefore mostly characterized by large reaction rates over which the cycle can proceed relatively quickly. This underlined the importance of the carbon cycle as an important energy source in hydrogen burning stars. In particular, Fowler highlighted the importance of the $^{14}N(p,\gamma)^{15}O$ capture reaction as the slowest reaction in the cycle. This radiative capture process therefore determines the time scale and the energy generation rate for the cycle. A year later, in 1955, Fowler, together with the astronomer couple Margaret Burbidge (b. 1919) and George Burbidge (1925–2010), published the latest results in the *Astrophysical Journal* and placed them within the framework of observed element abundances in stars.[62] This work went well beyond the carbon cycle, and it also postulated a series of nuclear reactions that could lead to the formation of the heavy elements by alpha- and neutron-capture reactions.[63] Only one year later (1956), the author team published a review article, together with the British astrophysicist Fred Hoyle (1915–2001), which is the first comprehensive presentation of the theory of element synthesis in our universe.[64] The article is often referred to as B2FH in specialist literature. It is still regarded today as a standard work of the literature.[65] Based on the results published there, Willi Fowler received the Nobel Prize for Physics in 1983.

### *CNO Experiments from the 1970s to the Present*

Based on early experiments, it became obvious that the *pp* chains were indeed the dominant energy source in the sun. It was also shown, by these first experiments studying proton capture on carbon and nitrogen isotopes, that the early predictions of reaction rates had to be changed as shown in figure 5.[66] In particular, the results on $^{15}N(p,\alpha)^{12}C$ demonstrated that this reaction was much stronger than previously predicted by Bethe. Consequently, the branching ratio was such that about one thousandth of the original $^{12}C$ carbon amount was converted to $^{16}O$. Fowler argued that this would not have a major impact on energy production, since the material lost from the so-called CN cycle was processed back into the same cycle by an ON reaction sequence: $^{16}O + p \rightarrow {}^{17}F$; $^{17}F \rightarrow 17O + \beta^{+}$; $^{17}O + {}^{1}H \rightarrow {}^{14}N + {}^{4}He$. This means that hydrogen burning would not be characterized by just a single cycle, but a bi-cycle, the so-called CNO cycle. The significance is that beside $^{12}C$, the presence of $^{16}O$ in the interior of the star could be an additional source of energy. Salpeter argued at the same time for a considerably extended cycle structure. This so-called NeNa cycle should be similar in structure to the carbon cycle, but based on the catalyst elements neon and sodium.[67]

In the 1970s, new detectors were developed based on the semiconductor element germanium, which yielded a considerably improved resolution in the measurement of $\gamma$ radiation. A new generation of young experimenters around Claus Rolfs (b. 1941) used these possibilities to systematically expand on the previously incomplete measurements of the reactions that characterized the postulated cycles. It was shown that the $^{16}O(p,\gamma)^{17}F$ reaction was extremely slow compared to the other capture reactions since it was primarily based on a non-resonant cross section.[68] This means that the energy contribution by the NO cycle is limited and CNO burning has a relatively small effect on the abundance of the $^{16}O$. The $^{17}O(p,\alpha)^{14}N$ reaction on the other hand is determined by numerous resonances, which cause a fast $^{17}O$ processing and a low equilibrium abundance. Rolfs and William S. Rodney (1926–2007) showed in 1973 that the $^{17}O(p,\gamma)^{18}F$ trapping reaction has a comparable cross section and thus opens a third cycle: $^{17}O + p \rightarrow {}^{18}F{+}\gamma$; $^{18}F \rightarrow {}^{18}O + \beta^{+}$; $^{18}O + {}^{1}H \rightarrow {}^{15}N + {}^{4}He$,[69] which again feeds into the first cycle.[70] In further experiments the possibility of a fourth cycle ($^{18}O + p \rightarrow {}^{19}F$; $^{19}F + {}^{1}H \rightarrow {}^{16}O + {}^{4}He$[71]) was shown, which in turn feeds material into the second cycle.[72] Figure 6 shows schematically the reaction

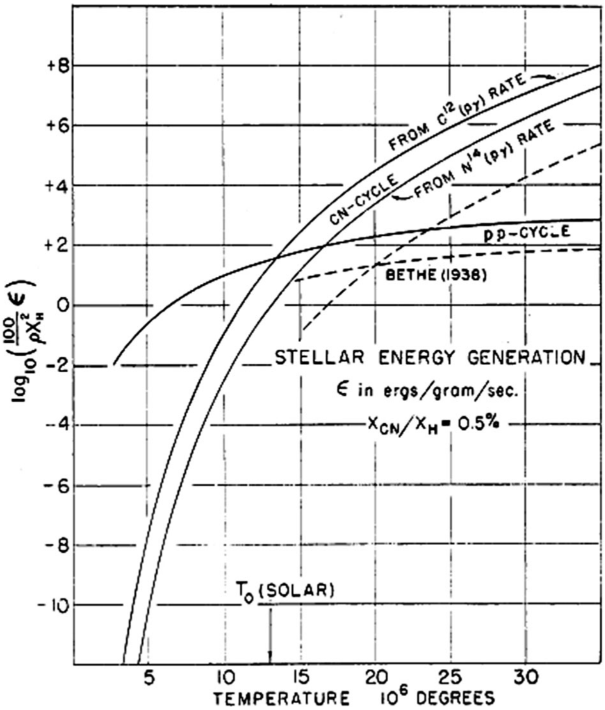


**Fig. 5.** The reaction rates of the *pp* chains and the carbon cycle as a function of temperature in the stars, as originally predicted by Bethe in 1939 and recalculated by Fowler in 1954 on the basis of new experimental information. The experimental increase of the rates with the temperature is determined by the tunnel probability through the Coulomb barrier. The change in the strength of the rates is due to the more accurate determination of the weak interaction in the *pp* chains and the electromagnetic interaction in the reactions of the carbon cycle. Source: Fowler, ''Nuclear Reactions in Stars'' (ref. 61). With permission from Société Royale des Sciences de Liège

sequence of these cycles. This experimentally confirmed multi-cycle structure influences, in particular the abundance evolution of the various C, N, and O isotopes in stellar hydrogen burning, which can have a considerable influence on the reaction sequences in subsequent helium and carbon burning phases.[73]

Already at an early stage, Hoyle and Fowler postulated an extension of the carbon cycle by considering the previously neglected possibility of proton capture at the radioactive isotope $^{13}$N.[74] The idea was that this could provide a possible energy source for supernovae, a thought that was quickly rejected. Instead, it was suggested that this reaction may open a new energy source for novae.[75] The reaction sequence (in modern terminology)*:

* The modern terminology for nuclear reactions follows the scheme A(*a*,*b*)B, with A being the target nucleus, *a* the projectile, *b* the reaction product, and B the nuclear recoil nucleus.

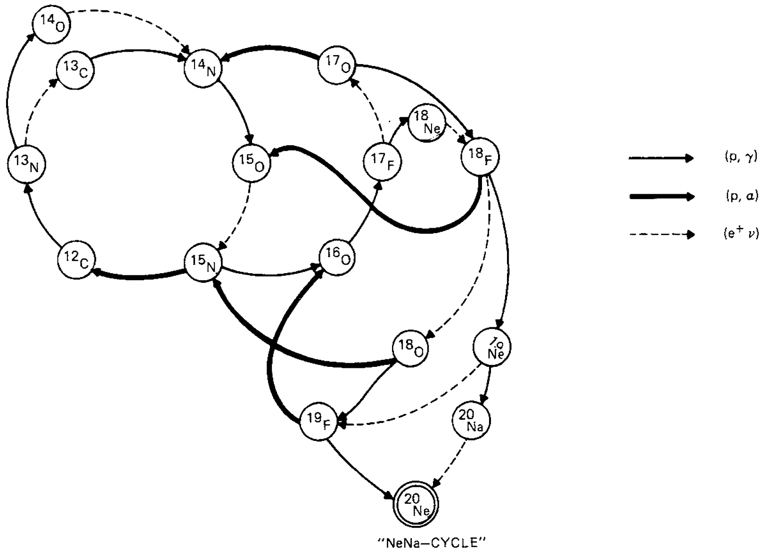


**Fig. 6.** Schematic representation of CNO multicycles including the NeNa cycle. The strength of the lines symbolizes the strength of reaction flows. Source: Figure collection of the author

$$^{12}\mathrm{C}(p,\gamma)^{13}\mathrm{N}\left(\beta^{+}\nu\right)^{13}\mathrm{C}(p,\gamma)^{14}\mathrm{N}(p,\gamma)^{15}\mathrm{O}\left(\beta^{+}\nu\right)^{15}\mathrm{N}(p,\alpha)^{12}\mathrm{C},$$

changes to the sequence

$$^{12}\mathrm{C}(p,\gamma)^{13}\mathrm{N}(p,\gamma)^{14}O\left(\beta^{+}\nu\right)^{14}\mathrm{N}(p,\gamma)^{15}O\left(\beta^{+}\nu\right)^{15}\mathrm{N}(p,\alpha)^{12}C,$$

the so-called hot carbon cycle. This change, which may appear minor for the layman, had enormous consequences for both theoretical astrophysics and experimental nuclear astrophysics. The classical carbon cycle was determined mainly by the rates of the different capture reactions, in particular the slowest reaction $^{14}\mathrm{N}(p,\gamma)^{15}\mathrm{O}$, and thus extremely dependent on the temperature in the stellar burning zone. The rates of the capture reactions also determined the time scale of the cycle and thus the energy generation rate. In the hot carbon cycle, however, the reaction rates were faster than the temperature-independent $\beta$ decay rates. Since the fluorine isotopes $^{15}\mathrm{F}$ and $^{16}\mathrm{F}$ were particle-unbound, that is, immediately disintegrated into an oxygen isotope $^{14}\mathrm{O}$ or $^{15}\mathrm{O}$ and a proton, the two reactions $^{14}\mathrm{O}(p,\gamma)^{15}\mathrm{F}$ and $^{15}\mathrm{O}(p,\gamma)^{16}\mathrm{F}$ are not allowed. The time scale of the cycle is determined only by the lifetimes of these two isotopes. For this reason, the hot CNO cycle is often called the $\beta$-limited CNO cycle, since the energy production rate is temperature-independent and corresponds to about 27 MeV/min.

Similar phenomena characterize other sections of the cycles.[76] When the $^{17}\mathrm{F}(p,\gamma)^{18}\mathrm{Ne}$ reaction becomes faster than the $^{17}\mathrm{F}$ $\beta$ decay, the time scale of the

NO cycle is correlated with the lifetime of $^{18}$Ne. Likewise, when the rate of proton induced reactions with the radioactive $^{18}$F becomes faster than the $\beta$ decay, the possibility of two extended reaction sequences becomes possible: a cyclic hot CNO configuration

$$^{16}\mathrm{O}(p,\gamma)^{17}\mathrm{F}(p,\gamma)^{18}\mathrm{Ne}\left(\beta^{+}\nu\right)^{18}\mathrm{F}(p,\alpha)^{15}\mathrm{O},$$

and a linear sequence of proton capture reactions

$$^{16}\mathrm{O}(p,\gamma)^{17}\mathrm{F}(p,\gamma)^{18}\mathrm{Ne}\left(\beta^{+}\nu\right)^{18}\mathrm{F}(p,\gamma)^{19}\mathrm{Ne}(p,\gamma)^{20}\mathrm{Na}.$$

The latter sequence would be an outbreak of the C, N, and O region because there is no energetically permitted ($p$,$\alpha$) reaction for processing material back from the Ne, Na into the C, N, O region. Further break-out reactions by proton capture are not possible. The remaining possibilities are alpha-capture reactions on the $^{15}$O- and $^{18}$Ne-isotopes enriched in the hot CNO-burning, which are converted into short-lived sodium ions via the $^{15}\mathrm{O}(\alpha,\gamma)^{19}\mathrm{Ne}(p,\gamma)^{20}\mathrm{Na}$ and $^{18}\mathrm{Ne}(\alpha,p)^{21}\mathrm{Na}$ isotopes.[77]

The discussion about the hot CNO mechanisms opened a new chapter for the community of experimental nuclear astrophysicists. Although the experiments had so far concentrated largely on gradually improving the measurement of reactions on stable CNO isotopes, the verification and quantification of reactions associated with the hot CNO cycle required the development of experiments with short-lived particles: this was the birth of nuclear physics with radioactive beams.

## The Role of the CNO Cycles in Astrophysics

The carbon cycle in its various configurations plays an enormous role in a number of stellar scenarios. With respect to our sun, the contribution of the carbon cycle to its energy production is about 3%. Although this has a very small impact on the solar energy budget, it offers the new possibility of investigating the metallicity of the solar interior, independently of solar model parameters.[78]

The experiment-based reaction rates also show that for stellar masses above one-and-a-half solar masses, the carbon cycle starts to dominate the energy production in main-sequence stars. Since the energy generation rate depends directly on the CNO reactions, such as $^{14}\mathrm{N}(p,\gamma)^{15}\mathrm{O}$, this has a considerable influence on the lifespan of these stars and can thus be used directly for the age determination of stellar clusters.

On the other hand, the phenomenon of novae is determined by explosive burning of the hot carbon cycle. Accurate knowledge of these nuclear reactions can be implemented directly in calculating information about ignition conditions and explosion periods of novae.

Further, the outbreak of the hot CNO cycles determines the ignition of many other cataclysmic events, namely those of the X-ray bursts discovered in the 1970s, which are now regarded as one of the most energetic types of hydrogen explosion in the universe. In the following, these four scenarios are discussed in greater detail in order to clarify the far-reaching significance of the carbon cycle in astrophysics today. A more comprehensive summary, with more detailed literature information, can be found elsewhere.[79]

*The Carbon Cycle in the Sun and the Solar Metallicity*

In their first estimates of solar energy production through the *pp* chains, Bethe and Critchfield,[80] as well as Salpeter,[81] neglected the influence of the neutrinos, as quasi-massless particles. The predictions for the interaction probability of neutrinos with matter are extremely small. Therefore, neutrinos can freely escape from the sun's interior. In addition to the $^3$He + $^3$He fusion forming $^4$He in the *pp* chains, two other reaction branches exist that are triggered by the fusion process:

$$^3\mathrm{He}\ +^4\mathrm{He}\ \rightarrow^7\mathrm{Be}\ +\gamma.$$

These are the so-called *pp*-II reaction chain,

$$^3\mathrm{He}(\alpha,\gamma)^7\mathrm{Be}(e^-,\nu)^7\mathrm{Li}(p,\alpha)^4\mathrm{He},$$

and the *pp*-III chain,

$$^3\mathrm{He}(\alpha,\gamma)^7\mathrm{Be}(p,\gamma)^8\mathrm{B}\left(\beta^+\nu\right)2^4\mathrm{He}.$$

Although these contribute only a few percent to the energy generation, they also influence the production of the so-called solar neutrinos, by the associated weak interaction processes. Raymond Davis, Jr. (1914–2006) recognized in the early 1960s the possibility of measuring the solar neutrino flux as a direct signature for observing the reactions occurring in the sun's interior and to test independently the temperature in the interior, which had previously been based only on the surface luminosity data. To achieve this, Davis built a detector tank, in the Homestake Goldmine in South Dakota, which was filled with chlorine. By means of radiochemical methods, he analyzed the radioactive Ar products of the neutrino-induced reactions on chlorine. These measurements yielded a neutrino flow that was considerably weaker than predicted. This discrepancy opened one of the most important questions in nuclear astrophysics, called the solar neutrino problem.[82] This discovery marks the birth of the new field of neutrino astrophysics. The solar neutrino problem was eventually explained by neutrino oscillations between three neutrino configurations, by which the solar neutrinos were partly converted into other non-detectable neutrinos on the way from the sun to the earth. This interpretation remained unconfirmed until the turn of the century when new generations of giant detectors were installed deep underground to reduce the influence of cosmic radiation on neutrino detection.[83] For his measurement, Ray Davis was awarded the 2002 Nobel Prize for Physics.

The neutrino detectors eventually became so sophisticated that today the direct measurement and identification of neutrinos from weaker burning processes, such as the carbon cycle, are being considered.[84] These neutrinos are mostly associated with the $\beta$-decay of the $^{13}N$ and the $^{15}O$ generated by the two reactions $^{12}C(p,\gamma)^{13}N$ and $^{14}N(p,\gamma)^{15}O$. If the reaction rates of these processes are known with high accuracy then direct conclusions can be drawn from the measured neutrino flux about the metallicity, that is, about the carbon and oxygen of the solar interior.[85] Such statements have hitherto only been made on the basis of helioseismic measurements,[86] and these results have been in disagreement with the observed abundances in the solar atmosphere, which should be comparable to the core metallicity according to the solar solar model.[87] This contradiction can only be solved by independent measurements of the CNO neutrinos.[88]

## *The Carbon Cycle in Massive Stars and the Age of the Universe*

One of the classical methods for age determination of stellar clusters is the analysis of the Hertzsprung-Russell diagram, in which the stars are sorted according to brightness and color (spectral classes). Stars in the hydrogen-burning phase are located along the diagonally extending main sequence, with the more massive stars being located in the upper left region because of their greater brightness. Stars in the helium-burning phase of their development are located in the so-called red giant branch, on the right, above the main sequence. Low-mass stars, after the helium burning, develop to white dwarfs, which are located to the left, below the main sequence. Because of the short burning time, massive stars in the later phases of carbon, neon, oxygen, and silicon burning are difficult to observe. Stars located between the main row and the red giant branch, are in the transitional phase from hydrogen to helium burning. The position of the kinking point or knee determines the mass range of these stars (figure 7).

Since the reaction rates of the *pp* chains and CNO cycles are directly linked to the lifetimes of stars, the age of the star cluster can be directly determined from the position of the position of the knee in the HR diagram of a specific cluster.

Of particular importance are globular clusters that have formed hundreds of millions of years after the Big Bang, and are among the oldest observable configurations of stars. The age determination of globular clusters is therefore one of the cosmological methods for the age determination of our universe. Since the duration of the hydrogen burning in massive stars depends directly on the reaction rates of the carbon cycle, the accuracy of age determination correlates directly with the accuracy of the nuclear physics measurements, as demonstrated by the results of measurements of the $^{14}N(p,\gamma)^{15}O$ reaction.[89] At present, considerable efforts are being made to improve the measurements of the CNO reactions in the stellar energy range and to obtain more precise information on the lifetime of such globular cluster configurations.[90]

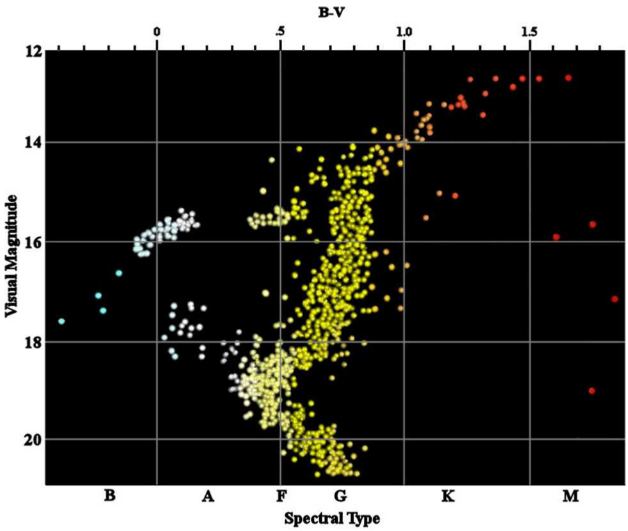


**Fig. 7.** Color-magnitude diagram for the globular cluster M3. Note the characteristic "knee" in the curve at magnitude 19 where stars begin entering the giant stage of their evolutionary path. Source: R. J. Hall, CC SA 1.0 (http://creativecommons.org/licenses/sa/1.0/)

*The Hot CNO Cycle as Energy Source for Nova Explosions*

After the question about the origin of stellar energy was largely solved at the beginning of the 1950s, the remaining problem was the energy source of variable stars, especially of the frequently observed stellar explosions such as novae and supernovae. These observations were characterized by a sudden increase in the stellar luminosity by several orders of magnitude.[91] The physics of supernova explosions has little to do with CNO hydrogen burning and cannot be covered in the context of this paper.[92] For novae, however, detailed calculations demonstrate that the sudden energy release is associated with the onset of the hot CNO cycles.[93]

Novae represent thermonuclear explosions at the surface of a white dwarf in a close binary star system accreting mass from its companion star through its gravitational attraction. Due to the temperature and density conditions at the surface of the white dwarf, the accumulated material is subject to so-called degenerate conditions, where the pressure is determined by the pressure of electrons and not by the gas pressure as in low density environments. When enough hydrogen-rich material has accumulated, nuclear reactions ignite between the protons and the carbon-oxygen-rich material of the white dwarf. The temperatures rise abruptly due to the degenerate gas conditions, leading to an exponential increase in the reaction rates and energy release. The temperatures reach the ignition conditions of the hot CNO cycle, causing a thermonuclear explosion in the atmosphere of the white dwarf. It is only when temperature and pressure conditions are high enough to lift degeneracy that the gas expands and cools. The cooling conditions are determined by the radioactive decay of the short-lived CNO products $^{14}$O, $^{15}$O, $^{18}$Ne and $^{18}$F and possibly NeNa products such as $^{22}$Na.

The rate of the hot CNO reactions, such as $^{13}N(p,\gamma)^{14}O$ and $^{17}F(p,\gamma)^{18}Ne$ and $^{18}F(p,\alpha)^{15}O$, determines the abundance of their respective radioactive products in the expanding atmosphere of the white dwarf. New methods of observation, such as gamma astronomy, have concentrated on directly measuring the characteristic $\gamma$ activity of the decay products. This is predominately the 511 keV $\gamma$ line of positron annihilation, but in the case of $^{22}$Na, the decay populates the first excited state of $^{22}$Ne, which decays to the ground state by emitting 1.26 MeV $\gamma$ radiation. Systematic investigations of the $\gamma$ activity of novae have been made, in particular, by the Gamma satellite observatories INTEGRAL and FERMI from ESA and NASA, respectively. However, previous measurements had only been able to establish upper limits for the intensity of the $\gamma$ radiation emitted, which were in contradiction to the theoretical predictions of the nova models (figure 8).[94]

In the 1970s, with improved methods for observing stellar objects in the X-ray wavelength range, a large number of short-lived X-ray sources were discovered along the galactic plane. These objects are characterized by a rapidly increasing X-ray luminosity, within two to three seconds, followed by a much slower exponential decay over minutes, back to the normal level. The burst activity appears with a frequency of hours to days and the object is referred to as an X-ray burster. To date, more than one hundred of these X-ray bursters have been identified.

These types of eruptions were described as thermonuclear explosions within the atmosphere of neutron stars, and first nuclear physics–based models were developed for describing the driving mechanism.[95] This is interpreted as a phenomenon, occurring in accreting close binary star systems, similar to the novae, except that the dense component is not a white dwarf but a neutron star, a remnant of a supernova event. As a result, the temperature and density conditions at the surface are much higher. The hot CNO cycles are insufficient to generate the observed rapid energy release because of the associated slow $\beta$ decays of $^{14}$O and $^{15}$O; they only provide a simmering prior to ignition. The ignition of the thermonuclear explosion itself occurs with the breakout from the hot CNO cycle, primarily via the $^{15}O(\alpha,\gamma)^{19}Ne$ reaction, and parallel to it the reaction sequence:

$$^{14}\mathrm{O}(\alpha,p)^{17}\mathrm{F}(p,\gamma)^{18}\mathrm{Ne}(\alpha,p)^{21}\mathrm{Na}.$$

This causes a rapid transfer of CNO material towards higher masses. This CNO material on the other hand is rapidly replenished by the so-called *triple-alpha process*. In the triple-alpha process, three alpha ($^4$He) particles are fused to carbon $^{12}$C. The triple-alpha process had already been discussed by Salpeter in 1953 as a

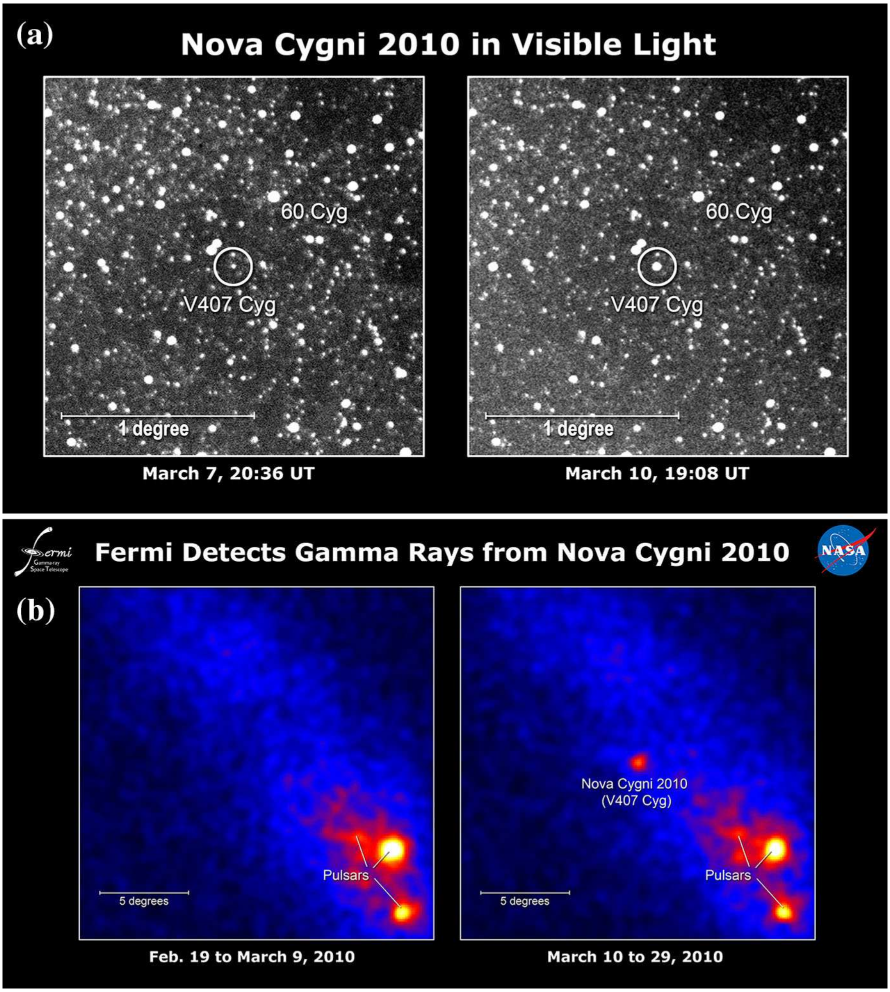


**Fig. 8.** Images of Nova V407 Cygni observed in the visible range of the electromagnetic spectrum by amateur astronomers and in the high energy gamma range by the Fermi Gamma-ray Space Telescope prior and during the explosion. Credits: K. Nishiyama and F. Kabashima/H. Maehara, Kyoto University and the NASA/DOE/Fermi LAT Collaboration. Reproduced with permission from NASA

potentially important mechanism in stellar helium burning.[96] Only one year later, this process was described on a quantitatively reliable basis by Hoyle. He predicted a resonance in the $^{12}C$ compound system necessary for facilitating the process as a driver for stellar helium burning, but also for explosive helium burning processes.[97]

The breakout from the hot CNO cycles triggers a reaction chain by which the initial $^{4}$He and CNO material is processed within seconds towards the Ni range by a sequence of alpha and proton capture reactions. This mechanism is called *αp* and *rp process*.[98] The fusion energy is released as intense $\gamma$ rays, which are rapidly converted to an intense X-ray flux by photon scattering in the atmosphere of the neutron star. The rp process is currently of great theoretical interest because it offers the possibility of observing nuclear physics processes at extreme densities.

The reaction rates of the breakout reactions determine the ignition conditions for the thermonuclear runaway, but have so far only been calculated on the basis of indirect measurements of various possible reaction components. The timescale of the explosion, the released energy, as well as the nucleosynthesis processes that occur during this process, which determine the abundance distribution in the ash, have only been estimated theoretically. These quantities determine the current models that have been developed to describe the ignition timing, time scale, luminosity, and periodicity of the X-ray burster.[99]

### *The CNO Isotopes as a Chemical Evolution Tool*

It always has been a major goal to compare the observed CNO abundances with the predictions made by stellar model simulations based on CNO cycle reaction rates. That would be the ultimate direct demonstration for how the cycles work. The cosmic reality is however that the CNO cycle operates at different temperature and density conditions depending on the stellar environments that include low mass to massive stars and contributions from explosive hydrogen burning such as novae. An additional challenge presents the impact of alpha induced reactions such as $^{14}$N($\alpha$,$\gamma$)$^{18}$F($\beta^{+}\nu$)$^{18}$O and $^{12}$C($\alpha$,$\gamma$)$^{16}$O during the stellar helium burning phase that alters the abundance distribution in the CNO ashes from the preceding hydrogen burning phase. Over the last decades, the relative abundances of C, N, and O isotopes have emerged as powerful tool to assess burning, convection and mixing processes in stars. In this approach, the isotopic ratios in stellar atmospheres and in meteoritic inclusions are compared with the expectation from nucleosynthesis in a large number of stellar environments that are expected to affect the CNO abundances and stellar evolution models. That knowledge can be used to derive constraints about chemical evolution of our universe and also about the initial mass function (IMF) or mass distribution of stars in our galaxy.[100] This demonstrates that the once revolutionary predictions about the nature of the CNO cycle now became a tool for interpreting the chemical evolution of our universe and a stepping stone toward analyzing larger statistical phenomena of star formation and stellar mass distribution in our galaxy and universe.

### New Experiments on the CNO Cycles

Exact quantitative analysis of the above-mentioned scenarios requires a much better understanding of the underlying nuclear processes. This in turn requires much more accurate and reliable cross section measurements of the different reactions in the CNO cycles. Using low-energy particle accelerators, the reaction cross sections have been measured down to very low energy levels.

But when progressing toward the actual stellar energies, the natural cosmic background radiation in the detectors becomes considerably stronger than the exponentially decreasing intensity of the reaction signals that are to be measured.[101] This occurs at energies far above the typical stellar energy range, the so-called *Gamow window*.[102] Figure 9 displays the current state of the experimental results of the CNO reactions; the curves show the cross sections of the different reactions as a function of the energy of the interacting particles. The Gamow window is between 20 and 60 keV, far below the measured data points. Traditionally, the experimental cross sections are extrapolated into the stellar energy range by mathematical polynomial series.[103] Nuclear reaction theories such as the *R-matrix* theory are increasingly used for extrapolation, as shown in figure 7, in order to consider all possible reaction components and the quantum mechanical interference effects.[104] Since the R-matrix theory is a phenomenological approach, reliable application and extrapolation require extensive measurements of all reaction components, in the low energy range of the reactions.

The need for better experimental data for the stable CNO isotopes near the Gamow range has stimulated the development of accelerator laboratories in underground laboratories. These facilities are located hundreds of meters deep in the earth in order to successfully shield the cosmic radiation.

The measurement of reactions on the short-lived CNO isotopes raises other questions. Since these reactions only play a role in explosive processes, the temperature is higher than in quiescent stellar environments and consequently the Gamow range corresponds to higher energies. At such energies the cross section is much higher than for stellar burning conditions. The challenge in the measurements is more in the short life time of the nuclei that cannot be used as target material. The reaction yield must be measured in inverse kinematics, with short-lived projectile nuclei bombarding as radioactive particle beam light hydrogen target material. In those cases it is not necessarily the light particle or $\gamma$ reaction products that are being measured, but the heavy recoil nuclei itself that are being separated and detected in so-called recoil separator devises. To facilitate such inverse kinematics experiments, accelerator devices have been developed worldwide that can produce and accelerate such short-lived radioactive beams.

The following provides a brief overview describing the current state of underground laboratories and accelerators for radioactive nuclei that currently determine experimental events in nuclear astrophysics.[105]

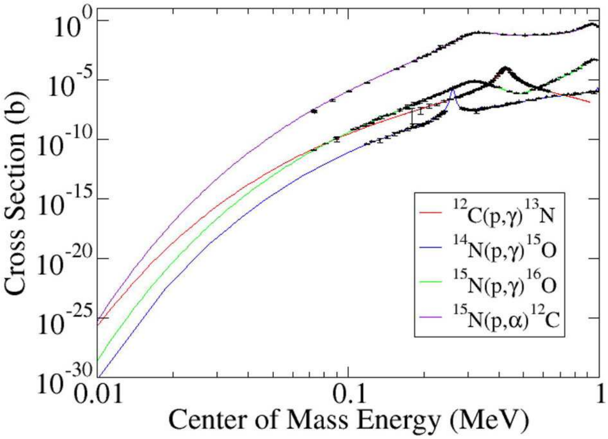


**Fig. 9.** Cross section of the most important reactions of the carbon cycle, shown as a function of the center of mass energy of the reaction components. The reaction probability declines exponentially towards lower energies. The data points show the experimental results obtained over several years by different groups. The data points were extrapolated down to the Gamow range using the R-matrix theory. The Gamow window corresponds to an energy range of 0.02–0.06 MeV. It is clear that the slowest reaction is $^{14}N(p,\gamma)^{15}O$ and the fastest reaction is $^{15}N(p,\alpha)^{12}C$. Only a small percentage of material is lost through the $^{15}N(p,\gamma)^{16}O$ reaction from the carbon or CN cycle to the ON cycle (see Figure 6). Source: Wiescher, "Carl Friedrich von Weizsäcker" (ref. 112)

## *Experiments in a Background-Free Environment*

The possibility of low-energy measurements has been significantly improved with the installation of the first accelerator laboratory in the Gran Sasso laboratory, located in a side tunnel of the highway connection Rom-Ravenna, almost 2000 m below the Gran-Sasso massif in Italy. The laboratory was primarily intended for the measurement of rare decay products such as neutrinos and dark matter signatures, which required background-free conditions. Within the Gran Sasso laboratory environment, the Laboratory Underground for Nuclear Astrophysics, LUNA first operated only a 50 keV accelerator, which was used to measure key reactions of the *pp* chains in the solar energy range. Later, a 400 keV accelerator was installed, allowing LUNA researchers to concentrate largely on the measurement of the CNO cycle reactions.[106] The measurements allowed researchers to significantly reduce the background and generate data at much lower energies than accessible at accelerator facilities above ground. The new results led to unexpected changes in the extrapolation of the cross section to stellar energies. Inspired by these results, the installation of another 3 MeV accelerator is planned to measure the reactions of helium burning. At the same time, a further accelerator laboratory, the Compact Accelerator System for Performing

Astrophysical Research, CASPAR has been installed at the Homestake Mine in South Dakota, and started full operation in fall 2017.[107]

### *Experiments Far from Stability*

With the growing interest in the role of the hot CNO cycles for explosive hydrogen combustion, interest in the experimental investigation of the proton capture reactions also increased. Since radioactive CNO isotopes are usually very short lived, these reactions cannot be measured traditionally by sending an intense proton beam to a target of isotopically enriched material. Rather, special techniques are required to produce an intense beam of radioactive isotopes, which is then sent to a hydrogen or helium target. Such methods for radioactive beam production were first developed at the cyclotron laboratory of the Université de Louvain-la-Neuve in Belgium. The first success was the measurement of $^{13}N(p,\gamma)^{14}O$,[108] followed by measurements of $^{19}Ne(p,\gamma)^{20}Na$ and $^{18}F(p,\alpha)$ $^{15}O$ reactions.[109] In addition to the $^{17}F(p,\gamma)^{18}Ne$ reaction, the latter reaction was extensively studied in the following years, at the *Holifield Radioactive Ion Beam Facility* of the Oak Ridge National Laboratory.[110]

## Review and Outlook

The carbon cycle, as conceived by Weizsäcker and Bethe in 1938, is recognized to be one of the most important processes for energy generation in stars. Predicted lifetimes and brightness of massive main-line stars are determined by the reaction rates of the CNO cycles, this provides a signature the age determination of star clusters. The abundance distribution of the CNO isotopes in stellar atmospheres and meteor inclusions is now being used for determining chemical evolution and stellar mass distribution in our universe. New astronomical observations, such as gamma astronomy or neutrino astronomy, correlate closely with the theoretical predictions for reaction rates, based on the experimental cross section data. This allows for new, accurate observation and analysis of burning conditions in the center of stars and stellar explosions. These results and possibilities could not have been known in the late 1930s and are primarily based on post–World War II developments.

Weizsäcker was one of the first to recognize the close relationship between nucleosynthesis and energy generation. In his two papers on the subject, he highlighted the importance of microscopic nuclear processes for the macroscopic physics of the life and death of stars. Many objections and prejudices against these ideas had to be overcome. Even Bethe characterized these developments as largely speculative before his participation in the Washington conference of 1938. Only one year later, he provided the mathematical formalism for the quantitative understanding of the cycle. Today, the carbon cycle has a central place in the physics of element synthesis.

Although Bethe and Weizsäcker deserve credit for formulating the carbon cycle, the history of the origin of this idea is an example of how new models and ideas emerge from a network of personal relationships and the exchange of information that began being practiced in the science of the twentieth century. It was no longer the world of the nineteenth century, where individual naturalists "standing on the shoulders of giants" formulated new groundbreaking ideas in the tranquility of their personal study.[111] International conferences, discussions and information exchange had become an important ingredient, through which scientists exchanged ideas and laid the foundations for new ideas. Within this exchange, the idea of the carbon cycle has been born. It is possible that Weizsäcker and Bethe came independently to the idea, within the network, and then raced for the solution to the problem of the stellar energy source. It is more likely, however, that George Gamow played the role of catalyst, bringing the Weizsäcker idea of catalytic burning to Washington and allowing Bethe to make the transposition of the "helium cycle" to a "carbon cycle." This was the idea that then returned with Gamow to Berlin. Although this question of origin can no longer be answered, the idea of the carbon cycle was accepted within a few months and is now an integral part of astrophysical thinking and methodology. However, the actual experimental verification required decades of tedious work. Research today focuses on the quantitative detail in order to determine predictable and observable signatures of the cycle, as well as to analyze and understand the intricacies of the inner conditions of stars and stellar explosions.

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[22] Helge Kragh, *Cosmology and Controversy*, 2nd ed. (Princeton, NJ: Princeton University Press 1999), 97–101.

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[24] George Gamow, "The Energy Producing Reactions in Stars," *Astrophysical Journal* **89** (1939), 130–33.

[25] Weizsäcker in his 1978 interview with Karl Hufbauer (http://www.aip.org/history/ohilist/4948.html) remains somewhat ambivalent in this point: "The things I remember are quite limited. At that time I had the idea of the carbon cycle, and I felt that this was the solution, and Gamow came and told me that Bethe had probably found the solution to the problem and that it was the carbon cycle. Then I said, 'Well, I think he's right, I found it too,' and my paper at that time was perhaps already in print, I don't remember. In any case, I felt that I had already done it and submitted it for print. But on the other hand, it was very good if Bethe had done it too, and it was not the first time I had done something parallel with Bethe. It had been the same thing with the mass-defect

formula for the atomic nuclei, of which I spoke before. Then I felt that at least he should tell Bethe that I had done it. And I might even have written a letter to Bethe about that. But since Bethe didn't have it, perhaps I didn't. Perhaps I asked Gamow to tell him. Then I was a little bit disturbed by the fact that Bethe's paper didn't appear earlier—because it was delayed, because it was submitted for some Festschrift—because that gave the impression that I had true priority, while I would say that we were just independent." The two known letters of Weizsäcker to Bethe from September 30, 1936, and September 24, 1937, respectively are mainly concerned with nuclear physics questions related to his first hypothesis, in particular the question of the possible existence or longevity of $^{4}$H, $^{4}$Li, $^{5}$He, and $^{5}$Li, which was of existential importance for his theory of element formation.

26 Hans A. Bethe and Charles L. Critchfield, "The Formation of Deuterons by Proton Combination," *Physical Review* **54** (1938), 248–54.

27 In modern nuclear physics terminology, this reaction sequence would be formulated as: $^{12}\mathrm{C}(p,\gamma)^{13}\mathrm{N}(\beta^{+}\nu)^{13}\mathrm{C}(p,\gamma)^{14}\mathrm{N}(p,\gamma)^{15}\mathrm{O}(\beta^{+}\nu)^{15}\mathrm{N}(p,\alpha)^{12}\mathrm{C}$.

28 Weizsäcker, "Über Elementumwandlungen II" (ref. 11), 639.

29 Weizsäcker, "Über Elementumwandlungen II" (ref. 11), 639.

30 Karl Hufbauer does not agree with this thesis. On the basis of Weizsäcker's statements in the 1978 interview (http://www.aip.org/history/ohilist/4948.html), he believes that between January and May 1938, Weizsäcker came independently to the realization that the structural hypothesis is untenable and must be replaced by an alternative process, such as the carbon cycle. Karl Hufbauer, "Stellar Structure and Evolution 1924–1939," *Journal for the History of Astronomy* **37** (2006), 203–27.

31 Carl Friedrich von Weizsäcker, "Über die Entstehung des Planetensystems," *Zeitschrift für Astrophysik* **22** (1943), 319–55.

32 Mark Walker, "Mit der Bombe leben—Carl Friedrich von Weizsäckers Weg von der Physik in die Politik," *Acta Historica Leopoldina* **63** (2014), 343–56.

33 Subrahmanyan Chandrasekhar, *An Introduction to the Study of Stellar Structure* (1958; New York: Dover, 1967), 468–86.

34 Strömgren stayed only for two years at Yerkes. In 1939 he was offered a professorship in Copenhagen and spent the following years there. He maintained scientific connections with his German counterparts and was the only Danish scientist to take part in the DPG meeting in Copenhagen in 1941 to meet his former friends Heisenberg and Weizsäcker.

35 Teller stayed there until 1941 and was then recruited by Bethe to Los Alamos to participate in the Manhattan Project. After the war in 1949 he instigated and supervised the development of the hydrogen bomb at the newly founded Livermore National Laboratory.

36 This was a second article of a three-part series of works that Bethe had published in the 1930s. Following the example of Weizsäcker's monograph *Der Atomkern*, Bethe wanted to summarize in this series all the knowledge on the physics of atomic nuclei. Still famous today, this work is referred to as the "Bethe Bible." Hans Bethe, "Nuclear Physics B. Nuclear Dynamics, Theoretical," *Review of Modern Physics* **9** (1937), 69–246.

37 Sylvan S. Schweber, "The Happy Thirties," in *Hans Bethe and His Physics*, ed. Gerald E. Brown and Chang-Hwan Lee, 131–45 (Singapore: World Scientific, 2006).

38 George Gamow, *My World Line* (New York: Viking, 1970), 136.

39 Sylvan S. Schweber, *Nuclear Forces: The Making of the Physicist Hans Bethe* (Cambridge, MA: Harvard University Press, 2012), 315–60.

40 George Gamow, *The Birth and Death of the Sun* (New York: Viking, 1940), 112–13.

[41] Hans A. Bethe, "My Life in Astrophysics," in *Hans Bethe* (ref. 37), 22–47.

[42] Neutrinos had been postulated by Wolfgang Pauli (1900–1958) as early as 1930, but found their way into astrophysics only after the war.

[43] Bethe and Critchfield, "Formation of Deuterons" (ref. 26).

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[46] Karl Hufbauer, "Stellar Structure and Evolution, 1924–1939," *Journal for the History of Astronomy* **37**, no. 2 (2006), 203–22, and Giora Shaviv, *The Life of Stars: The Controversial Inception and Emergence of the Theory of Stellar Structure* (Heidelberg: Springer, 2009).

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[48] In modern nuclear physics terminology, these reactions would be formulated as: $^{2}H(p,\gamma)^{3}He$; $^{2}H(p,n)2^{1}H$, $^{2}H(d,p)^{3}H$; $^{2}H(d,\gamma)^{4}He$.

[49] In modern nuclear physics terminology, this is formulated as: $^{1}H(p,\nu\gamma)^{2}H$; $^{2}H(p,\gamma)^{3}He$; and $^{3}He(\tau,2p)^{4}He$.

[50] Edwin E. Salpeter, "Energy Production in Stars," *Annual Review of Nuclear Science* **2** (1953), 41–62.

[51] Bethe, "Nuclear Physics, B" (ref. 36).

[52] Hans A. Bethe, "Recent Evidence on the Nuclear Reactions in the Carbon Cycle," *Astrophysical Journal* **92** (1940), 118–21.

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*Atomforscher* (Bern: Scherz Verlag 1956), as well as a more recent book by Richard Rhodes, *The Making of the Atomic Bomb* (New York: Simon and Schuster, 1986).

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