NUCLEAR SYNTHESIS IN NATURE

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Summary

The manuscript reviews our current understanding on nucleosynthesis. It presents an overview of the environmental conditions in which the elements around us can be produced. It discusses the stellar sites and scenarios which provide these often extreme conditions in nature. It also reviews the micro-physics input which is both necessary for interpreting the wealth of recent observational results and for formulating today's theory of the origin of elements.

1. The General Concept

The general concept of the synthesis of elements in the universe has been formulated now more than 40 years ago by Burbidge, Burbidge, Fowler and Hoyle. According to these ideas, the light elements (mainly hydrogen and helium) have been made during the Big Bang, while the breeding places for most of the other elements are the interiors of stars. The stars generate the energy, which allows them to stabilize and shine for many millions of years, by transmuting nuclear species, thus forming new elements. These processes occur deep inside the star, but the freshly formed nuclei are eventually released. The release either takes place by convective dredge-up processes from the burning zones to the stellar atmosphere followed by mass loss due to radiation pressure driven winds. This scenario often forms planetary nebulae observed as vast gas clouds surrounding a center star. Alternative release mechanisms are stellar explosions where the freshly produced nucleosynthesis products are expelled by an explosion shock front. In both cases the freshly bred nuclear material is mixed into the interstellar medium (ISM) and will become part of the initial abundance composition for new stars to be formed. Thus the galactical chemical evolution represents a 'cosmic cycle'; the ashes of stellar burning become the breeding material for new stellar generations. The observed elemental abundance distribution by Grevesse et al. reflects therefore the nucleosynthesis history of our universe, modeling and explaining these observed abundances requires the simulations of the formation of a galaxy, its stellar mass distribution, the birth, evolution, lifetime, and death of stars. During their lifetime stars go through various burning stages igniting nuclear fuel with increasingly higher charge numbers (hydrogen, helium, carbon, neon, oxygen, silicon) at increasingly higher core densities and temperatures, while fuel with lower charge numbers is burnt in shells outside the core. Stars with masses $M < 10M_\odot$ (with the solar mass $M_\odot$) reach only condition in the center which are sufficient for core helium and carbon burning; these stars produce mainly carbon, nitrogen, and half of the nuclei heavier than iron. More massive stars basically make the elements between oxygen and zinc, and, likely during their type II supernova explosion, also the other half of the elements heavier than iron. Finally, type Ia supernovae produce roughly half of the fraction of nuclei in the iron mass region, but also some portion of intermediate mass nuclei. While the elements lighter than $A \approx 60$ are made by fusion reactions involving charged particles, the heavier nuclides are produced by neutron capture reactions. These capture reactions have to compete with nuclear β decays. One distinguishes between the slow neutron capture process (short s-process), for which β decay half lives τ_β are shorter than the competing neutron capture times τ_n, and the rapid neutron capture process (r-process), for which one has $\tau_n << \tau_\beta$. As τ_n is inversely proportional to the available neutron density, the r-process is expected to occur under extreme neutron fluxes and evolves through very neutron-rich, unstable nuclei. As $\tau_\beta < \tau_n$ for the s-process, the reaction path, on the contrary, runs along the valley of stability.

2. Big Bang Nucleosynthesis

Besides isotropy and homogeneity, the standard Big Bang model assumes that the early universe is governed by the same laws of physics as today's universe. Based on the assumption that no other kind of particles than known today existed during this period of nucleosynthesis, the thermal history of the early universe is reconstructable. One finds the relations

$$\mathrm{T}(\mathrm{t}) \sim R(t)^{-1}; \;\; T(t) \approx \tfrac{1.3 \cdot 10^{10}}{t^{1/2}} \qquad (1)$$

which describes the cooling of the universe (temperature T) as a function of the expansion (length scale R) and time (t in seconds). The evolution of the early universe is characterized by a thermal equilibrium of the abundant particles existing at the temperature T. The equilibrium is ensured by reactions among these particles for which the rates are greater than the expansion rate of the universe. In thermal equilibrium, reactions proceed in both directions at the same rate; in particular this is valid for the particle-producing and particle-annihilating reactions

$$\text{Particle} + \text{antiparticle} \leftrightarrow \textit{photon.} \qquad (2)$$

If the temperature decreases significantly below the mass of a particle ($kT < mc^2$), reaction (2) proceeds dominantly to the right; i.e. particles and antiparticles annihilate and die out. From Eq. (2) it seems that matter and antimatter should always exist in exactly the same amounts. But this is not necessarily the case, as grand unification theories predict that the decay of the gauge bosons, which mediate the transformations of quarks and leptons at energies above 10^{18} MeV, violates the CP symmetry and thus might generate a small surplus of matter (nucleons, electrons) over antimatter (antinucleons, positrons). Consequently, at $T \approx 10^{12} K$, all antinucleons will have annihilated with nucleons, leaving a tiny surplus of nucleons, which would then become the breeding material for the primordial (and later stellar) nucleosynthesis. Besides a small concentration of protons and neutrons, at $T = 10^{12}\mathrm{K}$ the universe initially is made mainly of electrons, positrons, neutrinos, antineutrinos and photons which all existed in thermal and chemical equilibrium. The ratio of the number of protons, $N_p(T)$ and neutrons, $N_n(T)$, is determined by reactions mediated by the weak interaction:

$$\mathrm{n} + \nu \leftrightarrow p + e^-; \qquad (3)$$

$$\mathrm{n} + e^+ \leftrightarrow p + \overline{\nu}; \qquad (4)$$

$$\mathrm{n} \leftrightarrow p + e^- + \overline{\nu}; \qquad (5)$$

Protons and neutrons also can fuse and form deuterons

$$\mathrm{n} + \mathrm{p} \leftrightarrow \gamma + d \qquad (6)$$

but the large number of energetic photons (the ratio of photons to baryons exceeded 10^9) immediately photo-dissociate the produced deuteron. Thus, a significant concentration of deuterons is not been formed until the temperature drops considerably below the deuteron binding energy $E_B = 2.23\ \mathrm{MeV}$. Before this happens at $T \approx 10^9\ \mathrm{K}$ (about 100 keV), two events occur which determine the N_n/N_p ratio. First, the weak interaction rates cannot keep pace with the expansion rates of the universe, and consequently neutrinos drop out of equilibrium. Secondly, electrons and positrons annihilate at $T \approx 5 \cdot 10^9\mathrm{K}$, heating up the photon bath, but not the neutrinos which are already decoupled. As a consequence of these two events, baryons and leptons decouple and the $N_n(T)/N_p(T)$ ratio is frozen at a constant value. Taking the neutron decay (5) into account one finds a ratio of one neutron per seven protons at the onset of nucleosynthesis at $T \approx 10^9\mathrm{K}$. At $T \approx 10^9\mathrm{K}$, the primordial nucleosynthesis bottleneck is overcome when deuterons begin to form in significant concentration. The subsequent reactions proceed rapidly as (1) the binding energies of ^{3}H, ^{3}He and ^{4}He are larger than that of the deuteron and (2) the rates of the reactions $d(p,\gamma)^3\mathrm{He},\ d(n,\gamma)^3\mathrm{H},\ d(d,p)^3\mathrm{H}, d(d,n),\ ^3\mathrm{He}\,^3\mathrm{H}(d,n)^4\mathrm{He},\ ^3\mathrm{He}(d,p)^4\mathrm{He}$ and $^3\mathrm{H\ e}\ (^3\mathrm{He},2p)^4\mathrm{He}$ are large.

Primordial nucleosynthesis essentially comes to an end with the production of ^{3}He, as the nonexistence of stable nuclei with mass numbers 5 and 8, the growing Coulomb barrier between the nuclei, and the rapidly falling temperature prevent the production of heavy nuclei. Primordial nucleosynthesis is finished at $T = 10^8\ \mathrm{K}$. In the standard model, most of the existing neutrons are used essentially to produce $^4\mathrm{He}$, while only small traces of other light elements (deuteron, $^3\mathrm{He}$, and $^7\mathrm{Li}$) are made. Simulations of primordial nucleosynthesis depend only on one free parameter, the baryon-to-photon ratio η. By comparing the calculated and observed primordial abundances for the elements $d,{}^3\mathrm{He},{}^4\mathrm{He}$ and $^7\mathrm{Li}$, the value for η can be restricted to

$$2.9\ 10^{-10} < \eta < 3.810^{-10} \qquad (7)$$

From the value of η the mass density of baryons Ω_B in the universe can be deduced and one finds that Ω_B is only a few percent of the critical mass density Ω_{cr} necessary to just close our universe. From the fact that $\Omega_B/\Omega_{cr} < 1$, it is usually concluded that our universe must contain a dominant amount of dark matter if it is closed.

3. Stellar Nucleosynthesis

The formation of elements heavier than A=4 takes place inside of stars at fairly high densities and temperatures. Such conditions are necessary to allow nuclei to interact and to overcome the Coulomb barrier. The different nucleosynthesis steps are characterized by the subsequent phases of stellar evolution which, depending on the initial mass of the star, lead to the formation of a white dwarf after significant radiation driven mass loss or to the core collapse triggering a type II supernova event.

3.1 Stellar Core Burning

During hydrogen burning in the so called main sequence stars four hydrogen atom fuse to helium releasing about 25 MeV per fusion event. For stars with less than 1.5 solar mass the fusion process is dominated by the pp-chains. The slowest reaction, the p + p fusion to deuterium determines the lifetime of the hydrogen burning phase. This reaction is mediated by weak interaction. Although its present rate is based on theoretical calculations, it is generally believed to be quite accurate. Other critical reactions are the $^{3}\mathrm{He}(\alpha,\gamma)^{7}\mathrm{Be}$ and $^{7}\mathrm{Be}(\mathrm{p},\gamma)^{8}\mathrm{B}$ capture processes which determine to a certain extend the neutrino flux originating from these stars. Detailed knowledge of the rates is necessary for the interpretation of the solar neutrino flux measured with solar neutrino detectors. For more massive stars the hydrogen burning is controlled by the CNO-cycles which have significant influence on the change of isotopic abundances of carbon and oxygen to nitrogen within the stellar core. The power generated by the CN cycle is limited by the slow $^{14}\mathrm{N}(\mathrm{p},\gamma)^{15}\mathrm{O}$ reaction which also causes a nearly complete conversion of the initial carbon and oxygen content to ^{14}N. Red Giant stars are identified as stars in the He-burning phase. The lifetime depends on the triple alpha reaction, the sequential fusion of three ^{4}He particles to ^{12}C. Since He-burning reactions are typically harder to measure than H-burning reactions (because of increased Coulomb barrier and higher background levels), some very basic questions concerning He-burning still remain unanswered. The concept of the triple alpha reaction is understood, the rate is determined by the α-cluster structure of the associated compound nuclei ^{8}Be and ^{12}C and is extremely temperature sensitive. The $^{12}\mathrm{C}(\alpha,\gamma)^{16}\mathrm{O}$ reaction is of enormous significance for late stellar evolution. It helps first to determine the mass of the core following He-burning. Secondly, it determines – together with the $^{16}\mathrm{O}(\alpha,\gamma)^{20}\mathrm{Ne}$ reaction – the $\mathrm{C/O}$ ratio which in turn influences the following burning sequences of the star. Helium burning is also responsible for producing neutrons that lead to the synthesis of heavy elements via the s-process. The actual neutron production processes are only marginally understood. This may have significant consequences for our present interpretation of s-processes nucleosynthesis within the framework of stellar models (see below). The subsequent heavy ion burning phases like carbon and oxygen burning depends on the nucleosynthesis of ^{12}C and ^{16}O during the He-burning phase. The burning itself relies not only on the fusion processes, ^{12}C + ^{12}C, ^{12}C + ^{16}O, and ^{16}O +^{16}O but also on many α and p capture processes on the fusion products. Burning stages beyond oxygen burning, which is relevant for the synthesis for nuclei heavier than calcium in the pre-supernova phase of the star, increasingly occurs in a state of full or partial nuclear statistical equilibrium. Thus binding energies and partition functions of the nuclei involved mainly determine the abundance. As long as the “freeze-out” is sufficiently rapid nucleosynthesis is less sensitive to individual reaction rates. Yet, reaction rates remain important for nucleosynthesis in the subsequent cooling phase of the event since the equilibrium breaks down below temperatures of roughly three billion degrees K.

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Biographical Sketches

Karlheinz Langanke, was born in Hamm, Germany in 1951. He received his diploma and Ph.D. from the University of Münster, Germany, both for work done on the microscopic description of nuclear reactions. In 1982/83 visited California Institute of Technology with a scholarship of the Deutsche Forschungsgemeinschaft, where he worked on nuclear astrophysics together with Nobel Prize winner William A. Fowler and began a long lasting collaboration with Steven E. Koonin. In 1985 he received his habilitation in physics from the University of Münster and was on its faculty as professor during 1987-1992. During 1992-1996 he has been Senior Research Associate at California Institute of Technology, before accepting the succession of Jens Lindhard as Professor of Physics at the University of Aarhus, Denmark.His research is focused on the theoretical studies of many-body problems in nuclear and atomic physics, often motivated by astrophysical quests. He has worked on the determination of astrophysically crucial reaction rates, on atoms in strong magnetic fields, on helium plasma at extreme densities, on electron screening effects on nuclear reactions in the laboratory and in stellar plasma, on neutrino-nucleus reactions with relevance for accelerator-based experiments, developments of supernova neutrino detectors and stellar environments. For his development of computer software for classroom teaching he received the Deutsche Hochschul-Software-Preis in 1990. Recently his interest has concentrated on stellar weak-interaction rates which are crucial for core-collapse supernovae.In 1998 has been guest professor of the Austrian government, he is NSCL adjunct professor at Michigan State University and Distinguished Visiting Scientist at Oak Ridge National Laboratory. He is currently a member of the Program Advisory Committees at INTC/CERN and GSI, of the Board of Directors at the European Center for Theoretical Studies in NuclearPhysics ECT*, at the Nordic Institute for Theoretical Physics NORDITA and at the Joint Institute for Nuclear Astrophysics JINA in the USA. He also currently serves on the National Advisory Committee of the Institute for Nuclear Theory in Seattle and the GANIL Planning Advisory Board in France. He is Supervisory Editor of Nuclear Physics A and a member of the Associate Editorial Boards of Atomic Data and Nuclear Data Tables and of Few-Body Systems.

Michael Wiescher, was born in Wuppertal, Germany in 1949. In 1974 he received his Diploma degree at the Institute of Physics at the University of Muenster in solid state physics on "Measurements of the Fano Effect on Cs-Surfaces". He switched to Nuclear Physics and joined the group of Claus Rolfs at the Nuclear Physics Institute at the University of Muenster. He received in 1980 a PhD in nuclear astrophysics with a thesis on "Measurements of Reactions in the CNO Cycles". He went to Ohio State University as a postdoctoral fellow from 1981 to 1983 where he got involved in the first attempt to develop a radioactive beam facility. In 1984 he worked at the Kellogg Laboratory at Caltech as a visiting fellowon capture measurements with long-lived radioactive targets. He joined the group of K.L. Kratz in Mainz in 1984 as a senior research associate and lecturer. He focused his research on r-process studies at the ISOLDE separator at CERN and the OSTIS separator at the ILL, Grenoble. In 1986 he joined the faculty of the University of Notre Dame where he presently holds the Freimann Chair of Physics. Since 2002 Michael Wiescher serves as director of the Joint Institute of NuclearAstrophysics (JINA), a Physics Frontier center of the National Science Foundation between the University of Notre Dame, Michigan State University, and the University of Chicago.His research is concentrated on experimental and theoretical studies of the rp-process in explosive stellar scenarios where he investigates nuclear reactions and nuclear structure far off stability using radioactive ion beam techniques. Another topic of interest is the experimental and theoretical study of critical reaction processes during stellar evolution where he concentrates on reaction and structure studies near the particle thresholds. He is a member of the American Astronomical Society, the Deutsche Physikalische Gesellschaft, and a Fellow of the American Physical Society. On sabbaticals and leaves he has visited and performed experiments at the radioactive beam facility at Louvain la Neuve, Belgium, Forschungszentrum, Karlsruhe, Kellogg laboratory, Caltech, the NSCL at Michigan State University, Argonne National Laboratory, Oak Ridge National Laboratory and at n-ToF CERN.Michael Wiescher has served as a member of the Executive committee of the Division of Nuclear Physics of the American Physical Society from 1999-2001. He is a member of the National Steering Committee for the Rare Isotope Accelerator RIA, the National Steering Committee on Opportunities in Nuclear Astrophysics, he chaired the DNP/NSAC long range plan committee on Nuclear Structure and Nuclear Astrophysics in 2001, and he served on the NuPECC working group on Nuclear and Particle Astrophysics. He served on several review and advisory boards for Argonne, Berkeley, and Oak Ridge National Laboratories as well as for TUNL at Duke University and the NSCL at Michigan State University. In 2003 he received the Hans A. Bethe Prize by the Divison of Astrophysics and the Division of Nuclear Physics of the American Physical Society