BIG BANG NUCLEOSYNTHESIS

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Contents

Summary

Primordial nucleosynthesis provides information on the baryon density of the Universe only a few minutes after the Big Bang; hence its knowledge is of overwhelming importance. In this paper the author reviews the current status of the Big Bang Nucleosynthesis (BBN), the key physics that controls the synthesis of the various elements in the early Universe and the predictions of the BBN in the framework of the standard (and some non standard) models of cosmology and particle physics. The observational data available to infer the primordial abundances are also reviewed and used, in conjunction with the BBN predictions, to derive the baryon density of the early Universe. The baryon density obtained by means of the temperature fluctuation spectrum of the cosmic microwave background (CMB) radiation is also discussed and compared with that obtained by means of the BBN. Agreement and discrepancies between the two predictions are extensively discussed in the framework of both the standard and non standard cosmological models.

1. Introduction

The crucial role that the hot Big Bang might have for the origin of the elements was recognized for the first time by Gamow and his coworkers since the early 1940s (Alpher, Bethe & Gamow 1948, Alpher & Herman 1950). In fact, they pointed out that if the Universe was in the past at temperatures larger than 10^9 K, the nuclear reactions were efficient enough to built up heavier nuclei out of nucleons. The Gamow model begun with only neutrons, but this assumption was later shown to be invalid (Hayashi 1950, Alpher, Follin & Herman 1953) since at sufficiently high temperatures ($T > 10^{10}\,\mathrm{K}$) the weak interactions, governing the interchange between protons and neutrons, are in equilibrium, making neutrons and protons almost equally abundant. In spite of this, however, such a model still constitutes the basic idea of the Big Bang Nucleosynthesis (BBN).

The stability gaps corresponding at atomic masses of 5 and 8, prevented the synthesis of all the elements during the early Universe. Hence, the matter coming out from the BBN was mainly composed of light nuclei. The synthesis of the heavier elements should have occurred in sites of higher density and longer lifetimes (like the stars) where the mass gaps could be bridged by the 3 reactions (Salpeter 1952, Hoyle 1954). Big Bang nucleosynthesis calculations performed by several groups (Hoyle & Tayler 1964, Peebles 1966, Wagoner, Fowler & Hoyle 1967) in the early 1960s showed, indeed, that about 20-30% of the matter synthesized in the early Universe was composed in a substantial amount by ^{4}He. These theoretical predictions were surprisingly in good agreement with the observed abundances in a variety of objects, providing strong evidence in favor of this model. Needles to say, however, the strongest evidence for the hot Big Bang came with the discovery of the cosmic microwave background (CMB) radiation in 1965 (Penzias & Wilson 1965). In fact, the only natural explanation of the observed 3K blackbody spectrum was that the early Universe has been sufficiently hot and dense that the scattering was frequent in the uniform primeval fireball. Other models that do not involve such a high temperature and high density birth cannot explain the existence of such a radiation.

Many progresses have made since those pioneering works, both from the theoretical and observational side, that nowadays a very detailed comparison between the theoretical predictions of the Big Bang nucleosynthesis and the pre-galactic abundances of the elements inferred from the observations can be made.

In this paper the author will provide an overview of the standard hot Big Bang model, focusing on the physics relevant for the primordial nucleosynthesis. Then, the author will present the theoretical predictions of the primordial abundances based on BBN calculations in the framework of the standard hot Big Bang model as well as in the context of some very general extension of the standard models of cosmology and/or particle physics. Next, the author will review the current status of the observations available in order to infer the primordial abundances. The predicted and observed abundances will be compared in order to test the internal consistency of the standard model and to derive the baryon density of the early Universe. Constrain extensions beyond the standard model will be also discussed. The temperature fluctuation spectrum of the CMB radiation, established several hundred thousand years later than the BBN, provides probe of the baryon density at a completely different epoch in the evolution of the Universe and hence it is complementary to that provided by the BBN. The parameter estimates from both the BBN and CMB are finally compared, again testing the consistency of the standard model and probing or constraining some classes of non standard models.

2. Brief Historical Overview

In the 1920s Edwin Hubble and his colleagues made several discoveries that changed completely our perspective of the Universe in which we live. In particular, they found that the faint spiral nebulae were actually galaxies very distant to our Milky Way (Hubble 1920, 1925) and that they were moving away from us with velocities v proportional to their distance r (Hubble 1929). All these pieces of information were summarized by the famous Hubble law $v = H_0 r$, where H_0 is the Hubble constant. This law was consistent with a uniformly expanding Universe, i.e., the same law holding for any observer on any galaxy.

The implications of such a finding were essentially two opposing categories of models:

1. The big bang models describing a universe emerging from an initial state of temperature and density much higher than the present ones. These models were originally proposed and developed by Friedmann (1922) and Lamaître (1927) within the framework of the general relativity and later investigated also by Gamow (1948).

2. The steady state models, originally proposed by Bondi & Gold (1948) and Hoyle (1948), describing a universe evolving at constant density in spite of the expansion, by assuming the creation of new matter at a rate depending on the rate of expansion. In this universe the only sites of sufficiently high temperatures and densities for the nucleosynthesis of heavier and heavier elements are the interiors of the stars.

The discovery that the radio sources did not seem to remain uniformly distributed as one looked out to greater distances (Ryle 1968) was the first evidence against the steady state model. However, it was definitely ruled out with the discovery of the cosmic microwave background radiation (Penzias & Wilson 1965) and the subsequent proof that it has a blackbody spectrum. The density of the steady state model of the universe is constant by definition, i.e., it was always like it is today, hence far too low to provide the photon interactions needed for thermalization. When Penzias & Wilson (1965) discovered that the background noise in their satellite-monitoring antenna was at a temperature of a few degrees in all the directions, people began to believe that we did indeed live in a big bang universe. Many subsequent observations of this relic radiation at long wavelengths were in fact consistent with a blackbody spectrum of temperature $T = 2.90 \pm 0.08$ K (Woody et al. 1975).

Additional evidence for the universal origin of this radiation was its isotropy. The measurements of its intensity gave the same value in all the directions to within about

0.1% on all angular scales that were investigated (Peebles 1971). No galactic source models for this radiation can take into account of such an isotropy. In the big bang models, on the contrary, this isotropy reflects the uniformity of the universal plasma at the recombination era, when this radiation decoupled from the matter. From this stage onward, photons were able to freely propagate in the space with their blackbody spectrum continuously shifted toward lower and lower temperatures because of the universal expansion.

There were also other types of observational evidences in favor of the big bang models. These included the result that quasars seemed to be much more common at high redshifts (Schmidt 1968), implying that they were more prevalent in the past. The same held for most radio sources, indicating that galaxies were more likely to be strong radio sources in the past than in the in the present (Ryle 1968). This was clearly against the steady state model in which no property can change during the evolution of the universe. Other evidence came from the determinations of the present deceleration parameter $q_0 \equiv -\ddot{R}R / \dot{R}^2$, where the universal scale factor $R(t)$ is proportional to the distance between galaxies. These determinations (Sandage & Hardy 1973, Gunn & Oke 1975) provided a value which was larger than -1 , i.e., the value predicted by the steady state model. Finally, as it will be shown in what follows, the primordial helium abundance provided a strong evidence supporting the big bang models, since no other method of production gives the amount observed in such a natural way. However, the most striking reason for believing that our universe emerged from a big bang still was the 3 K background radiation.

3. The Standard Hot Big Bang Model

3.1 Basic Assumptions.

The element production in the early universe is considered, generally, within the framework of two sets of basic assumptions. The first set of basic assumptions defines what is generally meant by big-bang model. The second set of model assumptions defines a specific big-bang model, i.e., the "standard" model.

The first basic assumptions are that:

1. The principle of equivalence is valid. This means that the (non gravitational) lows of physics, as expressed in their usual special-relativistic form, hold locally in all freely falling frames. This assumption actually implies that the theory of gravitation is described by a metric theory.

2. The Universe was, once, at sufficiently high temperature to ensure statistical equilibrium among all constituents present. This assumption basically allows the investigation of the element production in the early universe at a time when most properties of the constituents of the universe are known, independent of the previous history. Typically the minimum temperature required is $\sim 10^{11}$ K. In fact, the particle energies are such that the laws governing their interactions are known at that time and must not be specified as initial conditions.

The “standard” big bang model is defined by the following additional assumptions, in addition to the previous basic ones discussed above:

3. The lepton number of the universe is less than the photon number. This assumption is equivalent to the requirement that all types of neutrinos are non degenerate. Neutrino degeneracy, i.e. an excess of neutrinos over antineutrinos, or vice versa, would increase the expansion rate of the universe because it increases the density of neutrinos (see below). Moreover, degeneracy of electron neutrinos or antineutrinos would shift the neutron to proton equilibrium ratio established by the weak interactions affecting significantly the big bang nucleosynthesis (as we see below).

4. The baryon number of the universe is positive. This assumption implies that $n_{\bar{\mathrm{B}}} \ll n_{\mathrm{B}} = \eta n_{\gamma}$ where $n_{\bar{\mathrm{B}}}, n_{\mathrm{B}}, n_{\gamma}$ are the number densities of antimatter, matter and photons respectively. η is the so called baryon to photon ratio.

5. Only relativistic baryons and leptons presently known (in addition to photons) were present and magnetic fields were negligible. Possible violations of this assumption include the presence of free quarks, superbaryons, and new types of neutrinos. In the standard model the only particles present at the time of nucleosynthesis are photons, electron and muon neutrinos and antineutrinos, electrons, positrons, neutrons and protons.

6. The cosmological principle was valid. This means that the universe is homogeneous and isotropic.

7. General relativity is valid. This assumption concerns the nature of the gravitational interaction which controls the large scale dynamics of the universe and hence its effect on the nucleosynthesis is through the expansion rate.

3.2 Thermodynamic History of the Universe

The framework for understanding the nucleosynthesis processes during the big bang is the evolution of the various constituents of the early Universe. Indeed, for the nucleosynthesis purposes, we only need to know what occurs after the temperature has dropped below about 10^{11} K (10 MeV), since above this temperature the electromagnetic, strong and weak interactions keep all the particles in statistical equilibrium, making most of their properties independent of the previous history of the universe. In order to understand this result we must first know the history of the expansion rate of the Universe.

On the largest scales the present Universe is observed to be homogenous and is expanding isotropically. Assuming exact homogeneity and isotropy (the cosmological principle), the space-time is described by a unique metric, the Robertson-Walker metric

$$ds^2 = -c^2 dt + R^2(t)\left[\left(1 - ku^2\right)^{-1} du^2 + u^2\left(d\vartheta^2 + \sin^2\vartheta d\varphi^2\right)\right] \qquad (1)$$

Where $R(t)$ is a time-dependent scale factor, k is a dimensionless constant which measures the three-space curvature and u is a radial comoving coordinate (particle world lines are given by $u, \vartheta, \varphi = const.$). The evolutionary history of the cosmological model describing our Universe is contained in the time dependence of the scale factor $R(t)$ which, in general, is obtained by solving the Einstein field equations. By using the Robertson-Walker metric in the Einstein field equations, the Friedmann models are obtained. For the Robertson-Walker-Friedmann models, the evolution of the scale factor is described by the solutions to

$$H^2 = \left[\frac{1}{R(t)}\left(\frac{dR(t)}{dt}\right)\right]^2 = \frac{8\pi}{3}G\rho - \frac{kc^2}{R^2(t)} + \frac{\Lambda}{3} \qquad (2)$$

where $H = H(t)$ is the Hubble parameter, $\rho = \rho(t)$ is the total mass-energy density and Λ is the cosmological constant (G and c are the Newton's constant and the speed of light respectively). For non relativistic matter, the mass density is proportional to the particle number density, $\rho_{\mathrm{b}} = mn$, where (for conserved particles) $n \propto R^{-3}$. In contrast, the mass (energy) of relativistic (R) particles (radiation) is proportional to the number density times the average energy per particle. Now, since all momenta are inversely proportional to wavelengths, $p \propto \lambda^{-1}$, and since all wavelengths scale linearly with the scale factor, $\lambda \propto R^{-1}$, it turns out that $p \propto R^{-1}$ and hence $\rho_{\mathrm{R}} \propto R^{-4}$.

Equation 2 can be conveniently re-written in terms of the present values (indicated by the subscript zero) of the various quantities:

$$\left(\frac{H}{H_0}\right)^2 = \Omega_{\mathrm{R}}\left(\frac{R_0}{R}\right)^4 + \Omega_{\mathrm{M}}\left(\frac{R_0}{R}\right)^3 + \frac{kc^2}{H_0^2 R_0^2}\left(\frac{R_0}{R}\right)^2 + \frac{\Lambda}{3H_0^2} \qquad (3)$$

where we have introduced $\Omega = \rho/\rho_{\mathrm{c}}$, being $\rho_{\mathrm{c}} = 3H_0^2/8\pi G$ the "critical" (or Einstein-de Sitter) density and H_0 the famous Hubble constant.

The early ($t \ll t_0$) evolution of the Universe is dominated by radiation, since for $R \ll R_0$

$$H^2 \approx \frac{8\pi}{3}G\rho_{\mathrm{R}} \qquad (4)$$

Integrating Eq. (4) we obtain

$$\frac{32\pi}{3} G\rho_{\mathrm{R}} t^2 = 1 \tag{5}$$

Since for radiation the energy density scales as the fourth power of the temperature T, it follows from Eq. (5) that $T \propto t^{-1/2}$, i.e., as the time goes on the Universe expands and cools. These relations, coupled with the conservation of energy and conservation of baryons allow one to describe the time evolution of all the universal properties relevant for nucleosynthesis (i.e., temperature and baryon density). These are summarized below:

$$T_9 = \begin{cases} 10.4 \cdot t^{-1/2} & T_9 \gg 3 \\ 13.8 \cdot t^{-1/2} & T_9 \ll 3 \end{cases} \qquad \rho_B = \begin{cases} \varphi_0 \cdot T_9^3 & T_9 \gg 3 \\ \varphi \cdot T_9^3 & T_9 \ll 3 \end{cases} \tag{6}$$

where T_9 is the temperature in units of 10^9 K, ρ_{B} is the baryon density in units of g cm^{-3} and φ is related to the baryon to photon ratio $\eta = n_{\mathrm{B}} / n_\gamma$ by the expression:

$$\varphi = 3.37 \cdot 10^4 \cdot \eta \tag{7}$$

Note that the conservation of baryons guarantees that φ remains constant during the Universe evolution except for a decrease by a factor 2.75 during pair annihilation (see below), if there is no other source of entropy. For this reason in Eq. (6) we have introduced $\varphi_0 = 2.75 \cdot \varphi$ for temperatures much larger than $T_9 = 3$ (i.e. the temperature corresponding to the electron pair annihilation).

3.3 Big Bang Nucleosynthesis Chronology

When the Universe is ~10^{-2} s old, and the temperature is ~10^{11} K (10 MeV), the electromagnetic, strong and weak interactions keep all the Big Bang Nucleoynthesis key actors (neutrinos, electrons, positrons, photons and nucleons) in statistical equilibrium. As a consequence we can start the description of BBN chronology at this epoch. Early in this epoch, the charged current weak interactions, i.e., $\mathrm{n} + \mathrm{e}^+ \rightleftharpoons \mathrm{p} + \bar{\nu}_{\mathrm{e}}$, $\mathrm{n} + \nu_{\mathrm{e}} \rightleftharpoons \mathrm{p} + \mathrm{e}^-$, occasionally beta decay (also inverse decay) $\mathrm{n} \rightleftharpoons \mathrm{p} + \mathrm{e}^- + \bar{\nu}_{\mathrm{e}}$, occur sufficiently rapidly to keep the proton to neutron ratio at its equilibrium value given by

$$\frac{n}{p} = \exp\left[\frac{\left(M_{\mathrm{p}} - M_{\mathrm{n}}\right)c^2}{kT}\right] \tag{8}$$

As the Universe expands and cools the lighter protons are favored compared to the heavier neutrons, hence the n/p ratio decreases tracking the equilibrium value. When the temperature drops to $T \sim 10^{10}$ K ($t \approx 1$ s), the charged current weak interactions became too slow and are no longer able to keep the neutrons and protons in their equilibrium abundance ratio (Eq. (8)). As a consequence the n/p ratio, while continuing to decrease, tends to deviate progressively from its equilibrium value (see Figure 1) reaching an almost constant level.

Since the departure from the equilibrium value strongly depends on the competition between the weak interaction rate and the early Universe expansion rate, deviations from the standard model (i.e., a different expansion rate) would change, even significantly, the relative numbers of protons and neutrons available for the following BBN.

For high temperatures, $e^{\pm}$'s and γ's are maintained in equilibrium by pair production and annihilation ($e^+ + e^- \rightleftharpoons \gamma + \gamma$) and by Compton scattering ($e^{\pm} + \gamma \rightleftharpoons e^{\pm} + \gamma$). As the temperature drops below the energy corresponding to the electron mass ($T \sim 3\times 10^9$ K, $t \approx 10$ s), annihilation proceeds but pair production effectively ceases, since only the very few photons in the tail of the Planck distribution has sufficient high energy to produce a $e^{\pm}$ pair. The annihilations of the $e^{\pm}$'s heat the gas and more photons are produced.

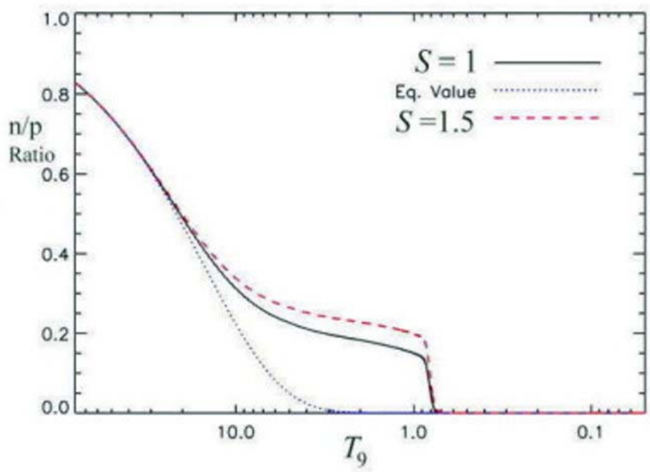

Figure 1. Evolution of the neutron to proton ratio as a function of the temperature in units of 10^9 K. The black solid line refers to the true variation in the standard hot Big Bang model ($S = 1$). The blue dotted line corresponds to the equilibrium n/p ratio (Eq. (8)). The red dashed line is the same as the black line but for a faster early Universe expansion ($S = 1.5$).

During these stages photodisintegrations prevent nuclear reactions from building up other nuclei. Actually, nuclear reactions among neutrons and protons ($p + n \rightleftharpoons {}^2H + \gamma$) proceed very rapidly. However, due to the background of high energetic photons, any deuterium nucleus produced by this reaction is quickly photo dissociated before it can capture another neutron or proton. As a consequence the equilibrium abundance of deuterium is kept at a very small value and constitutes a bottleneck to any further nucleosynthesis of heavier nuclei. As the temperature decreases the deuterium equilibrium abundance tends progressively to increase and fewer and fewer deuterium photodisintegrations occur. When the temperature drops to $T \sim 10^9$ K ($t \approx 100$ s), the deuterium abundance becomes high enough to allow a significant building up of heavier nuclei and BBN effectively takes place. Tritium and ^{3}He are formed through the following reactions: $^2\mathrm{H(n,\gamma)}^3\mathrm{H}$ [where the notation $i(j,k)l$ is equivalent to $i + j \rightarrow k + l$], $^2\mathrm{H}(^2\mathrm{H,p})^3\mathrm{H}$, $^2\mathrm{H(p,\gamma)}^3\mathrm{He}$ and $^2\mathrm{H}(^2\mathrm{H,n})^3\mathrm{He}$; $^3\mathrm{H}$ and $^3\mathrm{He}$ interact directly via $^3\mathrm{He}(\mathrm{n},p)^3\mathrm{H}$ and $^3\mathrm{H} \rightarrow {}^3\mathrm{He} + \mathrm{e}^- + \overline{\nu}_\mathrm{e}$. Tritium is converted into $^4\mathrm{He}$ through $^3\mathrm{H(p,\gamma)}^4\mathrm{He}$ and $^3\mathrm{H}(^2\mathrm{H,n})^4\mathrm{He}$, while $^3\mathrm{He}$ is burned into $^4\mathrm{He}$ through $^3\mathrm{He(n,\gamma)}^4\mathrm{He}$, $^3\mathrm{He}(^2\mathrm{H,p})^4\mathrm{He}$ and $^3\mathrm{He}(^3\mathrm{He,2p})^4\mathrm{He}$. The occurrence that no stable nuclei are present with atomic mass of 5 and 8, respectively, constitutes a bottleneck for the nucleosynthesis of heavier nuclei. However, even in absence of such gaps, the rapid decline of the temperature due to the expansion of the Universe, making the Coulomb barrier more important, would prevent the synthesis of elements heavier than helium in a sizeable amount. Some amounts of $^7\mathrm{Li}$ and $^7\mathrm{Be}$ are produced via $^4\mathrm{He}(^3\mathrm{H},\gamma)^7\mathrm{Li}$ and $^4\mathrm{He}(^3\mathrm{He},\gamma)^7\mathrm{Be}$.

When the temperature drops down to $T \sim 4\times10^8$ K ($t \approx 10^3$ s), the Coulomb barriers become so large that nucleosynthesis is effectively terminated. Because of the gap corresponding to the atomic weight 5 and the Coulomb barrier, most of the neutrons that were present when nucleosynthesis began are incorporated in $^4\mathrm{He}$, i.e., the most tightly bound light isotope. Since each alpha particle contains two neutrons, a rough estimate of the primordial abundance of $^4\mathrm{He}$ by number is half of the initial neutron abundance at the time the nucleosynthesis began. The temporal evolution of the abundances of the light elements n, p, ^{2}H, ^{3}He, ^{4}He, ^{7}Li, ^{7}Be is shown in Figure 2 for the standard Big Bang model and for $\eta = 3.4\times10^{-10}$.

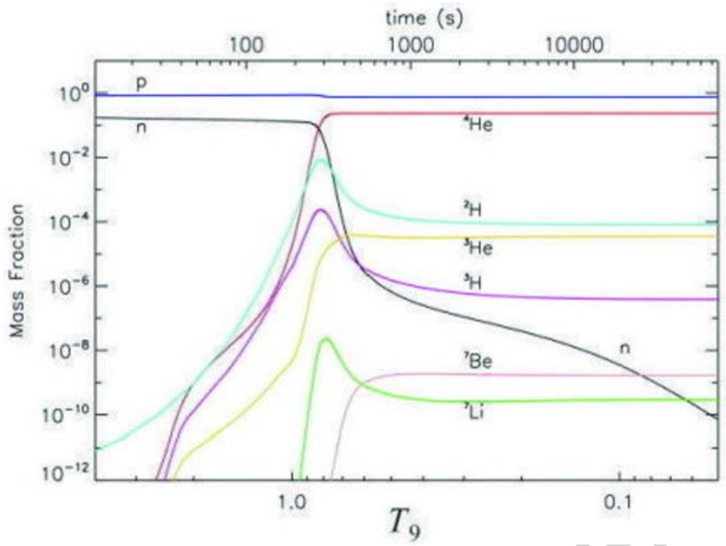

Figure 2. Evolution of the various nuclear abundances as a function of both time and temperature during the expansion of a standard hot Big Bang model with $\eta = 3.4 \times 10^{-10}$.

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Biographical Sketch

Marco Limongi earned his Ph.D. in 1995 at the University of Rome “La Sapienza” and since 1995 he is a staff research astronomer of the Italian National Institute for Astrophysics at the Observatory of Rome. Currently he is also an adjunct professor at the University of Rome, a member of the Italian Astronomical Society, a joint appointments at the Institute for the Physics and the Mathematics of the Universe (Tokyo, Japan), a honorary member of the Maths Department and Center for Stellar and Planetary Astrophysics at Monash University (Australia) and the Vice President of the Organizing Committee of the International Astronomical Union (IAU) - Division IV – Commission 35 “Stellar Constitution”. Marco Limongi’s research centers on theoretical stellar evolution, more specifically, the study of the evolutionary properties of stars in a wide range of initial masses and initial compositions. His current projects include modeling the evolution of massive stars (in the range 8-140 times the mass of the sun) through all the hydrostatic nuclear burning stages up to the pre-explosive stage in order to obtain realistic pre-supernova stars and detailed nucleosynthesis of all the isotopes lighter than Molybdenum. These calculations, continuously repeated with improvements in the microphysics (nuclear reaction rates, opacities, equation of state) and with the inclusion of physical phenomena like mass loss, rotation and magnetic fields, are fundamental in many fields of astrophysics among which, the chemical evolution of the galaxies, the g-ray astronomy, the nuclear astrophysics, the understanding of the explosion mechanism for core collapse supernovae.