Nuclear astrophysics

M Arnould †§ and K Takahashi‡‖

† Institut d'Astronomie et d'Astrophysique, Université Libre de Bruxelles, Campus Plaine, CP 226, B-1050 Bruxelles, Belgium   marnould@astro.ulb.ac.be

‡ Max-Planck-Institut für Astrophysik, Karl-Schwarzschild-Str. 1, D-85740 Garching, Germany   kjt@mpa-garching.mpg.de

Abstract.

Nuclear astrophysics is that branch of astrophysics which helps understanding the Universe, or at least some of its many faces, through the knowledge of the microcosm of the atomic nucleus. It attempts to find as many nuclear physics imprints as possible in the macrocosm, and to decipher what those messages are telling us about the varied constituent objects in the Universe at present and in the past. In the last decades much advance has been made in nuclear astrophysics thanks to the sometimes spectacular progress made in the modelling of the structure and evolution of the stars, in the quality and diversity of the astronomical observations, as well as in the experimental and theoretical understanding of the atomic nucleus and of its spontaneous or induced transformations. Developments in other sub-fields of physics and chemistry have also contributed to that advance. Notwithstanding the accomplishment, many long-standing problems remain to be solved, and the theoretical understanding of a large variety of observational facts needs to be put on safer grounds. In addition, new questions are continuously emerging, and new facts endangering old ideas.

This review shows that astrophysics has been, and still is, highly demanding to nuclear physics in both its experimental and theoretical components. On top of the fact that large varieties of nuclei have to be dealt with, these nuclei are immersed in highly unusual environments which may have a significant impact on their static properties, the diversity of their transmutation modes, and on the probabilities of these modes. In order to have a chance of solving some of the problems nuclear astrophysics is facing, the astrophysicists and nuclear physicists are obviously bound to put their competence in common, and have sometimes to benefit from the help of other fields of physics, like particle physics, plasma physics or solid-state physics. Given the highly varied and complex aspects, we pick here some specific nuclear physics topics which largely pervade nuclear astrophysics.

PACS numbers: 00.00, 20.00, 42.10

§ to whom correspondence should be addressed.

‖ supported by the SFB 375, Astro-Particle Physics, of the Deutsche Forschungsgemeinschaft

Contents

1. Introduction
2. Observational foundation
   2.1. The Hertzsprung-Russell diagram (HRD)
   2.2. Electromagnetic spectra and abundance determinations
      2.2.1. The spatio-temporal evolution of the composition of our Galaxy
      2.2.2. The composition of other galaxies
      2.2.3. Abundances in evolved or exploding stars
      2.2.4. A special electromagnetic message from the sky: γ-ray line astrophysics
   2.3. The composition of the solar system
      2.3.1. The bulk solar-system composition
      2.3.2. Isotopic anomalies in the solar composition
      2.3.3. The composition of cosmic rays and solar energetic particles
   2.4. Neutrino astronomy
3. The contributors to nuclei in the Cosmos
   3.1. Some generalities about stellar structure and evolution
      3.1.1. $M \gtrsim 10$ $M_\odot$ stars
      3.1.2. $0.45 \lesssim M \lesssim 8$ $M_\odot$ stars
      3.1.3. $8 \lesssim M \lesssim 10$ $M_\odot$ stars
      3.1.4. Binary stars
   3.2. Spallation reactions
   3.3. The Big Bang contribution to nucleosynthesis
   3.4. The chemical evolution of galaxies
4. Nuclear data needs for astrophysics: Nuclear masses, decay modes
   4.1. The masses of "cold" nuclei
   4.2. Nuclei at high temperatures
   4.3. Nuclei at high densities
   4.4. Nuclear decays and reactions via weak interaction
      4.4.1. Various β-decay modes in astrophysics
      4.4.2. Neutrino reactions
      4.4.3. β-decays from nuclear excited states
      4.4.4. β-decays at high ionization
   4.5. Nuclear decays and reactions via electromagnetic interaction
   4.6. Nuclear decays via strong interaction
5. Thermonuclear reactions in non-explosive events
   5.1. Energy production in the Sun, and the solar neutrino problem
   5.2. Non-explosive stellar evolution and concomitant nucleosynthesis
      5.2.1. Hydrogen burning
      5.2.2. Helium burning and the s-process
      5.2.3. Carbon burning
      5.2.4. Neon, oxygen, and silicon burning

6. Thermonuclear reactions in explosive events
   6.1. Big Bang nucleosynthesis
   6.2. The hot modes of hydrogen burning
      6.2.1. The hot p-p mode
      6.2.2. The hot CNO and NeNa-MgAl chains
      6.2.3. The rp- and αp-processes
   6.3. The He to Si explosive burnings
   6.4. The α-process and the r-process
   6.5. The p-process
7. Nuclear data acquisition for astrophysics
   7.1. Nuclear binding
      7.1.1. Nuclear mass models
      7.1.2. Nuclear equation of state at high temperatures/densities
   7.2. Nuclear decay properties
      7.2.1. Beta-decay half-lives and strength functions
      7.2.2. Bound-state β^- decays
   7.3. Charged-particle induced reactions: Experiments
      7.3.1. Direct cross-section measurements
      7.3.2. Indirect cross-section measurements
   7.4. Neutron capture reactions: Experiments
   7.5. Thermonuclear reaction rates: Models
      7.5.1. Microscopic models
      7.5.2. The potential and DWBA models
      7.5.3. Parameter fits
      7.5.4. The statistical models
8. Selected topics
   8.1. Heavy-element nucleosynthesis by the s- and r-processes of neutron captures
      8.1.1. Defining the s-process
      8.1.2. Defining the r-process
      8.1.3. The s- and r-process contributions to the solar-system composition
      8.1.4. Astrophysical sites for the s- and r-processes
      8.1.5. Heavy elements in low-metallicity stars
   8.2. Cosmochronometry
      8.2.1. Nucleo-cosmochronology: generalities
      8.2.2. The trans-actinide clocks
      8.2.3. The ^{187}Re - ^{187}Os chronometry
   8.3. Type-II supernovae
      8.3.1. Evolution of massive stars leading to neutrino-driven supernovae
      8.3.2. Nucleosynthesis in the hot bubble: Can the r-process occur ?
      8.3.3. Signatures of a large-scale mixing of nucleosynthesis products
9. Summary

References

1. Introduction

Uniting astronomy and physics, astrophysics aims at deciphering the macro-structure of the Universe and of its various constituents. To reach this goal the physical laws investigated on earth are systematically applied to the vast and diverse laboratory of space, and a key concept pervading the whole field is its being interdisciplinary. In particular, cosmology, every branch of astronomy, astronautics, elementary-particle-, nuclear-, atomic- and-molecular physics, and geo- and cosmo-chemistry have to take their worthy share to the common adventure.

More often than not the cosmic objects exhibit macroscopic properties that bear clear fingerprints of the micro-physics of the elementary particles or nuclei making up the matter. This review deals with the very special interplay between nuclear physics and astrophysics, which is embodied into a field commonly referred to as "nuclear astrophysics." Its main goal is to explain the huge energy output from some cosmic objects, and especially from stars, as well as to provide a coherent picture for the spatial and temporal variations of the abundances of the nuclides in the Universe and its various constituent objects. Its adjacent and derivative sub-field of astrophysics is "particle astrophysics." It is not that nuclear astrophysics does not need to be well aware of the basic properties of the elementary particles in addition to those of the nuclei. But the very origin of these particles is outside of its realm. When it searches for the origin of the nuclides, for instance, nuclear astrophysics is quite content with the existence of the proton, and leaves the responsibility of unravelling its very origin to "baryosynthesis" models ([1]).¶

The hypothesis that the energy production in the Sun and other stars results from the energy output of nuclear reactions was formulated, apparently for the first time and soon after the first measurements of atomic masses, by Russell [2], followed shortly by Perrin [3] (see [4] for historical developments). Following the clarification of the composition of the atomic nuclei in 1932 with the discovery of the neutron, Gamow, von Weizsäcker, Bethe and others put that idea on a quantitative basis. In particular, the energy source of the Sun was ascribed to the so-called "p-p chain" of reactions, the net effect of which being the "burning" of four protons into a ^{4}He nucleus. The energy release is about 6 MeV per proton (meaning about 2×10^{19} kg or 10^{-11} $\mathrm{M}_\odot$ of protons burning per year presently in the Sun, where the mass of the Sun $\mathrm{M}_\odot \approx 2 \times 10^{30}$ kg). A myriad of further works have substantiated these early ideas beyond doubt.

The focal role played by the nuclear reactions in the "alchemy" of the Universe also started to be recognized, leading to the development of a major chapter of nuclear astrophysics referred to as the "theory of nucleosynthesis." Some nucleosynthesis models developed in the late 1940s assumed that the nuclides were built in a primordial "fireball" at the beginning of the Universe ([5]). In spite of some attractive features those models

¶ Though bulky it may be, the reference list is by no means meant to be complete. Throughout the text, therefore, the readers are kindly requested to interpret a doubly bracketed citation ([#]...) as (see e.g. [#] and the references therein...)

failed to explain the mounting evidence that all stars do not exhibit the same surface composition. They were also unable to explain the presence of the unstable element technetium (Tc) discovered by Merrill [6] at the surface of certain giant ("S-type") stars. (No technetium isotope lives more than a few million years.)

The problems encountered by those models of primordial nucleosynthesis put to the forefront the idea previously expressed by Hoyle [7] that stars are likely to be major nucleosynthesis agents. By the late 1950s the stellar nucleosynthesis model, substantiated by some seminal works including the famed B^{2}FH [8], was recognized as being able to explain the origin of the vast majority of the naturally-occurring nuclides with mass numbers $A \geq 12$. One key theoretical step in the development of these ideas was the identification [9, 10] of the so-called "3α" nuclear transformation enabling to bridge in stars the gap of stable nuclides at mass number $A = 8$. In this process the unbound ^{8}Be nucleus created in equilibrium with the $\alpha + \alpha$ system can capture an α-particle to produce ^{12}C, which is the starting point for the synthesis of heavier species. In considering the relative abundances of ^{4}He, ^{12}C and ^{16}O, Hoyle went so far as to predict the existence of a 7.7 MeV 0^+ excited state of ^{12}C as a resonant state in the ^{8}Be+α reaction that was soon discovered experimentally [11] - [13]. Despite these early successes, the natural abundances of the light nuclides (D, ^{3}He, ^{4}He, ^{6}Li, ^{7}Li, ^{9}Be, ^{10}B, ^{11}B) were difficult to explain in terms of stellar thermonuclear processes, and their very origin has remained puzzling for some time.

Since those pioneering works, nuclear astrophysics has advanced at a remarkable pace and has achieved an impressive record of success. Factors having contributed to the rapid developments include the progress in experimental and theoretical nuclear physics, ground-based or space astronomical observations, and in astrophysical modelling. In fact, nuclear astrophysics has constantly been challenged, and at the same time inspired, by new discoveries, many of them marking epochs in the history of science and leading to the birth of a new sub-field of research. We name here a few of such events in the observational front that have had a great impact on nuclear astrophysics:$^+$

(1) the discovery in 1965 of the 3K microwave background, which provided a major support of the Big Bang model and opened a new era of cosmology. In the realm of nuclear astrophysics it resurrected the "primordial nucleosynthesis" idea. However, in contradistinction to the earlier ideas referred to above, it appeared soon to be efficient for some light nuclides only;

(2) the detection in the late 1960s of the neutrinos from the Sun, providing the first "vision" of the very interior of a star. With time it appeared more and more convincing that the observed flux was lower than predicted by the solar models. The infamous "solar neutrino problem" was born, implying our incomplete understanding of the structure and evolution of the Sun (and likely of stars in general), of nuclear reactions in the solar plasma, of the neutrino properties, or possibly any combination thereof;

(3) the discovery in minute fractions of the meteoritic material of a suite of chemical

$^+$ Omitted here, the references will be given later along with further discussions of individual items elements exhibiting isotopic compositions that differ from those characterizing the bulk solar-system material. Quite remarkably, it was soon realized that some of these "isotopic anomalies" are due to the *in situ* decay of by now-extinct short-lived radionuclides with half-lives ($t_{1/2}$) ranging from about 10^5 to 10^8 years. A notable example of this type concerns ^{26}Al ($t_{1/2} = 7.4 \times 10^5$ y). Even the record of the *in situ* decay of the "ultra-short-lived" ^{22}Na ($t_{1/2} = 2.6$ y) and ^{44}Ti ($t_{1/2} = 60$ y) seems to have been kept in some meteoritic material;

(4) the discovery in the interstellar medium of a γ-ray line from the de-excitation of ^{26}Mg produced by the β-decay of ^{26}Al. This detection has led to the vigorous development of a new type of astronomy, i.e. the γ-ray line astronomy;

(5) the supernova SN1987A in the Large Magellanic Cloud has been a milestone for many fields of astrophysics. The detection of some neutrinos from this explosion has opened the new chapter of the astrophysics of non-solar neutrinos. More has been added to the growing γ-ray line astrophysics, as well as to nuclear astrophysics and particularly to the theory of nucleosynthesis in explosive environments.

In order to take up the continuous challenge from new observational facts, nuclear astrophysics concepts and models have to be put on a firmer and firmer footing. To achieve this goal a deeper and more precise understanding of the many nuclear physics processes operating in the astrophysical environments is crucial, along with improved astrophysical modelling. Naturally, the acquisition of new nuclear physics data is indispensable in the process. This quest is, however, easier said than done, given the fact that it is generally very difficult, if not impossible, to simulate in the laboratory the behaviour of a nucleus under relevant astrophysical conditions, or even to produce nuclei that might be involved in astrophysical processes. Consequently, the development of novel experimental techniques is not sufficient, and has to be complemented by the progress of the theoretical modelling of the nucleus. Both experimental and theoretical approaches face great difficulties of their own. It may be worth noting here that, although initially motivated by astrophysics, some experimental and theoretical nuclear physics efforts have provided on many occasions unexpected intellectual rewards in nuclear physics itself.

The items of relevance to nuclear astrophysics listed above by no means exhaust the questions this field of research has to tackle. They are in reality so varied that it appears impossible to review them all here in any decent way (this diversity is illustrated by the many contributions to recent nuclear astrophysics conferences; see e.g. [14] - [21]). We will consequently limit ourselves to a presentation of a selected set of questions involving what we consider to represent the earnest efforts made in recent years in order to decipher the nuclear fingerprints in the Universe with the help of the improved knowledge of nuclear data of astrophysical interest. In many instances, some astrophysics basics and motivations will also be provided in order to help the non-expert readers, who may very profitably refer to the textbooks [22] - [25] for many more details.

Section 2 reinforces with generalities the above discussion on observational facts having important bearings upon nuclear astrophysics. Section 3 presents an overview of the identified main contributing agents to nuclei in the Cosmos. In Sects. 4 to 7 we address the following broad questions: (1) what sorts of nuclear data are necessary for which astrophysical scenarios, (2) what are the changes in nuclear properties inferred when going from the laboratory to astrophysical sites, and (3) how can one acquire such data by laboratory experiments, or supplementarily by theoretical models ? For the sake of clarity we attempt to answer those questions successively, although considerable overlaps are inevitable.

For that, we first examine in Sect. 4 the static and decay properties of nuclei, and furthermore make the reader aware of the fact that astrophysics forces us to tackle some of those very basic nuclear physics questions in quite an unconventional way. With the basic nuclear properties provided, the most crucial knowledge in quest concerns the rates of various nuclear reactions in energy domains of astrophysical interest, which is a focus of continuing, dedicated laboratory studies.

The nuclear reactions to be dealt with are of "thermonuclear" or "spallative" nature. The latter ones act in low-temperature, low-density media through the interaction of non-thermally accelerated particles with the interstellar medium ("ISM" in the following), or with the material (gas or grains) at stellar surfaces and in circumstellar shells (Sect. 3.2). The former ones have developed at the cosmological level (Big Bang), and continue to take place in stars. They are charged-particle induced reactions, neutron-capture reactions, and photodisintegrations. We do not deal in this review with the nuclear physics aspects of spallation reactions, and concentrate instead on thermonuclear reactions. Sections 5 and 6 are devoted to some general considerations about such transmutations, which are divided into two categories: one concerned with non-explosive events, and the other with explosive phenomena. This is done in view of the different experimental and theoretical problems raised by the determination of the rates of the relevant reactions, as well as of the different and complementary roles they play in astrophysics.

In Sect. 7 we summarize the experimental and theoretical techniques for the acquisition of the relevant nuclear data. Section 8 presents a few topics that illustrate quite vividly the beauties, as well as the complexities, of nuclear astrophysics and of its relation to various sub-fields of astrophysics. A brief summary and outlook is given in Sect. 9.

2. Observational foundation

The observational foundation of nuclear astrophysics, and more specifically of the theory of nucleosynthesis, rests largely upon the determination of elemental and isotopic abundances in the broadest possible variety of cosmic objects, as well as upon the study of as complete a set as possible of observables that help characterizing the objects. This knowledge relies almost entirely on the detailed study of the light originating from a large diversity of emitting locations: our Galaxy (non-exploding or exploding stars of various types, the ISM), external galaxies, and perhaps even the early Universe.

Recent progress in optical astronomy, paralleled by the advent of a variety of "new" (in particular: infrared, UV, X- and γ-ray) astronomies, has led to the unprecedented vision we now have of the sky at all wave-lengths, ranging from radio-frequencies to γ-ray energies (up to the TeV and PeV domain). Very often these dramatic advances are directly related to those of the space technologies ([26]). The characteristics of the emitted light are often associated with the temperature in the environment ("heat radiation"), the most exemplary situation of this type being the black-body radiation. Non-thermal sources have also been identified, which emit generally high-energy photons (e.g. X- and γ-rays). Bremsstrahlung, synchrotron radiation and nuclear radioactivity are good examples of this sort.

The studies of the electromagnetic radiation are complemented with the careful analysis of the minute amount of matter of the Universe accessible to humankind. This matter is comprised for its very largest part in various types of solar-system solids. The rest is in the form of (extra-)galactic cosmic rays. The observation of solar and non-solar neutrinos has also been a major step for nuclear astrophysics as well as for many other fields of astrophysics.

It is impossible to review here the myriad of observational data that are relevant to nuclear astrophysics. In what follows we illustrate by way of selected examples the nuclear-astrophysics importance of the deciphering of some electromagnetic messages from the sky.

2.1. The Hertzsprung-Russell diagram (HRD)

The HRD represents a given sample of stars in a (colour, surface brightness) plane, or any equivalent plane, where the colour is replaced by a "colour index," "spectral type" or "effective temperature," and the surface brightness ("luminosity") by some "magnitude" scale (see [27] for the definitions of these various basic quantities, and for the relations among them). The adoption of the magnitude and colour scales leads to a "colour-magnitude" (C-M) representation of the HRD, examples of which are provided in Figs. 1 and 2.

The HRD is generally considered as the "Rosetta stone" of stellar evolution for the key role it has played in the development of the theory of stellar structure and evolution. The most remarkable feature of the HRD is undoubtedly the existence of concentrations of stars from a given sample along correlation *lines*. Various such lines can be identified. The most spectacular one is certainly the "Main Sequence (MS)" running diagonally in the HRD from its red low-luminosity sector to its blue high-luminosity one. Other concentrations are also visible, like the "Horizontal Branch (HB)," the "Red Giant Branch (RGB)" or "Asymptotic Giant Branch (AGB)." It is also very important to recognize that the relative populations of different correlation lines, or even of different portions of a given line, depend upon the selected star sample. For example, the RGB and AGB branches are almost totally vanishing, while the blue portion of the MS is well developed, in the HRD for samples of rather young stars located in the galactic disc

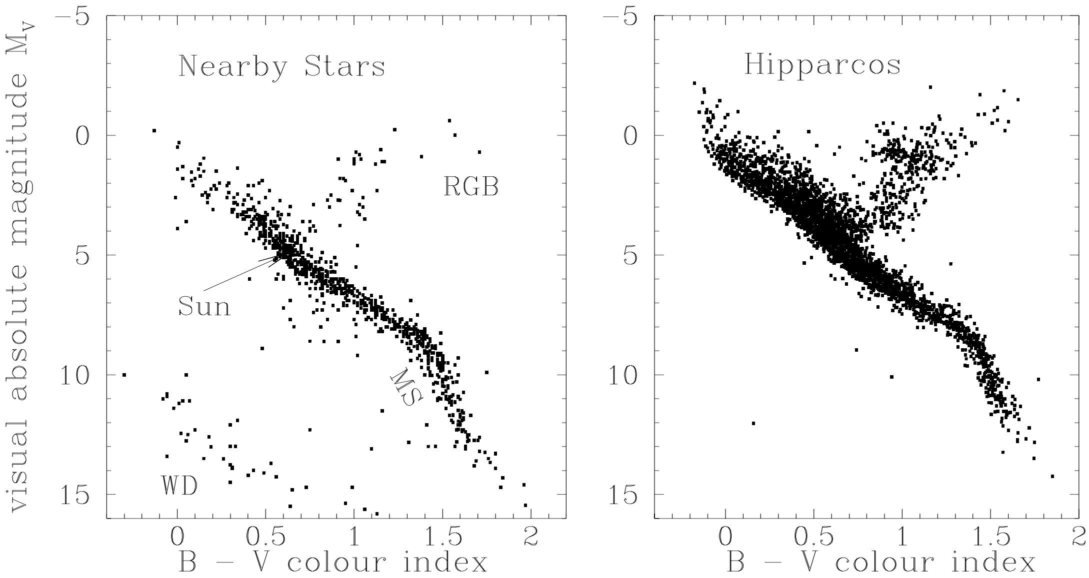

Figure 1. Examples of colour-magnitude diagrams. *Left panel:* for a sample of *ca.* 1000 nearby stars [28] with distances less than about 20 pc [1 pc (parsec or parallax second) = 3.086×10^{13} km]. *Right panel:* for a sample of *ca.* 5000 stars (most located in the 60 - 70 pc range) as observed by the HIPPARCOS satellite [29]. Each point represents a sample star. The labels MS, RGB and WD refer to "Main Sequence," "Red Giant Branch" and "White Dwarf" stars. The magnitudes displayed in ordinate are defined as decreasing by five units for a one hundred-fold increase of the luminosity (emitted power through the whole stellar surface), so that the lower the magnitude, the brighter the star at the origin. Thus the intrinsically brighter (dimmer) stars are located in the upper (lower) part of the displayed diagram. The observed luminosity (at the top of the Earth atmosphere), or the "apparent magnitude," decreases quadratically with the distance from the star. Given this distance, the "absolute magnitude" is defined to be what one would observe if the star were re-located at 10 pc. The visual absolute magnitude M_V and its counterpart (visual apparent magnitude) V are associated with the stellar brightness in the yellow (V) band of the widely used UBV trichromatic system ([27]). The abscissa displays the most commonly used colour index. It expresses the difference between the apparent magnitudes in the blue (B) and visual (V) bands. The lower the index, the bluer the star. The bluer (redder) stars are thus located more to the left (right) side in the diagram. For confrontations with model predictions it is operationally convenient to convert magnitudes into absolute luminosity values, and colour indices into "effective temperatures," $T_{\rm eff}$, defined as the temperatures of black bodies that would radiate the same flux of energy as the considered stars ([27] for details)

(like the nearby stars shown in Fig. 1), or stars belonging to so-called open clusters (left panel of Fig. 2). In contrast, the blue end of the MS almost vanishes, while the RGB or AGB branches are strikingly apparent, in the HRD for globular clusters populating the galactic halo and made of relatively old stars (right panel of Fig. 2).

The theory of stellar structure and evolution is now able to explain these specific characteristics of the topology of the HRD, often in a quite quantitative way ([33]). It is well beyond the scope of this review to discuss these questions at length. Let

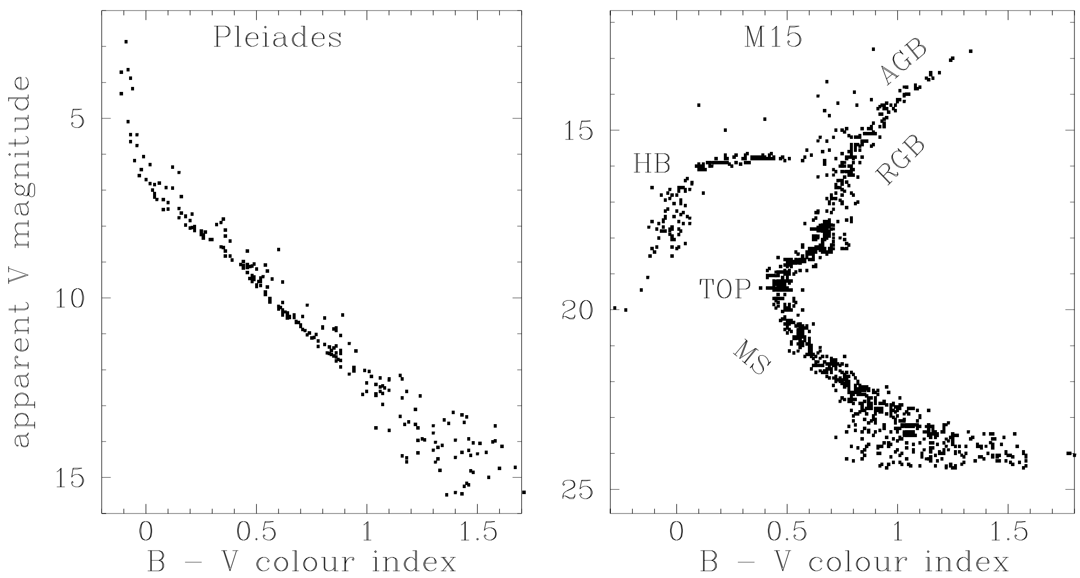

Figure 2. Same as Fig. 1, but for the Pleiades, a young galactic ("open") cluster (*left panel*), and for the old "globular cluster" M15 (*right panel*). The labels "HB" and "AGB" refer to "Horizontal Branch" and "Asymptotic Giant Branch" stars. The label "TOP" identifies the top of the MS branch. Note that all member stars of a globular or open cluster are at essentially equal distance from the observer, so that the transformation from apparent to absolute magnitudes in the HRD for a given cluster would just correspond to an equal shift of all the points by an amount dictated by the (squared) distance of that cluster. With the use of the observed distances, the ordinates are adjusted here in such a way that the M_V magnitudes for both clusters have the same scale height. The data points for the Pleiades are from [30]. (Omitted are half a dozen of the brightest stars, whose specific locations in the diagram require special attention because of their rapid rotation [31].) The data for M15 are from [32]

us just stress two basic findings: (1) *formally* it can be demonstrated that the very existence of correlation *lines* (as opposed to broad correlation *surfaces*) is the direct signature of stellar structures in which the energy output can be counter-balanced by a nuclear energy production, this situation being generally referred to in astrophysics as a state of "thermal equilibrium" ([34] for a discussion of this statement).* So, the observed HRD correlations bring nuclear physics and astrophysics closely together; and (2) *numerically* it appears that the MS, RGB, HB and AGB concentrations correspond in fact to stages of central H burning, shell H burning, central He burning, and double shell H-He burning. For a given star, the H-burning phase is by far the longest. On the other hand, calculations show that the duration of each burning stage decreases with increasing stellar mass. In between these phases the stars are out of thermal equilibrium and are predicted to evolve quickly, and more so with increasing stellar mass. These dissimilarities in evolutionary time-scales between thermal equilibrium and non-equilibrium and among stars of different masses account very well for the differences

* The situation concerning the white dwarf (WD) clustering involves a different physics which does not call for a nuclear energy source ([35])

in the populations of the diverse correlation lines of the HRD for a given sample of stars, as well as for the changes in the population of a given correlation line between HRDs for samples of, for instance, old and young stars. ([36] for details.) In particular, the location of the top of the MS of globular clusters (Fig. 2, right panel) is used to evaluate the age of these clusters ([37, 38]; Sect. 8.2)

2.2. Electromagnetic spectra and abundance determinations

Very roughly speaking, the light from the sky appears to demonstrate some uniformity of composition of the objects in the Universe, which is most strikingly exemplified by the fact that H and He are by far more abundant than the heavier species in the whole observable Universe. However, they also point to a great diversity of elemental and/or isotopic abundances that superimposes on that uniformity at all scales ranging from stars to galaxies and galaxy clusters. They imply diverse classes of objects, as well as a diversity of the objects belonging to a given class. It is impossible here to do justice to the richness of the information gained by now in this field, and we just limit ourselves to some guiding considerations.

2.2.1. The spatio-temporal evolution of the composition of our Galaxy This evolution can be traced by deriving the surface abundances for a suitably selected and large ensemble of stars. These stars are chosen on grounds of two requirements: (1) they have to span substantial ranges of ages and locations in our Galaxy. So, old halo or disc stars, old stars in globular clusters, as well as young disc stars have been under active scrutiny; and (2) their surfaces are likely not contaminated with nuclear-processed matter from their interiors, and have well preserved the composition of the Galaxy at the place and time of their birth. This is clearly an essential requirement in order for these stars to witness the large-scale time and space variations of the nuclear content of the Galaxy. Such information from stars is very usefully complemented with the analysis of the composition of the present-day ISM at various galactic locations.

¿From the large body of abundance observations, some very general trends emerge, which can just be sketched here:
(1) At a global scale the "metallicity"♯ increases with time at a pace that itself varies with time and place in the Galaxy, as sketched in Fig. 3. This leads to metallicity differences among the various galactic subsystems: halo, (thick and thin) disc, bulge, centre (for a discussion of the structure of our Galaxy, see Chap. 2 of [41]). Also metallicity gradients can exist in these subsystems, along with possible more local variations;
(2) Trends as well as scatters with respect to the metallicity index are identified in the abundances of a large variety of elements. These data concern elements ranging from Li, Be and B of cosmological importance ([42]) to the rare-earth elements ([43]). Figure 4

♯ The metallicity is generally measured by the sum of the abundances of all nuclides with mass numbers $A \geq 12$. An oft-used metallicity indicator is Fe. For certain classes of stars, and in particular old stars, this choice is probably not the most suitable one, and O may replace Fe as the reference element

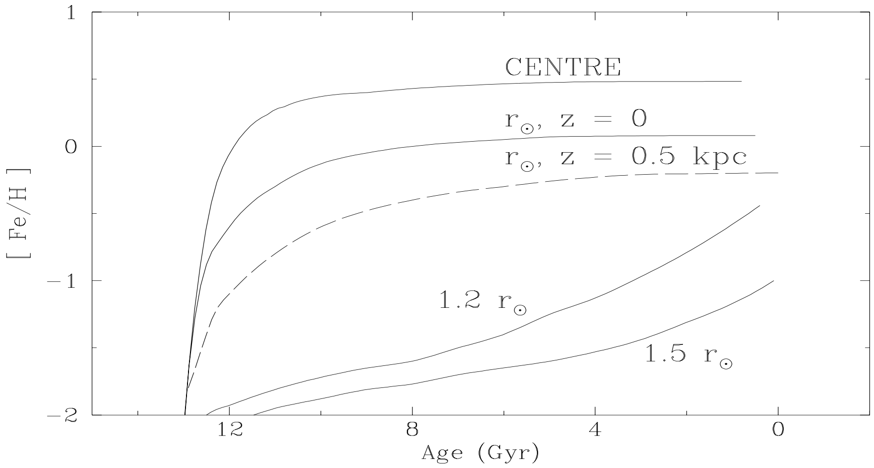

Figure 3. A "schematic suggestion" [39] of the age-metallicity relationships for five locations in the Galaxy: the galactic centre (CENTRE); at the distance of the Sun ($r_\odot$) measured from the galactic centre in midplane ($z = 0$) of the galactic disc; at $r_\odot$, but at a distance $z = 500$ pc from the galactic midplane; and 1.2 and 1.5 $r_\odot$ at $z = 0$. The metallicity in ordinate is expressed in the usual stellar spectroscopic notation [Fe/H] $\equiv \log_{10}(\mathrm{Fe/H})$ - $\log_{10}(\mathrm{Fe/H})_\odot$, where the chemical symbols represent abundances by number, and the subscript $\odot$ refers to the Sun, with $\log_{10}(\mathrm{Fe/H})_\odot \approx -4.5$ [40]

illustrates the metallicity dependence of the so-called "α-elements," each of which has the most abundant isotope (in the bulk solar-system at least; see Sect. 2.3) with a mass number equal to a multiple of four ($A = 4n \leq 56$). These variations again demonstrate that different elements or groups of elements accumulate at different rates at different locations of the Galaxy. This is certainly the signature of different nucleosynthesis processes acting with unequal spatial and temporal efficiencies.

A clear indication also emerges that mixing processes among the various galactic subsystems, or even at smaller scales within a given subsystem, may have had a limited efficiency. Among the demonstrated composition inhomogeneities within a given subsystem, let us note a very interesting difference in abundance patterns in certain elements between two of the oldest star populations in the halo, i.e., the field halo stars and those which are members of globular clusters ([48]);
(3) The abundance determinations obtained from the analysis of photospheric spectra are very usefully complemented with data derived from the study of the gas and grain components of galactic interstellar clouds and circumstellar envelopes. These observations are done at radio-wavelengths ([49]) as well as in the UV domain ([50]). They provide in particular a very interesting piece of information on the existence or absence in the galactic disc of radial gradients of isotopic ratios for some major elements, including C, N and O, and thus essential constraints to modern models for the evolution of the chemical content of the Galaxy.

2.2.2. The composition of other galaxies In addition to the very many abundance data concerning the various constituents of our Galaxy, information on other galaxies

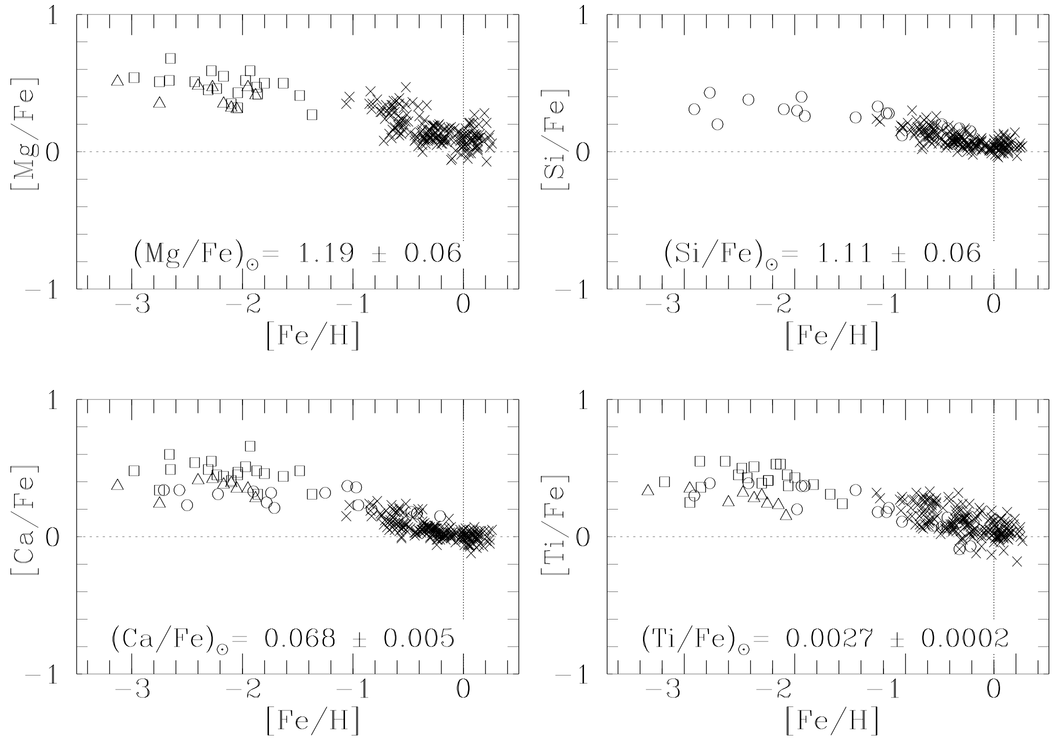

Figure 4. Metallicity dependence of various "α-elements," showing that the Galaxy has been enriched in the displayed elements more rapidly than in Fe. Roughly speaking, stars with [Fe/H] $\lesssim$ - 1 are in the halo, and more metal-rich stars are in the disc. The data are taken from: [44] (*squares*); [45] (*circles*); [46] (*crosses*); and [47] (*triangles*)

is now accumulating very rapidly. The analysis of such data forces the conclusion that abundances and their spatial trends may vary quite significantly from galaxy to galaxy, even within a given galaxy class. Substantial local variations are also observed in many instances. One of the most significant recent advances in the study of galactic abundances concerns high-redshift galaxies [referred to as "Damped Lyman α systems (DLAs)"], which provide information on their composition at an early phase in their evolution: the highest the redshift, the shortest the evolution history of their constituent elements from their pristine stage. An "age-metallicity relation" constructed from a sample of DLAs spanning a range of redshifts indicates that a DLA of a given age has a lower metallicity than do the disc stars of our Galaxy at the same age (Fig. 5). Data start accumulating on the DLA abundances for a variety of elements ranging up to Ni [51]. These observations will certainly provide a wealth of information, which the theory of nucleosynthesis and of the chemical evolution of galaxies will have to cope with.

2.2.3. Abundances in evolved or exploding stars On top of the spatio-temporal abundance variations that exist at all scales in galaxies or galaxy clusters, significant abundance differences are also well documented at the stellar scale, where individual *evolved* stars exhibit major abundance differences. In contrast to the un-evolved stars referred to in the previous subsections, the evolved stars are considered to have been able

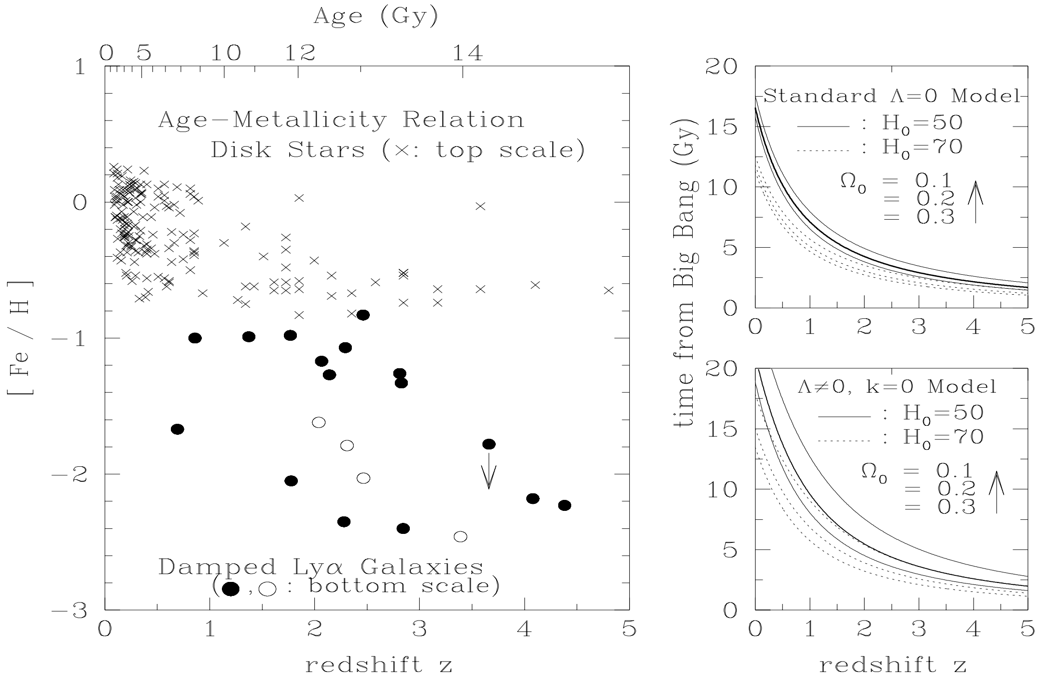

Figure 5. *Left panel*: Age-metallicity relations for disc stars of our Galaxy [46] (*crosses* referring to the top axis in Gy $\equiv 10^9$ y), and for DLA galaxies at various redshifts [51] (*circles* referring to the bottom axis, with open ones corresponding to cases where [Cr/H] replaces [Fe/H]). *Upper right panel*: age − redshift relations in the standard cosmological model, which assumes a Universe with zero cosmological parameter Λ. *Lower right panel*: the same but in a flat ($k = 0$) Universe with non-zero Λ. The parameters are the present-day Hubble constant H_0 (expressed in km/s/Mpc), and density Ω_0 relative to the "critical density" necessary for "closing" the Universe. The oft-used "deceleration parameter" relates to Ω_0 through $q_0 = \Omega_0/2$ in the standard model, and through $q_0 = (3/2)\Omega_0 - 1$ in the other model considered here. As in [51], the left panel is constructed with the choice of $H_0 = 50$ and $\Omega_0 = 0.2$ (the thick line in the upper right panel). See [52] - [54] for introductory reviews of the cosmological models; also see Sect. 3.3

to contaminate their surfaces at one point or another during their evolution with material processed in their very interiors. Various classes of "chemically peculiar" evolved stars have been identified. A non-exhaustive list of such objects includes the Barium stars or the various sub-classes of stars belonging to the RGB or AGB branches of the HRD ([55]). Let us also note that star-to-star variations, as well as correlations or anti-correlations, in the abundances of C, N, O, Na, Mg and Al are almost ubiquitous within red-giant globular clusters, with a clear additional diversity from one cluster to the other. These observations may imply the combination of initial abundance differences whose precise origin remains to be identified, and of intrinsic variable surface contaminations which are not predicted by standard stellar evolutionary models ([56, 57]).

In addition, exploding objects, like novae ([58]) and supernovae ([59]), also exhibit peculiar abundance patterns. It has to be noticed that a rich variety of chemical peculiarities are also observed in stars which would be suspected to belong to the class of un-evolved stars in the sense that they are not supposed to be able to transport nuclear-processed material to their surfaces. That is in particular the case for many classes of stars along the MS in the HRD. It is by now acknowledged that these composition peculiarities have nothing to do with nuclear physics, but are explicable in terms of diffusion-type processes operating in the stellar atmospheres ([60]). In this respect, nuclear astrophysics has to define its limits very carefully, and perhaps with modesty !

2.2.4. A special electromagnetic message from the sky: γ-ray line astrophysics At the beginning of the 1980s it was discovered that the electromagnetic message from the sky was even richer and more diverse than previously thought. In fact the ISM was seen to emit a γ-ray line resulting from the de-excitation of the 1.8 MeV level of ^{26}Mg fed by the nuclear β-decay of ^{26}Al ([61]). This discovery has been followed by the observation that the famed supernova SN1987A was emitting γ-ray lines originating from the $^{56}\mathrm{Ni}\to{}^{56}\mathrm{Co}\to{}^{56}\mathrm{Fe}$ decay chain and from the $^{57}\mathrm{Co}\to{}^{57}\mathrm{Fe}$ decay. The decay of ^{44}Ti in the young Cas(siopeia)-A supernova remnant has also been observed ([62, 63]). These observations provide an essential source of information, as well as constraints, on the operation of nuclear reactions in astrophysical sites. In particular the observed emission of γ-ray lines from supernovae was immediately recognized as the clearest demonstration of the operation of explosive nucleosynthesis processes (Sect. 6).

2.3. The composition of the solar system

The understanding of the composition of the solar system has always held a very special place in nuclear astrophysics. This relates directly to the fact that it provides a body of abundance data whose quantity, quality and coherence remain unmatched, despite the spectacular progress made in astronomical abundance observations. This concerns especially isotopic compositions, which are the prime fingerprints of astrophysical nuclear processes.

2.3.1. The bulk solar-system composition A milestone in the solar-system studies of astrophysical relevance was the realization that, in spite of large differences between the elemental compositions of constituent members, it was possible to derive a meaningful set of abundances likely representative for the composition with which the solar system formed some 4.6 Gy ago. Such an elemental abundance distribution is displayed in Fig. 6. It is largely based on abundance analyses in a special class of rare meteorites, the CI1 carbonaceous chondrites, which are considered as the least-altered samples of primitive solar matter presently available ([40, 64]). Solar spectroscopic data, which now come in quite good agreement with the CI1 data for a large variety of elements, have to be used for the volatile elements H, He, C, N, O and Ne, whereas interpolations guided by theoretical considerations are still required in some cases (Ar, Kr, Xe, Hg).

Starting from the composition displayed in Fig. 6, it is possible to account for the differences between the *elemental* compositions of the various solar-system solid

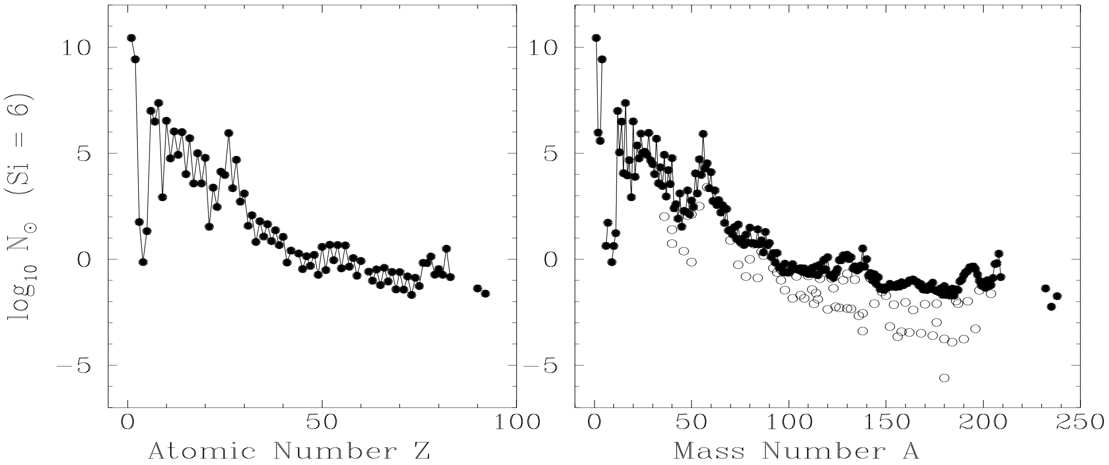

Figure 6. Bulk elemental (*left panel*) and nuclear (*right panel*) compositions of the galactic material from which the solar system formed about 4.6 Gy ago [40]. The abundances are normalized to 10^6 Si atoms. The elemental abundances are largely based on the analysis of meteorites of the CI1 carbonaceous chondrite type. The nuclear composition is derived from those elemental abundances with the use of the terrestrial isotopic composition of the elements, except for H and the noble gases. For a given A, the most abundant isobar is shown by a *dot*, and less abundant ones, if any, by *open circles*

constituents in terms of a large variety of secondary physico-chemical and geological processes. In contrast these secondary processes seem to have played only a minor role as far as the isotopic composition is concerned, save some specific cases. This fact manifests itself through the extremely high homogeneity of the bulk isotopic composition of most elements within the solar system. For this, terrestrial materials have been classically adopted as the primary standard for the isotopic composition characteristic of the primitive solar nebula. However, the choice of the most representative isotopic composition of H and the noble gases raises certain specific problems.

Even without going into details, some characteristics of the bulk solar-system composition (Fig. 6) are worth noticing. In particular, H and He are by far the most abundant species, while Li, Be, and B are extremely under-abundant with respect to the neighbouring light nuclides. On the other hand, some abundance peaks are superimposed on a curve which is decreasing with increasing mass number A. Apart from the most important one centred around ^{56}Fe ("iron peak"), peaks are found at the locations of the "α-elements." In addition a broad peak is observed in the $A \approx 80 - 90$ region, whereas double peaks show up at $A = 130 \sim 138$ and $195 \sim 208$.

It has been realized very early that these abundance data provide a clear demonstration that a close correlation exists between solar-system abundances and nuclear properties. As a simple example, a nuclide is observed to be more abundant than the neighbouring ones if it is more stable in the sense of nuclear physics. An intense nuclear-astrophysics activity has been devoted to unravel the details of the "alchemy" that has led to that nuclear imprint. In a word, very light ($A < 12$) nuclides are produced by Big Bang nucleosynthesis (Sect. 3.3) and/or by "spallation" reactions (Sect. 3.2), whereas the heavier ones result from the nuclear "cooking" inside stars. As will be detailed in Sect. 3.1, various charged-particle induced reactions are responsible for the synthesis of the vast majority of the nuclides up to the "Fe peak." In contrast, neutron capture chains, referred to as the "s(low)-" and "r(apid)-" processes (see Sect. 8.1 for their definitions), are called for in order to synthesize the heavier species. An additional mechanism, referred to as the "p-process," is dominated by photodisintegrations of pre-existing nuclides (Sect. 6.5).

2.3.2. Isotopic anomalies in the solar composition The solar-system composition has raised further astrophysical interest and excitement with the discovery that a minute fraction of the solar-system material has an isotopic composition which differs from that of the bulk. Such "isotopic anomalies" are observed in quite a large suite of elements ranging from C to Nd (including the rare gases), and are now known to be carried by high-temperature inclusions of primitive meteorites ([65]), as well as by various types of grains (diamond, graphite, SiC, corundum, refractory carbides of Ti, Mo, Zr and Fe, Si_3N_4) found in meteorites ([66] for many review papers). The inclusions are formed from solar-system material out of equilibrium with the rest of the solar nebula. The grains are considered to be of circumstellar origin and have survived the process of incorporation into the solar system.

These anomalies contradict the canonical model of a homogeneous and gaseous protosolar nebula, and provide new clues to many astrophysical problems, like the physics and chemistry of interstellar dust grains, the formation and growth of grains in the vicinity of objects with active nucleosynthesis, the circumstances under which stars (and in particular solar-system-type structures) can form, as well as the early history of the Sun (in the so-called "T-Tauri" phase) and of the solar-system solid bodies. Last but not least, they raise the question of their nucleosynthesis origin and offer the exciting perspective of complementing the spectroscopic data for chemically peculiar stars in the confrontation between abundance observations and nucleosynthesis models for a very limited number of stellar sources, even possibly a single one. This situation is in marked contrast with the one encountered when trying to understand the bulk solar-system composition, which results from the mixture of a large variety of nucleosynthesis events, and consequently requires the modelling of the chemical evolution of the Galaxy (Sect. 3.4).

Some further astrophysical excitement has followed the realization that some of the anomalies result from the decays within the solar system itself of radioactive nuclides with half-lives in excess of about 10^5 y. This is in particular the case for ^{26}Al ([67]). The possible presence of such short-lived radioactive nuclides in live form within the early solar-system has far reaching consequences for the understanding of its (pre)history and for the nuclear astrophysical modelling of the stellar origins of these radionuclides.

2.3.3. The composition of cosmic rays and solar energetic particles Much advance has been made in the knowledge of the elemental or isotopic compositions of the solar energetic particles ([68]) and galactic cosmic rays ([69, 70]). The accumulated data have had some significant impact on our understanding of the possible sources of cosmic rays and of their composition. Concomitantly they have triggered some nuclear astrophysics activities.

2.4. Neutrino astronomy

For years, neutrino astrophysics has built upon experiments designed to detect neutrinos emitted by the Sun, leading to the "solar neutrino problem" (Sect. 5.1). This type of astrophysics has entered a new era with the detection by the IMB and Kamiokande II collaborations of a neutrino burst from the supernova SN1987A [71, 72]. This remarkable observation seems to validate standard models of neutrino emission from supernovae, but the limited number of neutrino events observed apparently makes it difficult to validate or invalidate at a *quantitative* level the various choices of input physics in supernova modelling ([24, 73]). In any case, that observation has without any doubt opened the door to many new neutrino observatories. These developments have received a strong support from the speculation that high-energy neutrinos may originate from a large variety of cosmic objects, including active galactic nuclei or gamma-ray bursts, as well as from cosmological structures, like "strings" ([74]).

Clearly, a better understanding of the Universe and its constituents through the various astrophysical or cosmochemical approaches sketched above requires progress to be made in a large variety of observational or experimental devices. In very many instances it also goes through experimental and theoretical improvements in astrophysics and nuclear physics, as will be described later.

3. The contributors to nuclei in the Cosmos

The very nature of the phenomena responsible for the transformation of the composition of stellar surfaces and of the galaxies at various scales has been the subject of much work. We summarize here the main characteristics of some of the major nucleosynthesis agents.

3.1. Some generalities about stellar structure and evolution

In short, and as pictured very schematically in Fig. 7, the evolution of the central regions of a star is made of successive "controlled" thermonuclear burning stages and of phases of gravitational contraction. The latter phases are responsible for a temperature increase, while the former ones produce nuclear energy through charged-particle induced reactions. Of course, composition changes also result from these very same reactions, as well as, at some stages at least, from neutron-induced reactions, which in contrast do not play any significant role in the stellar energy budget. The nuclear reactions

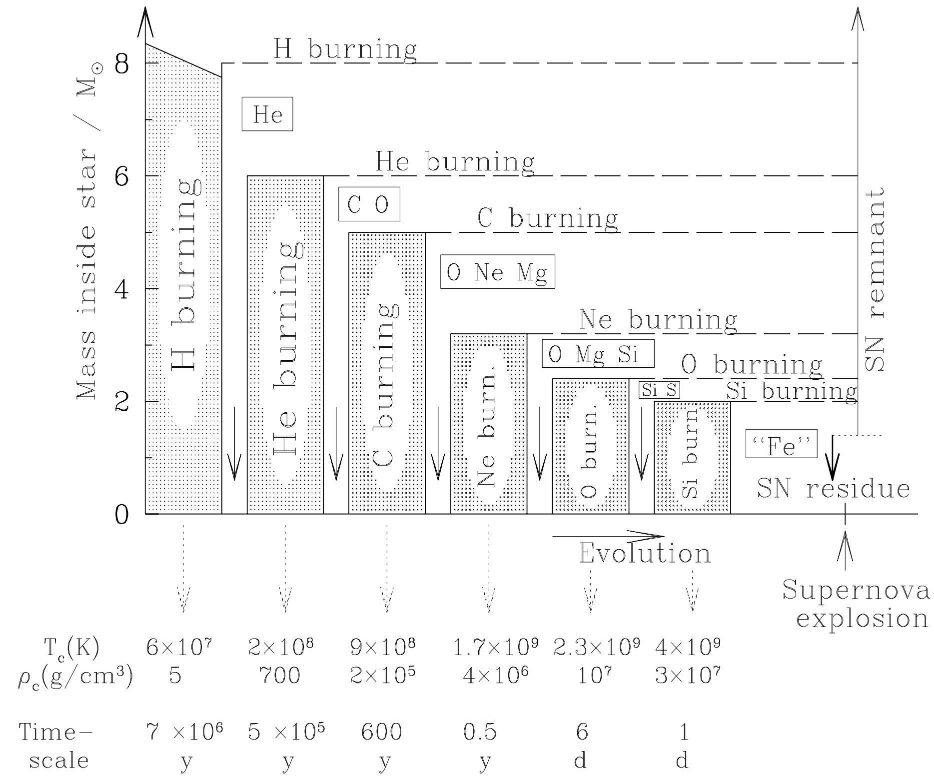

Figure 7. Schematic representation of the evolution of the internal structure of a spherically-symmetric massive ($M \approx 25$ M$_\odot$) star. The shaded zones correspond to nuclear burning stages. A given burning phase starts in the central regions (the central temperatures T_c and densities ρ_c are indicated at the bottom of the figure), and then migrates into thin peripheral burning shells. In between the central nuclear burning phases are episodes of gravitational contraction (downward arrows). The chemical symbols represent the most abundant nuclear species left after each nuclear-burning mode ("Fe" symbolizes the iron-peak nuclei with $50 \lesssim A \lesssim 60$). If the star explodes as a (Type-II) supernova, the most central parts may leave a "residue," while the rest of the stellar material is ejected into the ISM, where it is observed as a supernova "remnant"

involved in the different nuclear-burning stages are discussed in greater detail in Sect. 5. Let us simply emphasize here that such a sequence develops in time with nuclear fuels of increasing charge number Z and at temperatures increasing from several tens of 10^6 K to about 4×10^9 K. Concomitantly the duration of the successive nuclear-burning phases decreases in a dramatic way. This situation results from the combination of (i) a decreasing energy production when going from H burning to the later burning stages and (ii) an increasing neutrino production, and the consequent energy losses, with temperatures exceeding about 5×10^8 K (see [24] Chap. 10). Figure 7 also depicts schematically that a nuclear burning phase, once completed in the central regions, migrates into a thin peripheral shell. As a consequence the deep stellar regions look like an onion with various "skins" of different compositions.

It is quite important to notice that all stars do not necessarily experience all the burning phases displayed in Fig. 7 (see [24] Chap. 6.6 for details): while massive ($M \gtrsim 10$ $\mathrm{M}_\odot$) stars go through all those burning episodes, low-mass ($M \lesssim 8$ $\mathrm{M}_\odot$) stars stop their nuclear history already after completion of central He burning. Stars in the $8 \lesssim M \lesssim 10$ $\mathrm{M}_\odot$ range represent complicated intermediate cases. It has also to be stressed that the true stellar structure is certainly much more complicated than sketched in Fig. 7 (cf. Figs. 10.5-6 of [24]) even when effects like deviations from spherical symmetry (induced by rotation or certain mechanisms of transport of matter) are neglected. This spherically symmetric picture of a star may break down, especially during the advanced stages of the evolution of massive stars, and would lead to a dramatic growing of the complication of the stellar structure and evolution. This increased complexity is demonstrated by recent multi-dimensional simulations of the structure of massive stars ([75, 76]). The consideration of rotation of course brings additional difficulties ([77]). Finally, steady mass loss from a star may also affect its evolution in various ways ([78, 79]).

3.1.1. $M \gtrsim 10$ $M_\odot$ stars The evolution of these stars and the concomitant nucleosynthesis have been the subject of much computation, at least in spherically symmetric cases ([24, 80, 81]). After having experienced all the burning phases depicted in Fig. 7, these stars are seen to develop an Fe core that is lacking further nuclear fuels, any transformation of the strongly-bound Fe nuclei being endothermic. In fact this core becomes dynamically unstable and implodes as a result of free-electron captures and Fe photodisintegration, the former transformation playing an especially important role at the low end of the relevant stellar-mass range. Through a very complex chain of physical events the implosion can, in certain cases at least, turn into a catastrophic supernova explosion referred to as a Type-II supernova†† (see [24] Chaps. 12 and 13 in particular, for a detailed discussion of the implosion-explosion mechanism and for the model predictions of the supernova observables). In this sequence of physical events, neutrino production and diffusion through the supernova core material are now known to play a key role. These processes crucially help the generation and powering of a shock wave propagating outward through most of the supernova layers. This shock wave compresses the various traversed layers, heats them up before pushing them outward until their ejection into the ISM. This expansion is of course accompanied by a cooling of the material. This heating and cooling process of the layers hit by the supernova shock wave allows some nuclear transformations to take place during a quite brief time, modifying more or less significantly the pre-explosion composition of the concerned layers. The study of the composition of the ejected material that makes up the supernova

††Type-II supernovae are defined as those showing H-lines in their spectra. It is likely that most, if not all, of the exploding massive stars still have some H-envelope left, and thus exhibit such a feature. In contrast, Type-I supernovae lack H in their ejecta. Specific spectral features have led to the identification of different Type-I subclasses, among which are the Types-Ia, -Ib and -Ic. See [82, 83] for the classification scheme of supernovae

remnant is one of the main chapters of the theory of "explosive nucleosynthesis."

In this supernova picture not the whole of the stellar mass is returned to the ISM. The innermost parts are bound into a "residue," which may be a neutron star (observable as a pulsar if it is magnetized and rapidly rotating) or even a black hole (see [84, 85] for a detailed discussion of the physics of these objects). If a general consensus has been reached on the above description of massive star explosions, many very complicated astrophysics and nuclear physics questions have yet to be answered.

The Type-II supernova explosion sketched above is not the only way for massive stars to return material to the ISM. Hot stars are indeed observed to suffer steady (non-explosive) stellar winds which may carry non-explosively processed material, e.g., H- and He-burning products in the case of the so-called Wolf-Rayet stars ([86]). These stars eventually explode as supernovae with Type-Ib or -Ic spectral features, and thus add their share to the contamination of the ISM with explosive burning products [87].

Quite clearly, massive stars, through their pre-supernova and supernova evolution, are essential agents to the evolution of nuclides in galaxies. It is also considered nowadays that some isotopically anomalous grains identified in meteorites originate from supernovae. However, many detailed aspects of this contamination remain more or less uncertain. Some of these problems are of nuclear physics origin, while others are of purely astrophysics nature. In this respect it has to be stressed that the modelling of a spherically-symmetric supernova event already raises so many severe difficulties that very limited numbers of multi-dimensional simulations have been attempted to date ([88]).

3.1.2. $0.45 \lesssim M \lesssim 8\ M_\odot$ *stars* As noted above the nuclear history of these stars is essentially limited to H and He burnings that take place in the central regions before affecting peripheral shells. This nuclear activity is considered to be responsible for the many chemical peculiarities observed at the surface of a variety of RGB or AGB stars. Indeed these stars are expected to have their surfaces more or less severely contaminated with H- and He-burning ashes as well as with the products of a neutron-capture process known as the "s-process" (Sects. 5.2.2 and 8.1). This contamination is a direct consequence of episodes of extended mixing between nuclear-processed deep layers and the stellar surface which are referred to as "dredge-up" phases ([89]). The level of this contamination is also influenced by the considerable mass losses those stars experience during their AGB phase. This wind is also responsible for the formation of planetary nebulae, the cores of which evolve to white dwarfs essentially made of C and O, as well as for the enrichment of the galaxies with nuclear-processed material. Last but not least, some anomalous meteoritic grains are also suspected to form in AGB circumstellar wind-ejected shells.

The modelling of the stars in the considered mass range remains uncertain in various respects. Uncertainties in predicted surface composition, pre- or post-AGB evolution and galactic contamination relate in particular to the efficiency of the dredge-up episodes, or to the extent of the stellar winds during the AGB phase. The mass loss rates also influence the upper limit (taken here 8 $M_\odot$) for the initial masses of stars which leave C-O white dwarfs as residues ([90]).

3.1.3. $8 \lesssim M \lesssim 10\ M_\odot$ *stars* The evolution of these stars is expected to exhibit special and complex features that appear to depend very sensitively on the precise stellar mass in the considered range. The non-explosive history of some of these stars has been followed in detail recently [91]. The central and peripheral H- and He-burning episodes are complemented with a C-burning stage that starts off-centre before migrating to the more central regions. At the end of the C-burning phase an O+Ne-rich core is produced, while the surface compositions are expected to be modified by the dredge-up to the surface of the products of the nuclear burnings. The post C-burning evolution might be dominated by an increasing degeneracy of the free electrons, the Fermi energy of which could exceed the threshold for electron captures (Sect. 4.4.1) by dominant core constituents such as ^{20}Ne. These captures would result in a deficit of electron pressure, and consequently cause core collapse [92]. The details of this collapse are somewhat different from those of the implosion induced by iron photodisintegration in the cores of more massive stars, even if the end product may also be a Type-II supernova. Save the possibility of an O-deflagration leading to its complete disruption, such a star appears to form a neutron star of less than about 1.3 $M_\odot$ ([92]).

Extensive mass loss prior to an explosion might also have several interesting implications such as the possibility of production of an O+Ne white dwarf. This scenario would avoid a catastrophic supernova fate, at least if this white dwarf cannot increase its mass through the accretion of some matter from a companion in a binary system in particular (see below). The initial stellar-mass range for the "electron-capture triggered" supernovae may also be subject to changes depending on the (uncertain) treatment of convection ([93]).

3.1.4. Binary stars Roughly two-third of all stars in our Galaxy belong to multiple- (mainly binary-) systems, and many different types of observed astronomical events are now interpreted in terms of phenomena occurring in such systems. The effects of a binary companion on the evolution of a star are complicated and far from being fully explored. This concerns both purely structural problems and highly specific nuclear-physics questions (see [94] for extended reviews). We just highlight here some characteristics of direct relevance to nuclear astrophysics.

One of the most important characteristics of the evolution of binary systems is the existence of episodes during which matter is transferred from one component to the other. Such mass exchanges offer a rich variety of distinct astrophysical and nuclear scenarios. Various instabilities of nuclear origin may indeed develop in the transferred material at the surface of the accreting component. In particular, explosive H-burning at the surface of an accreting white dwarf or neutron star may be responsible for the occurrence of certain types of novae or of X-ray bursts, respectively. At least in the nova case, some nuclear-processed material is known to be recycled into the ISM. In addition to such "surface" effects, accreting WDs may also experience in their interiors explosive He- or C-combustions of the deflagration or detonation types, different burnings and different regimes possibly developing in a single object and in a sequential way. The net result may be the explosive disruption of the accreting WDs as Type-Ia supernovae ([83]). These are important contributors to the evolution of the composition of galaxies. They have also been viewed as possible providers of certain anomalous presolar grains. Under certain circumstances the white dwarf may collapse into a neutron star.

3.2. Spallation reactions

Spallation reactions† are essential agents in the shaping of the elemental and isotopic composition of the relativistic galactic cosmic rays (GCRs), and play a central role in "propagation models" attempting to determine the GCR abundance variations as the result of the interaction of the GCRs with the interstellar matter when they travel from the GCR source and the Earth ([95]). An important subset of the predictions of astrophysical interest from the propagation models concerns the production by spallation of the galactic Li, Be and B content. More specifically, it has been shown that the GCRs interacting with interstellar matter prior to the isolation of the solar-system material from the general galactic pool are responsible for the bulk solar-system ^{6}Li, ^{9}Be, ^{10}B, most of the ^{11}B, and at least some of the ^{7}Li [42].

Various non-exploding stars (including the Sun) or exploding ones are also known to accelerate particles into the approximate 10 to 200 MeV/nucleon range. These "stellar energetic particles" can interact with the material (gas or grains) at the stellar surfaces, in circumstellar shells, or in the local ISM. The outcome of these nuclear interactions has recently been the subject of a renewed interest following the determination of the Li, Be and B content of very old stars [96] - [98]. Some of these studies have also revisited the question of the light isotopes in the solar system with the conclusion that their solar energetic-particle production could cure the predicted insufficient ^{11}B production in the GCRs, while making still other ^{7}Li sources mandatory.

Spallation reactions also play an important role in other astrophysical questions, like the production by GCRs or solar energetic particles of stable and radioactive nuclides in extraterrestrial solar-system matter such as planetary surfaces, meteorites or cosmic dust [99].

The study of the exact role of spallation reactions in astrophysics raises very many specific questions concerning, in particular, the determination of the spectra of particles accelerated by various cosmic objects, or the experimental and theoretical studies of nuclear reactions taking place above the Coulomb barrier ([95, 99]).

† The terminology "spallation reaction" is used here in its historical context, independently of its exact meaning in nuclear physics, as a synonym for nuclear reactions induced by the interaction of primary particles with relative energies in excess of some tens of MeV/nucleon

3.3. The Big Bang contribution to nucleosynthesis

The standard hot Big Bang (SBB) model provides a very successful and economical description of the evolution of the (observable) Universe from temperatures as high as $T \approx 10^{12}$ K ($t \approx 10^{-4}$ s after the "bang") until the present epoch ($t \approx 10-20$ Gy). This model has many far-reaching implications not only in cosmology and particle physics, but also in high-energy nuclear physics (like the relativistic heavy-ion physics in relation with the quark-hadron phase transition), low-energy nuclear physics (like the physics of thermonuclear reaction rates in relation to the primordial nucleosynthesis episode), and in astrophysics (through the problems of the formation and initial composition of the galaxies). Many of these exciting questions, as well as the details of the thermodynamics of the SBB are dealt with at length in [100]. Here we just limit ourselves to a brief account of some basic aspects of the Big Bang, and in particular of the main features of the nucleosynthesis epoch of most direct relevance to nuclear astrophysics.

The observational evidence testifying to the validity of the SBB model is threefold: (1) the universal expansion discovered by Hubble in 1929: all galaxies, except those of the Local Group (a gravitationally bound group of about 20 galaxies to which our Milky Way Galaxy belongs), are receding from us (and from each other) with velocities proportional to their distances. The factor of proportionality is the Hubble parameter $H(t)$, the current value of which being the Hubble constant H_0. The precise value of H_0 has yet to be known in the approximate 50-100 km/s/Mpc range, although many recent determinations point to $H_0 \approx 70$ km/s/Mpc ([101]);
(2) the cosmic (microwave) background radiation, discovered by Penzias and Wilson in 1965 [102],‡ which is a unique laboratory for studying the initial conditions that gave rise to the observed Universe. It has a spectrum that fits with astonishing precision a black-body of temperature $T_0 \approx 2.7$ K, and its angular uniformity ($\Delta T/T < 10^{-4}$) combined with its presumed homogeneity ("Cosmological Principle") strongly argues for a hot and homogeneous early Universe, where matter and radiation were in equilibrium ([104]). Matter and radiation are predicted to have "de-coupled" a few 10^5 years after the "bang," when the temperature had decreased to about 3000 K. After this epoch, radiation cooled during the universal expansion to its present value of about 2.7 K more rapidly than matter did;
(3) most, if not all, of the universal content of D and ^{4}He are considered to originate from the hot early Universe. This is likely true also for the ^{7}Li observed in old un-evolved stars which are probably the good sites to have maintained the signature of the ^{7}Li content of the forming galaxies. The situation of ^{3}He appears to be less clear-cut, some being possibly of direct Big Bang origin, some coming from the stellar transformation of the primordial D, and some coming from H burning in stars. The nucleosynthesis epoch of the Big Bang is expected to have developed when the temperatures decreased to values in the approximate $10^9 \gtrsim T \gtrsim 10^8$ K range (corresponding to times $10^2 \lesssim t \lesssim 10^3$ s).

The confrontation between the SBB nucleosynthesis expectations and observations

‡ As for the theoretical predictions preceding the discovery, see [103], a bitter-sweet memoir

necessitates the consideration of a chain of theoretical and observational links, each of which bringing its share of uncertainties and difficulties. On the observational side, the determination of the "primordial" galactic abundances is far from being a trivial matter ([42, 100]). It necessitates not only direct abundance determinations by observations, but also an evaluation of the role of the oldest observable stars or of spallation reactions in modifying the early galactic content of nuclides like D, ^{3}He or ^{7}Li. The controversy over discrepant determinations (from the analyses of the spectra of distant quasars) of the D abundance in intergalactic clouds supposedly made of primordial material is an additional dramatic illustration of the problems one has to face in this field ([100], [105] - [107]). On the theoretical side, the SBB nucleosynthesis offers a variety of pleasing features. In particular, for the present temperature of the cosmic background radiation is quite accurately known, the calculated abundances depend only upon the ratio η of the total number of (bound and free) nucleons to the number of photons (which remains constant following the e^+e^- annihilation episode in the Big Bang thermodynamics). This is true at least in the Standard Model (SM) of particle physics, which involves three kinds of weakly-interacting massless neutrinos. The quantity η cannot be reliably determined on observational grounds, and is considered as a (the only) free parameter in the SBB+SM framework.

Due account being taken of the uncertainties of nuclear nature affecting the predicted abundances for a given η, the SBB+SM model is often regarded as being able to account for the presumed initial galactic content of D, ^{4}He and ^{7}Li for values of η in the approximate $2 \times 10^{-10} \lesssim \eta \lesssim 9 \times 10^{-10}$, the upper limit being imposed in particular by the low primordial D abundance claimed by some authors (see [42, 100, 108] for a more thorough discussion; see also [107]). This converging agreement for the primordial abundances, and the concomitant constraints on η are generally considered as a real triumph of the SBB model. These constraints have also far-reaching implications concerning the nature of the dark matter which is observed to dominate the dynamics of individual galaxies, as well as groups and clusters of galaxies ([109]). In particular, little room would be left for baryonic matter (in any form) for high values of the Hubble constant and high primordial D abundances. This conclusion would be invalidated if the initial galactic D content were indeed low ([100]).

This success notwithstanding, many variants of the SBB + SM model have been developed and studied to a varied extent, some of them stemming from the claim of a "SBB crisis" caused by a discrepancy between predicted and observed abundances [110]. Some of these variants call for gross departures from the standard cosmology, like alternate theories of gravity or anisotropic world models. Others restrict themselves to the standard cosmological models, but allow for some departures from the SM of particle physics. The interested reader is referred to e.g. [100, 111] for thorough presentations of these alternatives. Let us just note that various remedies to the SBB crisis have been proposed, some of them maintaining the SBB well alive. On the other hand, a Big Bang model which allows for some inhomogeneities at the epoch of nucleosynthesis has raised much excitement in part of the nuclear astrophysics community (Sect. 6.1).

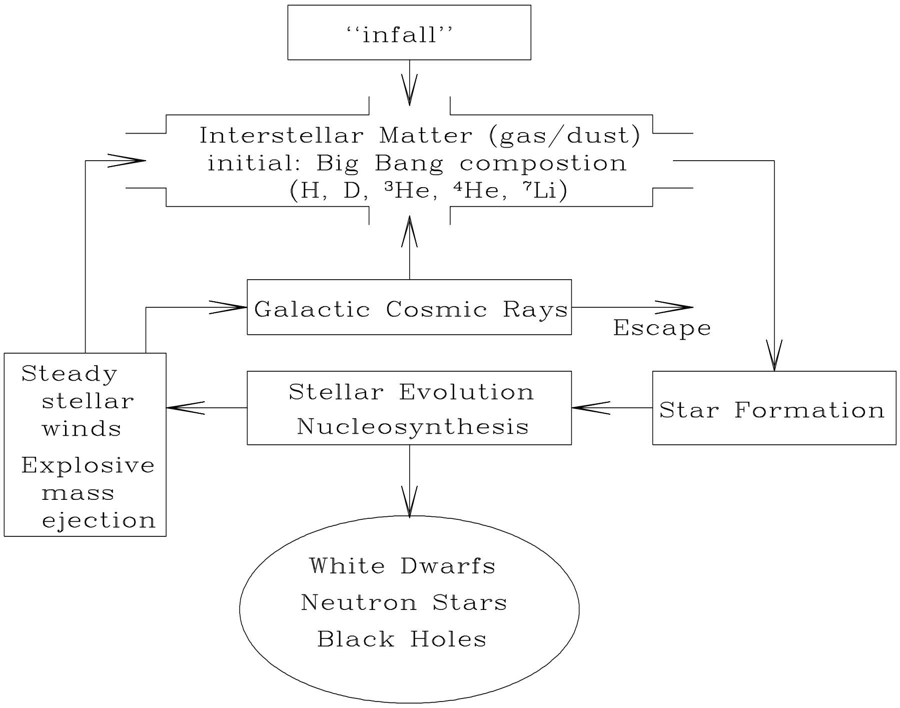

Figure 8. A very schematic picture of the galactic "blender" (see text)

3.4. The chemical evolution of galaxies

The modelling of the evolution of the nuclear content of galaxies (classically termed the"chemical" evolution of galaxies) is without any doubt one of the most formidable problems astrophysics has to face. This question has been tackled at various levels of sophistication, ranging from so-called "chemo-dynamical models" to simple " one-zone" models, the latter ones limiting themselves to the description of the evolution of the abundances in the solar neighbourhood. Because of their complexity, the first types of models are cruder in their nucleosynthesis aspects than the latter ones, which do not address any galactic thermodynamics- or dynamics-related issues. This immense problem ([25], [112] - [114]) cannot be reviewed here, and we limit ourselves to a very crude overview of its chemical aspects.

The way a galaxy evolves chemically is represented in a very sketchy manner in Fig. 8. Let us consider the ISM (made of gas and dust) right after galaxy formation. Its composition is assumed to be essentially the one emerging from the Big Bang, the standard model of which predicts the presence of significant amounts of just H, D, ^{3}He, ^{4}He and ^{7}Li.§ Part of the ISM material is used to form stars which, through a large variety of nuclear reactions, transform the composition of their constituent material

§ We neglect here any possibility of *pre-galactic* nucleosynthesis of thermonuclear nature ([115]) by still putative pre-galactic very massive stars ([116]), or of spallation type by "cosmological cosmic rays" [117]. These very early modifications of the Big Bang yields have been advocated at several occasions, but are usually not taken into account in galactic chemical evolution models

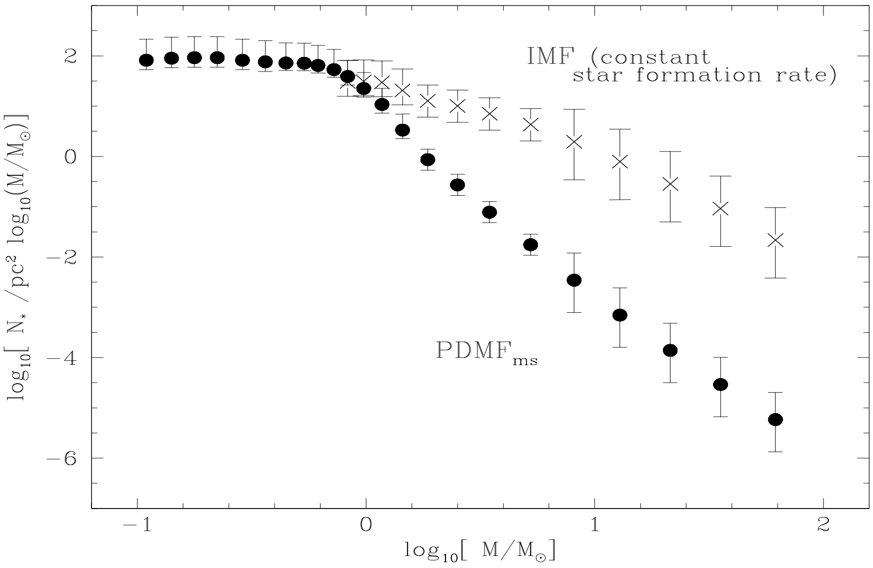

Figure 9. An Initial Mass Function (IMF) relevant to the disc of our Galaxy in the solar neighbourhood (adapted from [119]). It is derived from the observed present-day mass function for Main Sequence stars (PDMF$_{ms}$) under the assumption that the stellar birthrate is constant in time. The PDMF$_{ms}$ counts stars that are just leaving the MS in the HRD. The deviation of PDMF$_{ms}$ from IMF reflects the ratios of the MS lifetimes to the age of the Galaxy (assumed to be in the 9 - 15 Gy range)

during their evolution. At one point or another during that evolution, some material may be returned to the ISM through various mechanisms (Sect. 3.1). In general, all the stellar material with altered composition is not returned to the ISM. Part is locked up in stellar residues (white dwarfs, neutron stars, or black holes), and normally is not involved in the subsequent chemical evolution of the galaxies, at least when only single stars are considered. Also recall that a tiny fraction of the matter ejected by stars can be accelerated to galactic cosmic-ray energies. Spallation reactions by these high-energy particles interacting with the ISM material can be responsible for the Li, Be and B contents of the galaxies, and especially of the disc of our own Galaxy (Sect. 3.2). At least in spiral galaxies like our own, some fraction of the galactic cosmic-ray nuclei might escape the galactic disc. Part of the supernova ejecta might also be ejected from the disc (though not sketched in Fig. 8). In contrast, some material, possibly of Big Bang composition, might fall onto the galactic disc ("infall") from the galactic halo to dilute the stellar-processed material.

One basic ingredient of the models for the chemical evolution of the galaxies is the stellar creation function, that is, the number of stars born per unit area of the galactic disc (in spiral galaxies) per unit mass range and unit time interval. That question has been discussed at length in [118]. As supported to a large extent by phenomenological considerations, and also for obvious reasons of modelling facilities, it is generally assumed that the star formation is separable into a function of time only (the stellar birthrate, which is found not to vary widely with time, at least in the neighbourhood of the Sun),

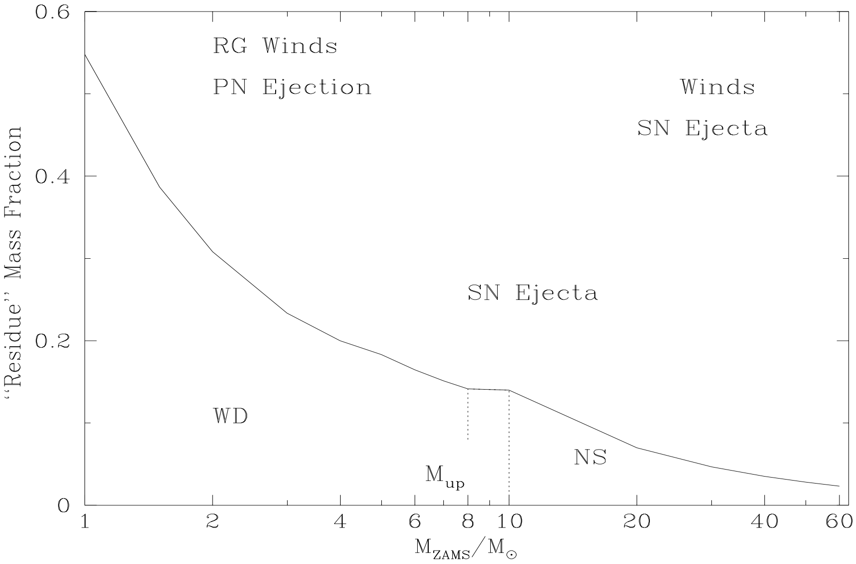

Figure 10. Schematic representation of the fraction of the initial ("zero-age main sequence") mass $M_{\rm ZAMS}$ of a single star that remains bound in a white dwarf (WD) or neutron star (NS) residue at the end of its evolution. The rest of the stellar material is ejected mostly by the indicated mechanisms. [RG, PN and SN stand for "Red Giant," "Planetary Nebula" and "Supernova," respectively.] Stars with initial masses up to $M_{\rm up} \approx 8$ M$_\odot$ are assumed to end their lives as WD with typical masses provided by stellar evolution models [90]. Stars with $M \gtrsim 10$ M$_\odot$ are assumed to leave a 1.4 M$_\odot$ neutron star (NS). In the remaining $8 \lesssim M \lesssim 10$ M$_\odot$ range, stars might explode leaving either a low-mass NS, or an O+Ne WD, or even possibly no residue. This overall picture is just meant to be a sketch, and is subject to various uncertainties

and a function of mass only, referred to as the "Initial Mass Function (IMF)." An IMF constructed in such a way from observational data is represented in Fig. 9. The main result of such studies is that, in the solar neighbourhood at least and apparently also in more general situations, the IMF is more or less steeply decreasing with increasing stellar mass, at least in the $M \gtrsim$ M$_\odot$ range.

Another main ingredient of the galactic chemical evolution models is the mass and composition of the matter ejected by a star with a given initial mass. This quantity is loosely referred to here as the stellar "yields." Its evaluation requires the modelling of the evolution of stars with initial masses in a broad range of values (essentially between about 1 M$_\odot$ and 100 M$_\odot$), as well as of the concomitant nucleosynthesis. The dominant mechanism(s) for the restitution of matter to the ISM by a star of given mass has(have) also to be known. These processes are depicted schematically in Fig. 10 as a function of the initial stellar mass, along with the fraction of this mass that is ejected.

It has to be noticed that some chemical evolution models also consider, though in a rather rough way, the specific role that could be played by certain binary systems. This concerns in particular the galactic enrichment by the explosively processed material ejected by novae or by Type-Ia SNe associated with the explosion of accreting WD.

4. Nuclear data needs for astrophysics: Nuclear masses, decay modes

As made clear in the previous sections, the Universe is pervaded with nuclear physics imprints at all scales. In order to decipher these messages from the macrocosm, it is unavoidable to start with a proper description of the basic properties, in particular masses and decay modes, of a very large variety of nuclei in laboratory conditions. This information, though necessary for the development of nuclear astrophysics, is by far not sufficient, however. A remaining essential task is to scrutinize how these properties can be affected under astrophysical environments, which are highly versatile and are often characterized by high temperatures and/or densities that are out of reach of laboratory simulations. Over the years these questions have been at the focus of a tremendous amount of experimental and theoretical work, as will be described in Sect. 7.

4.1. The masses of "cold" nuclei

Nuclear masses (equivalently, binding or separation energies) enter all chapters of nuclear astrophysics. Their knowledge is indispensable in order to evaluate the rate and the energetics of any nuclear transformation.

Figure 11 displays the approximately 2500 nuclides that have been identified by now in the laboratory. Among them, 286 are naturally occurring, the remaining ones being artificially produced. As extended as it is, this data set does not quite meet the astrophysics requirements. This is especially true when dealing with the r-process nucleosynthesis (Sect. 8.1), which involves a large number of nuclei unidentified in the laboratory. Theory is thus a mandatory complement to the experimental efforts.

4.2. Nuclei at high temperatures

The special conditions prevailing in astrophysical environments, and particularly in stellar interiors, bring their share of additional and sometimes major difficulties. Even the very basic concepts of nuclear "binding" or stability have to be handled with great care when dealing with certain astrophysical conditions. This comes about from the fact that nuclei exist not only in their ground state, but in excited states as well. These states are populated through particle (especially electron) or photon interactions. In stellar interiors (even in explosive situations), thermodynamic equilibrium holds in general, at least locally, to a high level of accuracy, so that the relative populations of the nuclear excited states are very well approximated by a statistical Maxwell-Boltzmann distribution law ([34]). Following this law, the thermal population of a nuclear excited state starts being significant as soon as the temperature [$kT \approx 8.6 \times (T/10^8\mathrm{K})$ keV] becomes commensurable with its excitation energy. At a given temperature the low-lying excited states of an odd-Z, odd-N heavy nucleus thus have an especially high equilibrium population.

Specific problems arise when dealing with isomeric states. In certain temperature regimes, their populations may indeed depart from the equilibrium values, in particular

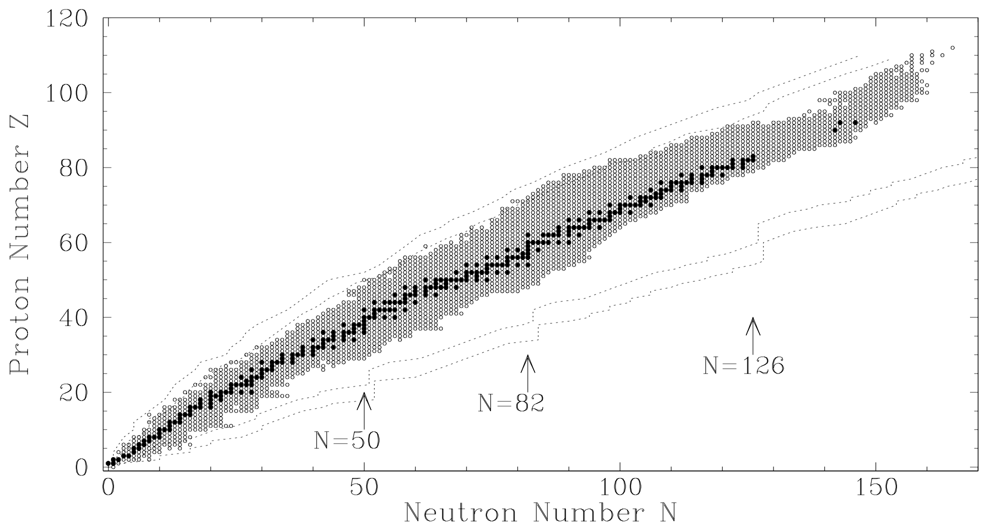

Figure 11. "Segrè chart" of the naturally-occurring stable and long-lived nuclides (laboratory half-lives $t_{1/2} \gtrsim 4.6$ Gy, the approximate age of the solar system) (*solid circles*). The radionuclide ^{234}U ($t_{1/2} \approx 2.5 \times 10^5$ y) is also found naturally on earth as a result of the ^{238}U decay chain; it is omitted in the figure. Artificially produced isotopes with known half-lives, and in many cases with measured masses as well, are represented by open circles. These data are from [120] supplemented by [121] for the lightest nuclides, and by [122] for the heaviest ones. The naturally-occurring nuclides form the "line of β stability" (or "Heisenberg's valley"). The species located to the right (left) of this line are referred to as "neutron-rich" ("neutron-deficient"), and undergo β-decays. Very heavy nuclides may additionally α-decay and/or fission. Far enough away from the line of stability, nuclei may even become unstable against the emission of a neutron or a proton. Some such emissions have already been observed in the laboratory. The ensembles of nuclei whose neutron or proton separation energies tend to zero define the neutron or proton "drip lines" (*dotted lines*) predicted from a mass model (Sect. 7.1.1). Double drip lines are shown to account for the nuclear odd-even effects. (Note that a negative proton separation energy does not necessary imply spontaneous proton emission, the reason being the Coulomb barrier effects.)

as a result of the selection-rule hindrance of the electromagnetic transitions between ground and isomeric levels. Interesting situations of this type concern, for example, ^{26}Al ([123]), ^{176}Lu ([124]), and ^{180}Ta ([125]). In all these cases, the thermalization requires a multi-step electromagnetic link involving higher excited states, which can be efficient at sufficiently high temperatures. For example, the ground state of ^{26}Al and its short-lived 228 keV isomer ($t_{1/2} \sim 6.3$ s) are expected to be in thermal equilibrium only at temperatures in excess of about 5×10^8 K [123].

The existence in a stellar plasma of nuclei in their ground as well as excited states has an important bearing on various decay modes or nuclear transmutations, and consequently on different nucleosynthesis processes. In many cases, therefore, the determination of the ground state mass is insufficient and the evaluation of "nuclear partition functions," i.e. sums of the equilibrium populations of the states of a nucleus, has to be carried out. This is typically the case when abundances have to be evaluated in conditions where reactions and their reverses equilibrate. An extreme case of this situation is the "nuclear statistical equilibrium (NSE)" regime.

The fact that nuclear excited states enter various nuclear astrophysics calculations obviously makes indispensable the knowledge of nuclear spins and energies of these states. Such information is often missing experimentally, especially when dealing with "exotic" nuclei far from stability, or even with stable nuclei when high temperatures have to be considered. In such cases, relatively high-energy levels may indeed be significantly populated.

4.3. Nuclei at high densities

At high densities, such as encountered in supernovae or neutron stars, the meaning of the nuclear binding has to be understood in terms of the nuclear equation of state (EOS), which describes the energy density and pressure of a system of nucleons and/or nuclei as a function of matter density.

At densities $\rho \lesssim 10^{-2}\rho_0$, where $\rho_0 \approx 3 \times 10^{14}$ g/cm^3 is the nuclear saturation density, NSE generally holds in realistic astrophysical conditions, so that the EOS can be derived from the laws of equilibrium statistical mechanics. A troublesome problem here is related to the fact that the matter in question may involve very neutron-rich nuclei whose partition functions, if not binding energies (which are essential quantities entering the statistical-mechanics equations), are unknown in the laboratory.

The nuclear EOS at densities ρ ranging from 0.01 to 10 times ρ_0 (or even slightly higher) is one of the most important ingredients for both supernova and neutron star models. In particular, the properties of the EOS around ρ_0 dictate to a large extent if a massive star can explode as a supernova or not. To cover the physics involved in the EOS in this wide density domain ([126, 127]) is far beyond the scope of the current review. Later in Sect. 7.1.2, however, we present a very brief description of EOS needs for studies of supernovae and neutron stars.

4.4. Nuclear decays and reactions via weak interaction

Weak interaction processes play a decisive role in a wide variety of astrophysical questions ([128]). Here we discuss very shortly a few problems of direct relevance to stellar evolution and nucleosynthesis, omitting such an important topic as the properties of neutrinos and their meaning in cosmology.‖

A very specific example of the importance of weak interaction concerns the starting transmutation $\mathrm{H} + \mathrm{H} \rightarrow {}^2\mathrm{H} + \mathrm{e}^+ + \nu_e$ of the p-p chain of reactions, which is the essential H-burning mode in the very large galactic population of stars with masses $M \lesssim 1\ \mathrm{M}_\odot$. In more advanced stages of evolution, various sorts of weak interaction processes occur, some of which are unknown in the laboratory, just as the H + H reaction.

‖ This exclusion applies to double-β decays, for instance, whose study is motivated by particle physics, although its methodology is of pure nuclear-physics nature

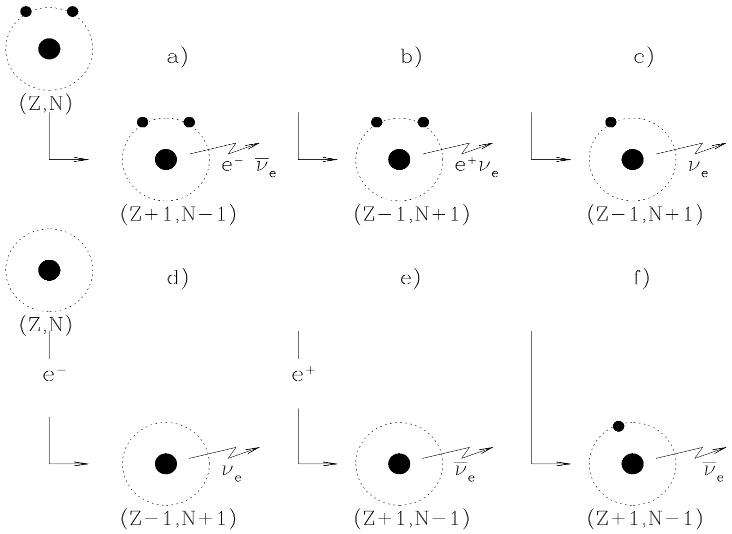

Figure 12. Various nuclear β-decay modes: (*a*) β^- decay, (*b*) β^+ decay, (*c*) orbital-e$^-$ capture, (*d*) continuum-e$^-$ capture, (*e*) continuum-e$^+$ capture, and (*f*) bound-state β decay. The processes a) - c) are the usual decay modes in the laboratory, while d) - f) can occur under stellar conditions

4.4.1. Various β-decay modes in astrophysics The most familiar forms of weak interaction in the laboratory are the β^--decay (e$^-$ emission), β^+-decay (e$^+$ emission), and orbital-e$^-$ capture processes depicted in Fig. 12 (a)-(c). The probabilities of these three processes may be quite different in laboratory and astrophysical conditions. One effect that can contribute to a deviation from the laboratory β^--decay half-lives relates to the possible reduction of the electron phase-space as the result of the degeneracy of the Fermi-Dirac electron gas that is encountered in a variety of stellar situations.¶ Additional effects concern the contribution to the decay process of excited states of a nucleus, or the ionization. This loss of bound electrons takes place in a large variety of stellar conditions, and especially at high temperatures. Atoms accelerated to relativistic cosmic-ray energies are also stripped of their electrons. Ionization may influence the nuclear half-lives in several ways. It has first the obvious effect of reducing the probability of capture of bound electrons. A less trivial consequence relates to the possible development of the process of "bound-state β-decay," which creates an electron in an atomic orbit previously vacated (in part or in total) by ionization [Fig. 12 (f); Sect. 4.4.4]. (This process accompanies β^- decays even in the absence of ionization, but its relative contribution is quite insignificant in such conditions.)

Other β-decay modes develop specifically in stellar plasmas. The "continuum-e$^-$

¶ Under local thermodynamic equilibrium conditions that prevail in most stellar interiors ([34]), the electron gas is well described by the classical Maxwell-Boltzmann distribution law. In various situations, however, use of the Fermi-Dirac distribution is made necessary. The electrons are then referred to as "degenerate," the degree of this degeneracy increasing with its "Fermi energy" (that is, with increasing density and decreasing temperature) capture" process [Fig. 12 (d)] is quite common, and often overcomes orbital-e^- captures in highly-ionized stellar material. In these conditions, atoms are indeed immersed in a sea of free electrons. Continuum-e^- captures display their most spectacular effects in situations where the electrons are degenerate. Highly stable nuclei in the laboratory may well become β-unstable if indeed the electron Fermi energy is large enough for allowing endothermic transitions to take place through the captures of free electrons with energies exceeding the energy threshold for these transitions. Clearly, the higher the electron Fermi energy, the more endothermic the transitions may be. The evaluation of the free-e^- capture rates may benefit from the laboratory knowledge of the rate of the inverse β^+-decays. In many instances, this information is insufficient, and additional theoretical predictions are required. Among the most spectacular endothermic free-e^- captures that can be encountered in astrophysics, let us mention those on ^{14}N, ^{16}O, ^{20}Ne or ^{24}Mg in certain WDs ([129] - [131]), or the transformations of protons into neutrons in the highly-condensed collapsing core of a massive star on the verge of experiencing a supernova explosion (Sect. 8.3). As a result, the neutron fraction may become as high as 90% in these locations. As the density increases further with the continuation of the collapse, the pressure exerted by this neutron gas may become sufficient for counter-balancing the gravitational forces, opening the possibility of forming a stable neutron star.

Positrons captures [Fig. 12 (e)] are also of importance in certain stellar situations, and especially in high-temperature (typically $T > 10^9$ K) and low-density locations. In such conditions, a rather high concentration of positrons can be reached from an $e^- + e^+ \leftrightarrow \gamma + \gamma$ equilibrium which favours the e^-e^+ pairs. The competition (and perhaps equilibrium) between positron captures on neutrons and electron captures on protons is an important ingredient of the modelling of Type-II supernovae.

4.4.2. Neutrino reactions Aside from the capture of continuum electrons on protons (and on iron-group nuclides), various weak-interaction processes involving neutrinos also have an important bearing on Type-II supernovae. The probabilities of production of all sorts of (anti-)neutrinos at the centre of a nascent (hot) neutron star, certain reaction cross sections that determine their transport rate to the neutron star surface, and the interactions of the emerging neutrinos with neutrons and protons near that surface are expected to be essential ingredients of the Type-II supernova models ([132] - [135]). Neutrinos emerging from the neutron star could also interact with pre-existing heavy nuclei as they pass through the outer supernova layers. This interaction might lead to a limited nucleosynthesis referred to as the ν-process ([136, 137]).[+]

While most of the β-decay processes of astrophysical interest mentioned above can be dealt with in the classical "V − A" theory of the weak interaction ([138]), the evaluation of neutrino interaction cross sections requires due consideration of both the charged- and neutral-currents of the unified electro-weak interaction ([139, 140]).

[+] Also note that the cross sections for the captures of high-energy neutrinos by certain heavy nuclei, like ^{71}Ga and ^{205}Tl, are needed for designing neutrino detectors

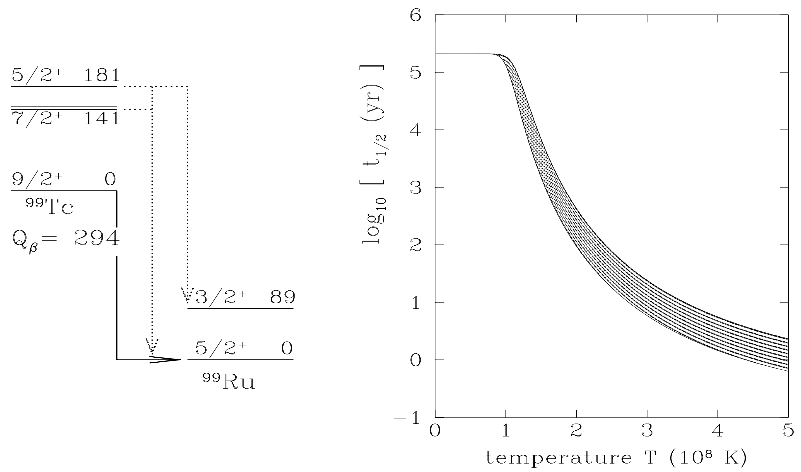

Figure 13. The low-lying levels of ^{99}Tc and of the β-decay daughter ^{99}Ru labelled by excitation energies (in keV) and spin-parity J^{π} (*left panel*), and its estimated effective β-decay half-lives versus temperature (*right panel*). The ^{99}Tc ground state decays to the ^{99}Ru ground state through a slow "second forbidden" transition. The β-decay of the 143 keV isomeric state is observed to be slow as well. When thermally populated, the levels at 141 and 181 keV are expected to undergo the fast "allowed" ("Gamow-Teller") transitions indicated by the dotted arrows of the left panel. The effective half-lives shown on the right panel are adapted from [144]. They are obtained under the assumption of thermally equilibrated population of the ^{99}Tc states, and from estimates of the experimentally unknown excited-state β-transition matrix elements. (Evaluated uncertainties translate into the displayed shaded area.) In this specific example, the rates are almost density-independent

Many interesting and complicated problems are also raised by various aspects of nucleon correlations and spin fluctuations in neutrino scattering at high densities ([141] - [143]).

4.4.3. β-decays from nuclear excited states As we have emphasized earlier, the excited levels and ground state of a nucleus are very often populated in thermal equilibrium, possible exceptions being certain isomeric states. These various levels may thus contribute to the decay of a nucleus, so that its effective β-decay half-life may strongly depart from the laboratory value.

A classical example of the importance of the β-decays from nuclear excited states concerns ^{99}Tc. Technetium observed at the surface of certain AGB stars is considered to be ^{99}Tc, which is a product of the s-process of neutron captures developing in the He-burning shell of these stars (Sect. 8.1). Under such conditions (typical temperatures in excess of about 10^8 K) the 141 and 181 keV excited states of ^{99}Tc can contribute significantly to the effective decay rate. Figure 13 shows a dramatic drop from the laboratory (ground state) $t_{1/2} \approx 2.1 \times 10^5$ y to as short as some 10 y at $T \gtrsim 3 \times 10^8$ K. This example illustrates quite vividly that the decay of thermally-populated excited states may alter laboratory half-lives most strongly in the following conditions: (1) the ground-state decay is slow, as a result of selection rules, and (2) (low-lying) excited states can decay through less-forbidden transitions to the ground and/or excited states of the daughter nucleus. Needless to say, the temperatures have to be high enough for the relevant excited levels to be significantly populated.

4.4.4. β-decays at high ionization It has already been stressed that ionization may affect β-decay lifetimes in various ways. This is illustrated here by way of two examples.

bound-state β-decay A theoretical conjecture of the existence of this process goes back to more than 50 years ago [145], but its experimental confirmation had to await until quite recently (Sect. 7.2.2). In fact, it had already been realized in the early 1980s that bound-state β-decay can be responsible for the transformation of some stable nuclides, like ^{163}Dy, in hot enough stellar interiors [146, 147]. Subsequently the interest for this process in astrophysics has been growing, in particular with regard to specific aspects of the s-process, and in relation to some cosmo-chronological studies ([148]; Sect. 8.2).

β-decays of radionuclides in cosmic-rays: The cosmic-ray abundances of some radioactive nuclides can be profitably used for estimating the age of these high-energy particles ([149]), or more precisely the time the cosmic rays have been confined within the disc, and possibly the magnetic halo of the Galaxy.* This concerns in particular ^{54}Mn, the neutral atoms of which are known to undergo orbital electron captures ($t_{1/2} = 312$ d). In high-energy cosmic rays, those orbital electrons are stripped off to leave bare ^{54}Mn, which is expected to transform very slowly via β^- and β^+-decays. The theoretical evaluation of the rates of these laboratory-unknown transitions encounters enormous difficulties [150], and their measurements are eagerly awaited. Recently, ^{26}Al has been resolved from the stable ^{27}Al in the cosmic radiation [151]. Due to the suppression of its e$^-$-capture mode resulting from its complete ionization, the cosmic-ray ^{26}Al half-life is increased up to 8.7×10^5 y from the laboratory value of 7.2×10^5 y. Another interesting case, in particular for γ-ray astronomy, concerns ^{44}Ti. Its half-life, the laboratory value of which has become well known to be close to 60 y [152] - [154], may be increased in young supernova remnants because of its possibly substantial ionization [155].

4.5. Nuclear decays and reactions via electromagnetic interaction

Nuclei immersed in a high-temperature stellar photon bath may be subjected to photodisintegrations of the (γ,n), (γ,p) or (γ,α) types. Because of the experimental (and theoretical) difficulties raised by the direct determination of photodisintegration rates, especially under the constraint that the photons obey a Plank distribution law,♯ use is usually made of the detailed balance theorem applied to the reverse radiative captures of nucleons or α-particles. This procedure makes clear that the photodisintegration rates depend on temperature T and on the reaction Q-value as

* There is substantial evidence from the observation of synchrotron emissions that a galaxy containing relativistic cosmic-ray electrons in its disc develops a magnetic halo. The galactic cosmic rays could spend part of their confinement time within such halos

♯ This is the case in stellar interiors, where local thermodynamic equilibrium holds to a very good approximation ([34])

exp(-Q/kT). Photodisintegrations thus play a more and more important role as the evolution of a star proceeds, i.e., as temperatures get higher (Fig. 7). They start contributing to the energetics and the nucleosynthesis during the Ne-"burning" stage of massive stars (Sect. 5.2.4), which is truly a Ne-photodisintegration phase dominated by $^{20}\mathrm{Ne}\,(\gamma\,,\alpha)\,^{16}\mathrm{O}$. The importance of photodisintegrations culminates at the supernova stage (Sect. 8.3).

4.6. Nuclear decays via strong interaction

As fissions, and in particular neutron-induced fissions, may dictate the nature of the heaviest nuclides that can be synthesized in the r-process (Sect. 8.1), it is no surprise that they have been under active astrophysical scrutiny in relation with the possibility of stellar production of super-heavy nuclei. Fissions, especially of the β-delayed type (i.e. those from levels fed by β-decays) have the additional interest of possibly being responsible for the cycle-back to lighter species of the heaviest r-process produced nuclides. This can also be achieved by α-decays. Finally, the energy released by fissions may play an important role in some scenarios of "quasi r-processing," such as the one associated with neutron stars ([156]; Sect. 8.1.4).

Nuclear α-decays have been studied extensively in the laboratory. Save some exceptional cases [157], the available data appear to be sufficient for astrophysical purposes. The situation is quite different regarding fission. In particular, the fission barriers of the very neutron-rich nuclides involved in the r-process cannot be measured in the laboratory with present techniques, and theory is the resort.

5. Thermonuclear reactions in non-explosive events

To the items of Sect. 4, one has certainly to add the knowledge of the rates of nuclear reactions in energy domains of astrophysical relevance. This is the focus of a very intense laboratory activity. As we have previously noted, the rest of this review is concerned with thermonuclear reactions only. For the details about spallation reactions, the readers are referred to the works quoted in Sect. 3.2.

The thermonuclear reactions of astrophysical interest concern mainly the capture of nucleons or α-particles. A limited number of fusion reactions involving heavy ions (^{12}C, ^{16}O) are also of great importance. As mentioned earlier, charged-particle induced reactions are essential for the energy budget of a star, as well as for the production of new nuclides in stellar and non-stellar (Big Bang) situations. In contrast, the role of neutron captures is largely restricted to nucleosynthesis, their energetic impact being negligeable.

In non-explosive conditions, corresponding in particular to the quiescent phases of stellar evolution which take place at relatively low temperatures, most of the reactions of interest concern stable nuclides. Even so, the experimental determination of their cross sections and the evaluation of the corresponding stellar reaction rates face enormous problems, and represent a real challenge ([23]).

The energy region of "almost no event" The experimental difficulties relate directly to the fact that the energies of astrophysical interest for charged-particle induced reactions are much lower than the Coulomb barrier. As a consequence, the cross sections can dive into the nanobarn to picobarn abysses. Thanks to their impressive skill and painstaking efforts, experimental physicists involved in nuclear astrophysics have been able to provide the smallest nuclear reaction cross sections ever measured in the laboratory. However, in very many cases, they have not succeeded yet in reaching the region of "almost no events" of astrophysical relevance. Theorists are thus requested to supply reliable extrapolations from the experimental data obtained at the lowest possible energies.

Electron screening corrections As if the evaluation of stellar reaction rates were not complicated enough, a whole new range of problems has opened up with the discovery through a series of remarkable experiments that the reaction cross sections measured at the lowest reachable energies are in fact "polluted" by atomic or molecular effects induced by the experimental conditions ([158] - [160]). As a result, the situation appears even more intricate than previously imagined, necessitating a multi-step process in order to go from laboratory data to stellar rates: before applying the usual electron screening corrections relevant to the stellar plasma conditions ([161]), it is required first to extract the *laboratory* electron screening effects from the experimental cross-section data in order to get the reaction probabilities for bare nuclei. In spite of heroic laboratory efforts and complementary theoretical modelling, much obviously remains to be done in order to get reliable estimates of the laboratory electron-screening factors. Uncertainties also remain in the evaluation of the stellar plasma screening, and may impede an accurate enough treatment of some specific problems, as exemplified in the following section.

5.1. Energy production in the Sun, and the solar neutrino problem

The Sun serves as a very important test case for a variety of problems related to stellar structure and evolution, as well as to fundamental physics. Surprisingly enough for a star that has all reasons to be considered as one of the dullest astrophysical objects, the Sun has been for years at the centre of various controversies. One of them is the solar neutrino problem, referring to the fact that the pioneering ^{37}Cl neutrino-capture experiments carried out over the years in the Homestake gold mine observe a neutrino flux that is substantially smaller than the one predicted by the solar models. That puzzle has led to a flurry of theoretical activities, and to the development of new detectors (namely Kamiokande II/III, Superkamiokande, and the SAGE and GALLEX gallium experiments). These activities have transformed the original solar neutrino problem into *problems*. The relative levels of 'responsibility' of particle physics, nuclear physics or astrophysics in these discrepancies have been debated ever since ([162] - [164]††). In what follows we address some questions that concern nuclear physics directly.

Much experimental and theoretical work has been devoted to the reactions of the p-p chains that are the main energy and neutrino producers in the Sun. (See [165] for a compilation and evaluation of the existing data (hereafter referred to as NACRE).) In spite of that, problems remain concerning the astrophysical rates of some of the involved reactions. This is especially the case for $^{7}\mathrm{Be}\,(\mathrm{p}\,,\gamma)\,^{8}\mathrm{B}$, which provides the main neutrino flux detectable by the chlorine detector, and is considered by some as one of the most important nuclear reactions for astrophysics. Improved low-energy data are also required for other reactions, like $^{3}\mathrm{He}(^{3}\mathrm{He},2\mathrm{p})^{4}\mathrm{He}$. They would additionally shed some light on the question of the laboratory electron screening. Since such low-energy measurements are predominantly hampered by the cosmic-ray background, improved data could be obtained by underground measurements. This was the aim of the installation of a 50 kV accelerator at the Gran Sasso laboratory within the pilot Italian-German project LUNA (Laboratory Underground for Nuclear Astrophysics), and the motivation for the extension of this project to new facilities [166].

Another nuclear physics activity that has an important bearing on the solar neutrino problem concerns the calibration through (p,n) reaction studies (Sect. 7.2.1) of the β-decay nuclear matrix elements involved in the rates of neutrino captures to excited states of ^{71}Ge, which are responsible for the largest uncertainties in the analyses of the SAGE and GALLEX experiments [167, 168].

5.2. Non-explosive stellar evolution and concomitant nucleosynthesis

As made clear in Sect. 3, many astrophysical problems, like the interpretation of the surface composition of chemically peculiar stars or the study of the chemical evolution of the Galaxy, require the modelling of the evolution of stars with initial masses in the approximate 1 to 100 $\mathrm{M}_{\odot}$ range, as well as of the concomitant nucleosynthesis ([80, 169]). We present here a brief summary of nuclear data typically in quest for studies of the controlled thermonuclear burning phases.

5.2.1. Hydrogen burning In addition to the p-p chains that operate in solar-type stars, energy production by H burning can also occur non-explosively through the cold CNO cycle. Some hydrogen can also be consumed by the NeNa and MgAl chains ([23]). These last two burning modes most likely play only a minor role in the stellar energy budget, but are of significance in the production of the Na to Al isotopes, especially in massive stars. Most important, the MgAl chain might synthesize ^{26}Al, which is a very interesting radio-active nuclide for γ-ray astronomy and cosmochemistry.

Much experimental and theoretical effort has been devoted to the reactions involved in these burning modes, as summarized in NACRE [165], which also provides typical

††In [163], the discussion is conducted in particular in the light of the Superkamiokande experiment supporting the ideas of 'oscillations' between different neutrinos types [374]

uncertainties still affecting the relevant reactions. The yields from the CNO, NeNa and MgAl burning modes based on previously adopted rates and their uncertainties have been analyzed in [170], and its update [171] based on the NACRE data. These predictions demonstrate that better determinations of certain reaction rates would be desirable in order to set up meaningful comparisons between certain abundance predictions and observations.

5.2.2. Helium burning and the s-process The main reactions involved in the He-burning stage have been discussed in many places ([23], NACRE [165]). Of very special and dramatic importance for the theories of stellar evolution and of nucleosynthesis is the famed $^{12}\mathrm{C}\,(\alpha\,,\gamma)\,^{16}\mathrm{O}$ reaction ([80]), which has been the subject of a flurry of experimental investigations, as well as of theoretical efforts ([16], NACRE [165]; Sect. 7.3.2). In spite of that, uncertainties remain, and preclude certain nuclear astrophysics predictions to be made at a satisfactory level ([80]).

Other α-particle induced reactions are of special importance, and have been the subject of many dedicated experimental and theoretical works. This is particularly the case with $^{13}\mathrm{C}\,(\alpha\,,\mathrm{n})\,^{16}\mathrm{O}$ and $^{22}\mathrm{Ne}\,(\alpha\,,\mathrm{n})\,^{25}\mathrm{Mg}$ [172]. These reactions are considered as the main sources of neutrons for the s-process nucleosynthesis (Sect. 8.1.4). A further reduction of the remaining uncertainties of those reaction rates would be highly desirable, as exemplified in [173].

The proper treatment of the s-process also requires the knowledge of a host of neutron-capture cross sections at typical energies from about 10 to 100 keV on targets in the whole $12 \leq A \leq 210$ mass range. Much dedicated experimental work has led to a substantial improvement in our knowledge of relevant (n,γ), as well as (n,p) and (n,α) cross sections. However, some of them are not yet determined with the required accuracy. This concerns especially reactions on unstable targets close to the valley of nuclear stability (Sect. 7.4). In these cases, the knowledge of the neutron-capture cross sections has to be complemented by the astrophysical rates of the competing β-decays. It has also to be emphasized that the bound-state β-decay process may well come into play for ionized atoms, and significantly affect the production of some specific s-nuclides.

5.2.3. Carbon burning The C-burning phase raises the very interesting question of the fusion of light heavy ions below the Coulomb barrier, and in particular of the origin of the very pronounced structures observed in the $^{12}\mathrm{C} + {}^{12}\mathrm{C}$ fusion cross section at low energies. The devoted experimental and theoretical works do not provide fully satisfactory solutions ([23, 174, 175]).

5.2.4. Neon, oxygen, and silicon burning The Ne-burning phase is initiated by $^{20}\mathrm{Ne}\,(\gamma\,,\alpha)\,^{16}\mathrm{O}$, the first major energetically significant photodisintegration reaction experienced by a star in the course of its evolution. Its rate is evaluated by applying the detailed balance principle to the inverse $^{16}\mathrm{O}\,(\alpha\,,\gamma)\,^{20}\mathrm{Ne}$ reaction. A complementary $^{20}\mathrm{Ne}$

destruction channel is $^{20}\mathrm{Ne}\,(\alpha\,,\gamma)\,^{24}\mathrm{Mg}$. Both α-capture reactions have been studied experimentally and theoretically ([176] - [178], NACRE [165]).

The $^{16}\mathrm{O}+^{16}\mathrm{O}$ fusion reaction that governs the O-burning phase does not exhibit intricacies comparable to those encountered with $^{12}\mathrm{C}+^{12}\mathrm{C}$. Yet, much has still to be learned about heavy-ion reaction mechanisms at low energy, and about the way to extrapolate the yields to the energy regions of astrophysical interest ([174] for references).

Silicon burning comprises a very complex pattern of nuclear reactions, and evolves into a nuclear statistical equilibrium (NSE) regime when the remaining Si has sufficiently low abundances [179]. Much effort has been devoted over the years to the measurement of α- or p-capture rates of interest in that burning phase ([180, 181] for references). Such experiments are also important for evaluating the virtues of statistical model calculations (Sect. 7.5.4) that have to be used in order to calculate the host of unmeasured reaction rates involved in the Si-burning modelling.

6. Thermonuclear reactions in explosive events

In stellar (such as nova and supernova) or non-stellar (Big Bang) explosions, the energies of astrophysical interest are typically larger than in the non-explosive situations, and can be of the order of the Coulomb barrier. In such conditions, the relevant cross sections are also larger, and may range between the micro- and the millibarn. Unfortunately, there is a very high price to pay in order to enter that cross section range.

The realm of exotic nuclei The thermal neutron, proton and α-particle bath present in an explosive astrophysical site is able to drive the nuclear flows to either very neutron-deficient or very neutron-rich nuclides. The precise description of these flows requires the knowledge of the rates of captures of neutrons, protons or α-particles by highly β-unstable nuclei. Except in some specific cases, those reactions have not lent themselves yet to a direct experimental scrutiny, so that their rates have to be evaluated theoretically.

Targets in excited states The reaction rate evaluation gets even much more complicated as a huge variety of target states can be significantly populated in very hot explosive sites, and thus contribute substantially to the effective reaction rates. In such conditions, a large resort to theory is mandatory in order to predict these rates, even in the case of stable targets.

Another general distinctive feature of the nuclear processes in explosive situations relates to the fact that the burning time-scales are much shorter (of the order of seconds to hours) than in quiescent conditions. In fact, a given burning phase may in certain cases stop well before exhaustion of the reactants, in contrast to the situation prevailing in non-explosive stellar evolution. This is a manifestation of the "freeze-out" of the charged-particle induced reactions. This regime develops when the typical expansion time-scales of the explosively processed material become shorter than mean lifetimes of nuclei against charged-particle captures. These nuclear time-scales indeed increase dramatically with the decreasing temperatures in an expanding material as a result of the decrease of the Coulomb-barrier transmission probability, which in turn owes to the decrease of the mean relative energies of the interacting particles.

The corresponding explosive nucleosynthesis has in many instances been studied in the framework of simplistic parametrized astrophysical models which allow avoiding the many intricacies of the (often unknown) explosion characteristics. The approximations are sometimes going so far as to adopt constant temperatures and densities for a given time-scale, with the presumed values of these quantities, as well as of the initial composition of the material to be processed, being just "inspired" by more detailed models (if they indeed exist !). In contrast, nuclear reactions are followed by detailed networks (see [24] Chap. 9). This approach, hybrid in the degrees of sophistication, has certainly some virtues. In particular, it provides clues to the general characteristics of a burning mode, and possibly some identification of the nuclear input of importance. It has also obvious shortcomings, and there is a danger for the conclusions drawn from such an approach to be over-interpreted in its astrophysics or nuclear physics aspects.

6.1. Big Bang nucleosynthesis

As reviewed in great detail by [182] (also NACRE [165]), the dedicated experimental and theoretical efforts for the determination of the rates of the reactions involved in the standard Big Bang nucleosynthesis model have succeeded in putting on a remarkably safe nuclear footing the conclusion that such a model is able to account for the pre-galactic abundances of the nuclides D, ^{3}He, ^{4}He and ^{7}Li derived from various astrophysical observations and from models for the chemical evolution of galaxies. A quite limited number of reactions, however, still suffer from some uncertainties. Even if they are relatively low, those uncertainties could have some impact on the yield predictions, and consequently on the acknowledged virtues of the standard Big Bang model.

Various non-standard Big Bang models, and in particular one invoking some inhomogeneities at the nucleosynthesis epoch, have raised much excitement in a fraction of the nuclear astrophysics community ([182, 183]). These models are indeed calling for many reactions that are not involved in the standard model, and whose rates are largely unknown. Of course, the interest of pursuing specific nuclear studies in relation with the inhomogeneous Big Bang clearly depends on the outcome of the investigation concerning the validity of that model, which is far from being fully ascertained yet ([100, 111]).

6.2. The hot modes of hydrogen burning

Hydrogen can burn explosively in various astrophysical events, like novae or X-ray bursts. The corresponding "hot" burning modes involve a large variety of unstable nuclei. These modes have specific nucleosynthesis signatures, and raise many difficult experimental and theoretical astro- and nuclear-physics problems.

6.2.1. The hot p-p mode This mode, as first recognized by [184], could in particular develop in nova explosions resulting from the accretion on a white dwarf of material from a companion star in a binary system. A variety of reactions of importance have been identified. One of the keys of this type of burning is the $^{8}\mathrm{B}\,(\gamma\,,\mathrm{p})\,^{7}\mathrm{Be}$ photodisintegration. This reaction impedes the transformation of ^{7}Be into ^{4}He which characterizes the cold p-p chain, and may thus be responsible for some ^{7}Li production (through the ^{7}Be decay) in nova situations ([58]).

Several of the hot p-p reaction rates have been scrutinized both theoretically and with the help of indirect experimental techniques. Let us note in particular that the rate of transformation through $^{11}\mathrm{C}\,(\mathrm{p}\,,\gamma)\,^{12}\mathrm{N}$ of the ^{11}C which could be produced by $^{7}\mathrm{Be}\,(\alpha\,,\gamma)\,^{11}\mathrm{C}$ has been measured in a Coulomb break-up experiment (Sect. 7.3.2), the results of which differ quite substantially from the predictions of a microscopic model (Sect. 7.5.1). Such a model has also been used to predict the rate of $^{8}\mathrm{B}\,(\mathrm{p}\,,\gamma)\,^{9}\mathrm{C}$, which might also have some importance in the nova scenario [185].

6.2.2. The hot CNO and NeNa-MgAl chains These hot H-burning modes develop when some produced β-unstable nuclei decay more slowly than they capture protons, which is in contrast to the situation characterizing the corresponding cold burnings. The high temperatures encountered in explosive situations are again demanded. This request relates directly to the fact that the β-decays of the involved light nuclei are essentially temperature-independent (in view of the paucity of excited states that can be significantly populated at the temperatures of relevance for these processes), while the proton capture rates increase dramatically with increasing temperatures (as a result of the larger Coulomb-barrier penetrability).

More specifically, the cold CNO switches to the hot CNO mode when $^{13}\mathrm{N}\,(\mathrm{p}\,,\gamma)\,^{14}\mathrm{O}$ becomes faster than the ^{13}N β-decay. This occurs typically at temperatures in excess of 10^{8} K. The cold NeNa and MgAl chains evolve into a hot mode at temperatures that are quite similar to the operating conditions for the hot CNO. In fact, novae could be favourable sites for the development of both the hot CNO and NeNa-MgAl chains.

As an immediate consequence of the definition of the hot H burning, many reaction rates on unstable nuclei come into play. Much theoretical and experimental effort has been devoted to a reliable determination of the rates of some of the reactions that have been identified as keys in the development of those processes. In general, those rates have not been measured directly (Sect. 7.3.1), and are rather evaluated indirectly (Sect. 7.3.2). There are, however, some noticeable exceptions to this situation. The first one concerns $^{13}\mathrm{N}\,(\mathrm{p}\,,\gamma)\,^{14}\mathrm{O}$. ¿From its direct measurement (which agrees with indirect determinations), it is concluded that the $^{13}\mathrm{N}\,(\mathrm{p}\,,\gamma)\,^{14}\mathrm{O}$ rate is now known well enough for practical astrophysical purposes [186]. Direct experiments have also been conducted on $^{22}\mathrm{Na}\,(\mathrm{p}\,,\gamma)\,^{23}\mathrm{Mg}$ and $^{26}\mathrm{Al}^{\mathrm{g}}\,(\mathrm{p}\,,\gamma)\,^{27}\mathrm{Si}$, which are important destruction channels of the ^{22}Na and $^{26}\mathrm{Al}^{\mathrm{g}}$ radionuclides of astrophysical importance. These experimental efforts have succeeded in reducing drastically the nuclear physics uncertainties affecting the explosive (nova) ^{22}Na and ^{26}Al yields, as can be seen from a comparison between the present situation ([123, 187]) and the one prevailing in the mid-1980s. Note that large uncertainties still remain in the $^{26}\mathrm{Al^g}\,(\mathrm{p}\,,\gamma)\,^{27}\mathrm{Si}$ rate at lower temperatures characteristic of quiescent stellar evolution phases. Those uncertainties, however, do not have a significant impact on the corresponding ^{26}Al yield predictions, as the ^{26}Al β-decay is likely to be the main destruction channel in those conditions (as an illustration of this claim, see [188] for a calculation of the ^{26}Al yields from non-exploding massive stars of the Wolf-Rayet type). On the other hand, in conditions where the $^{26}\mathrm{Al^m}$ isomeric state can have a significant thermal population, the contribution of the proton capture by $^{26}\mathrm{Al^m}$ to the net stellar ^{26}Al + p rate has to be taken into account. At present, this evaluation merely relies on a global statistical model calculation (NACRE [165]; Sect 7.5.4). Its direct experimental determination would require the development of a $^{26}\mathrm{Al^m}$ beam, which obviously represents an interesting technological challenge.

6.2.3. The rp- and αp-processes The hot CNO and NeNa-MgAl modes can transform into the so-called rp- or αp-processes when $^{15}\mathrm{O}\,(\alpha\,,\gamma)\,^{19}\mathrm{Ne}$ or $^{14}\mathrm{O}\,(\alpha\,,\mathrm{p})\,^{17}\mathrm{F}$ become more rapid than the corresponding β-decays. Alternatively, $^{18}\mathrm{Ne}\,(\alpha\,,\mathrm{p})\,^{21}\mathrm{Na}$ could play this role if its still-uncertain rate can indeed become faster than the ^{18}Ne β-decay in appropriate astrophysical conditions, which could be encountered in certain Type-I supernovae, or in X-ray bursters resulting from the accretion of matter on a neutron star. In such conditions, it is expected that the nuclear flow can go all the way from the C-N-O region up to, or even slightly beyond, the iron peak through a chain of proton captures (and their inverse) and β^+-decays. This chain of transformations is termed the rp-process ([189, 190]). It could transform into an αp-process at temperatures that are high enough for $(\alpha\,,\mathrm{p})$ reactions to play a leading role by bypassing the proton-capture + β-decay chains. It is sometimes speculated that the rp-process can even reach the vicinity of the $A \approx 100$ mass range [190].

A host of reactions on unstable neutron-deficient nuclei, some of them being close to the proton drip line, are involved in the rp- or αp-process (a few already partake in the hot CNO and NeNa-MgAl chains). A direct measurement of a significant fraction of all those potentially important reactions is difficult to conceive. To-date, and apart from the experiments on $^{13}\mathrm{N}\,(\mathrm{p}\,,\gamma)\,^{14}\mathrm{O}$ mentioned earlier, direct measurements have been conducted only for $^{18}\mathrm{F}\,(\mathrm{p}\,,\alpha)\,^{15}\mathrm{O}$ and $^{19}\mathrm{Ne}\,(\mathrm{p}\,,\gamma)\,^{20}\mathrm{Na}$, while preliminary results exist for $^{18}\mathrm{Ne}\,(\alpha\,,\mathrm{p})\,^{21}\mathrm{Na}$ rate (Sect. 7.3.1). The $^{18}\mathrm{F}\,(\mathrm{p}\,,\alpha)\,^{15}\mathrm{O}$ reaction is an efficient path in the transformation of initially present ^{12}C and ^{16}O into ^{15}O, while the ^{19}Ne and possibly ^{18}Ne destructions take part in the breakout from the C-N-O region. In fact, much of what is known on reaction rates involved in the rp-process has been derived from a variety of indirect techniques.

As a necessary complement to these experimental efforts, use is made of a global statistical model, which appears to be adequate except for reactions with low Q-values implying relatively low nuclear level densities. Reaction networks appropriate to the modelling of the rp- or αp-process also require the evaluation of β^+-decay rates (and possibly also of continuum-e^- capture rates if indeed high enough electron degeneracies are prevailing).

Obviously, much remains to be done in order to put the rp- and αp-processes on a safer nuclear footing. The proper target of these efforts, and especially the reliable identification of reactions which have to be painstakingly measured in the laboratory, is by far not a trivial matter. For example, no realistic astrophysical models have ever been used to analyze in a careful and detailed way the impact of reaction rate uncertainties on the observable properties of the highly complex objects, like X-ray bursts ([191]), where the rp- or αp-process is expected to develop. Rather, the identification of nuclides and reactions of putative importance relies on grossly simplified and schematic models ([189, 190]). In addition, the rates of some reactions claimed thereby to be important are often evaluated in a quite approximate way. All this might lead to some misleading evaluations of the true importance of some nuclear data. As illustrative examples, let us pick the proton captures on ^{27}Si, ^{31}S, ^{35}Ar and ^{39}Ca. They are considered as key reactions for the rp-process by [189], while [192] find no compelling reason for attempting to measure the corresponding rates using radioactive ion beams. Thus, nuclear physicists may find it desirable to be fully aware of this type of situations before embarking on very difficult experiments [193].

6.3. The He to Si explosive burnings

The explosive combustion of He, C, Ne, O and Si can also develop in a variety of situations, like the explosions in massive single stars, the accretion, or even merging, of white dwarfs in binary systems, as well as possibly the accretion of matter at the surface of neutron stars. As in the case of explosive H burning, these hot burning modes involve a variety of reactions on unstable targets that do not play any significant role in the corresponding cold combustions.

These various explosive burnings and the consequent "yields" of nuclides have been studied in either parametrized or more realistic explosion models ([24, 83, 194]).

6.4. The α-process and the r-process

The various non-explosive or explosive burning modes mentioned above cannot account for the synthesis of the neutron-rich $A > 60$ nuclides (called r-nuclides) at a level compatible with their bulk solar-system abundances. A specific mechanism, referred to as the r-process, is thus called for. It relies on a chain of captures of neutrons whose concentrations are by far higher than in the s-process (Sect. 8.1). As this requirement is clearly impossible to meet in quiescent evolutionary phases, deep supernova layers in the vicinity of a forming neutron star residue have been quite naturally envisioned as a possible r-process site. However, for decades, it has not been possible to substantiate this connection on grounds of detailed supernova models.

In this respect, recent progress in the modelling of Type-II supernovae has raised a lot of excitement and hope in that the r-process might happen in the so-called "hot bubble" region created by neutrino heating at the periphery of a nascent neutron star (Sect. 8.3). The hot bubble consists of a rapidly expanding matter with high entropy and with a more or less significant neutron excess. At short times, or at temperatures of about $(10 \sim 7) \times 10^9$ K, the bubble composition is determined by NSE favouring α-particles and some neutrons. As the temperature decreases further along with the expansion, the α-particles recombine to form heavier nuclides, starting with the $\alpha\alpha n \rightarrow {}^9Be(\alpha,n){}^{12}C$ reaction. It is followed by a complex sequence of α-particle and nucleon captures [especially of the (α,n), (p,n) and (n,γ) type], and of the inverse transformations, synthesizing heavy nuclei even beyond Fe. This is the so-called "α-process"† [195, 196]. If enough neutrons would be left at the freeze-out of the α-process at a temperature slightly in excess of 10^9 K, the r-process could start.

In addition to the astrophysics questions, the α- and r-processes raise major nuclear physics problems. They indeed involve a wealth of very neutron-rich $A \gtrsim 12$ nuclei whose properties are little known experimentally, a large fraction of them even remaining to be produced in the laboratory. In particular, masses, β-decay and neutron capture rates have in most instances to be estimated theoretically. The impact of the related uncertainties on abundance predictions has been discussed in many places (a few of them are quoted in Sect. 7). Neutron-induced fission, as well as β-delayed neutron emission or fission may also bring more uncertainties in the calculated r-process yields, and even in the very energetics of the process. These additional difficulties relate directly to our poor knowledge of fission barriers of very neutron-rich actinides.

6.5. The p-process

It was realized very early in the development of the theory of nucleosynthesis that the production of the stable heavy neutron-deficient nuclides requires a special mechanism, termed the p-process. It has by now become quite clear that this process can develop if pre-existing more neutron-rich (s- or r-) species can experience high enough temperatures ($T \gtrsim 2 \times 10^9$ K) for being photodisintegrated by more or less complicated sequences of (γ,n), (γ,p) and (γ,α) reactions. Such requirements are met in the O/Ne-rich layers of massive stars during their pre-explosion or supernova phase ([197]), as well as possibly in the material accreted at the surface of an exploding white dwarf ([198]). The latter possibility remains, however, to be scrutinized in the framework of detailed stellar models.

The main nuclear physics uncertainties that affect the modelling of the p-process concern the involved nucleon or α-particle captures by more or less neutron-deficient nuclides, as well as the relevant photodisintegrations. Except for few cases ([199] - [201]), no experimental data are available, and resort is classically made to statistical model predictions.

If it is not free from difficulties, the astrophysical site of the p-process may be considered as better known (at least in the limits of spherically-symmetric model stars)

† This must not be confused with the same term used by [8], which is now referred to as the "Ne burning"

than the (sometimes still putative) locations where the rp-, αp- or r-processes may develop. In addition, the p-process deals with nuclei that are closer to the line of stability than those involved in the other mentioned mechanisms, and at least some of the basic properties (like masses and β-decay half-lives) of a substantial fraction of them have been measured.

7. Nuclear data acquisition for astrophysics

We now turn to the on-going experimental and theoretical efforts devoted to the acquisition of the nuclear data needed in a variety of astrophysical problems. After a brief description of the advances concerning nuclear binding and β-decay properties, the current status of our knowledge of nuclear reaction rates is discussed in some detail.

7.1. Nuclear binding

Astrophysics requires approaching the question of the nuclear binding energies either "traditionally" through experiments or mass models concerned with isolated nuclei, or through a nuclear equation of state when a high-temperature and high-density plasma has to be dealt with.

In the last decade, much effort has been devoted to the measurement of nuclear masses ([202]) by ever-improving and innovative techniques. In particular, the development of radioactive beam facilities allows an increasing variety of proton- or neutron-rich nuclei to be studied ([203] - [207]), and this tendency will certainly develop further. The accuracy of the measurements is also significantly improving, and may now reach the 10 keV level, even for nuclei relatively far from the line of stability. Roughly speaking, these experiments involve high-precision direct mass measurements using high-resolution spectrometers, or indirect measurements based on the study of the energetics of a nuclear transformation from which an unknown mass can be deduced from the knowledge of the other participating nuclei ([208]). Despite the experimental advances, many masses remain to be measured in order to meet the astrophysics needs, so that recourse has to be made to theory.

7.1.1. Nuclear mass models Much theoretical progress has been made through the continued sophistication of the Droplet Model, the most matured version of which is the so-called "Finite Range Droplet Model (FRDM)" [209], and through the development of a global "microscopic" description of the mass surface that approximates the Hartree-Fock predictions. This approach is referred to as the "Extended Thomas-Fermi plus Strutinski Integral (ETFSI)" [210].

When compared with more sophisticated methods, those global models are favoured for nucleosynthesis calculations that require unknown nuclear masses. For example, calculations of the Hartree-Fock-Bogoliubov (HFB) type with the use of zero-range ("Skyrme") or finite-range ("Gogny") effective forces have not been able to reproduce the measured masses with the accuracies easily reached by those global models. Because of their complexities, in addition, such computations so far have been limited only to some selected sets of nuclei. The situation is similar for the "Relativistic Mean Field (RMF)" models, although systematic mass calculations appear less cumbersome. (See [211] for comparisons of those various methods and their results.)

Despite these shortcomings, further calculations based on the HFB or RMF methods are certainly of high value in the continuous attempt to improve the FRDM and ETFSI predictions meant for astrophysical applications [212]. Such improvements would certainly be of great value, given the sometimes large discrepancies between the predictions of the FRDM and ETFSI models for the masses of nuclei very far from the line of nuclear stability ([213]). The question of the evolution of the magnitude of the nuclear shell effects with neutron excess, as well as of the "magicity" of certain neutron numbers itself [214] has also raised some excitement and debate ([215, 216]), and remains to be settled by more nuclear physics investigations.

7.1.2. Nuclear equation of state at high temperatures/densities In supernovae or neutron stars, the thermodynamic conditions and neutron richness of the material are such that it appears difficult to extract useful nuclear information from e.g. heavy-ion collision experiments. Resort has thus to be made to theory ([126, 217]).

At temperatures in excess of about 5×10^9 K, NSE is establishment to a high level of accuracy, and the nuclear EOS can be appropriately calculated from statistical mechanics ("Saha equation"), at least if the densities do not exceed about one hundredth of the nuclear matter density. The task is then reduced to the evaluation of binding energies and nuclear partition functions, which is far from being trivial as very neutron-rich nuclei may be involved.

At higher, subnuclear densities, the Coulomb (lattice) correlations have to be properly taken into account. This has been attempted through a temperature-dependent Hartree-Fock method [218], or with the Thomas-Fermi (TF) approximation (combined with the RMF theory) [219]. The TF approximations have often been used for simplicity in studies of complex geometrical configurations that are expected just below the saturation density ([220, 221]).

The superfluidity that characterizes the crust and outer core of a neutron star has been investigated with the help of realistic nucleon-nucleon forces ([222]). Such studies may help understanding some puzzling phenomena, like the sometimes spectacular changes in rotational period ("glitches") of certain pulsars ([222] - [225]).

Beyond the saturation density, many microscopic calculations of the EOS have been performed ([217]). As yet, many of them are concerned with neutron or symmetric nuclear matter at zero temperature, and thus cannot be applied directly to the supernova or hot neutron star problems. Similarly microscopic methods have been used to study the pion condensation which is expected to occur in the inner core of a neutron star at a few times the nuclear density ([222]). The RMF model has been applied for studies of the EOS at even higher densities with the inclusion of various hyperon and lepton degrees of freedom ([226]).

Finally, a transition from the hadronic matter to a quark-gluon plasma is predicted by some QCD lattice calculations to occur at the extremely high temperatures and/or densities that could be reached in the innermost core of a neutron star ([227]). Similar conditions might have prevailed in the early Universe, with some nuclear astrophysics consequences if indeed the outcome has been the persistence of inhomogeneities at the epoch of Big Bang nucleosynthesis.

7.2. Nuclear decay properties

Of the various nuclear decay modes, β-decay processes enter astrophysical problems most importantly. A difficulty stems from the fact that, in many instances, β-decay strength functions have to be known in an energy range that is out of reach of standard β-decay experiments. Also, many β-decay processes may take place at temperatures that are inaccessible by laboratory simulations.

7.2.1. Beta-decay half-lives and strength functions As in the case of nuclear masses, much progress has been made in the experimental determination of β-decay half-lives and strength functions. In spite of this, a large variety of data required by astrophysics are still lacking, and one has to rely heavily on theory. This concerns in particular the β^--decays of very neutron-rich nuclei involved in the r-process, or the captures of highly-degenerate free electrons by protons or iron-group nuclides, which play an important role in the late evolutionary stages and final fate of a variety of stars ([228]). The latter (laboratory-unknown) process involves β^+-strength functions, particularly of the Gamow-Teller type, in a wide range of energies. Such data can be gained from the analysis of charge-exchange (n,p) reactions, but this approach has been applied so far in a limited number of cases only ([229, 230]).

As for β-decay properties of highly unstable nuclei, the development of radioactive beam facilities and of highly efficient detectors ([203] - [207]) has been quite beneficial. This is exemplified by the determination of the half-lives of the magic or near-magic nuclei ^{130}Cd, ^{79}Cu and of their neighbours taking part in the r-process [231, 232], which has been made possible with the development at ISOLDE/CERN of the target technology and of a highly efficient neutron-detection method. The use of the LISE spectrometer at GANIL in combination with a very fast in-flight separation technique and of the neutron counter developed at ISOLDE has led to the measurement of the β-decay properties of ^{44}S and $^{45-47}$Cl [233], which are of astrophysical interest. The β-decay half-lives of neutron-rich Fe, Co, Ni and Cu isotopes of r-process relevance have also been obtained following their production by neutron-induced fission at the Grenoble ILL high-flux reactor [234]. Measurements concerned with very neutron-rich nuclei have also been performed at GSI Darmstadt following their production in relativistic projectile fission ([235]) or in fragmentation reactions [236]. On the proton-rich side, experiments conducted at several facilities (GANIL, GSI, MSU and RIKEN) have helped clarifying the location of the proton drip line, and have provided an ensemble of β-decay rates of relevance to the rp- or αp-processes ([237]).

On the theoretical side, the evaluation of β-decay rates raises problems, in particular because this integrated nuclear quantity is highly sensitive to the energy distribution of a small fraction of the sum rule for the Gamow-Teller transition strength which is used up in the β-decay energy window of a given unstable nuclide. In fact, a major part of the sum rule is exhausted by the "Gamow-Teller giant resonance." The early prediction of this situation [238] has been confirmed by many (p,n) and some (^{3}He,t) experiments ([239, 240] for a retrospective).

The first attempt to consider the sum rule in predicting the half-lives of very unstable nuclides was of statistical nature, leading to the so-called "Gross Theory" ([241]). Various modifications to the original model have been proposed ([242]). ¿From a microscopic point of view, large-scale shell-model calculations are required. Modern shell model diagonalization techniques ([243]) using a huge, but still truncated, configuration space make it possible to deal with finite-temperature continuum-e$^-$ captures by pf-shell nuclei of interest in the late stages of the evolution of massive stars. A numerical approach of the nuclear shell model, referred to as the "shell model Monte Carlo" ([244]) employs an even larger model space allowing the calculation of the β-decay rates for nuclei with N and Z in the vicinity of 28 up to ^{63}Co. However, the method has a limited applicability to odd-A, and even more so to odd-odd nuclei.

A microscopic approach which makes feasible large-scale calculations of the β-decay properties of heavy nuclei is based on the so-called "quasi-particle random-phase approximation (QRPA)." This method has recently been adopted in conjunction with mean field models meant for systematic calculations of nuclear masses, and in particular with the FRDM and ETFSI models ([245, 246]).

In spite of these recent efforts, many difficulties obviously remain. They take the form of discrepancies between the predictions of the existing models, and deviations of all models with respect to one or another new measurement, especially near neutron-shell closures, as made clear by the NUBASE compilation [202]. Following recent experiments, a pessimistic view is expressed that "the large discrepancies found between the measured and the theoretical values emphasize that most recent theoretical work is not an improvement over calculations made almost a decade ago" [236].

The situation may look even more uncomfortable when dealing with the β-delayed neutron-emissions and fissions that have to be included in the detailed modelling of the r-process. The probabilities of these processes are little known experimentally, with laboratory data lacking also for the fission barriers of the neutron-rich actinides of interest. In these conditions, the uncertainties in the β-decay models combine to those in the barrier evaluations. There is some hope of improvement in the reliability of the latter predictions with the use of the ETFSI model. The results [212] appear, at least, to reproduce existing fission barrier data fairly well.

7.2.2. Bound-state β^- decays Bound-state β-decay can drastically affect the half-lives in extreme cases where the β-decay Q-values are small enough to be substantially affected by the ionization ([247]). Such an effect can even lead to the decay of terrestrially stable nuclides. This is notably the case for ^{163}Dy. A storage-ring experiment at GSI has confirmed that the half-life of fully-ionized ^{163}Dy^{+66} is 47 d [248], in excellent agreement with the theoretical prediction of 50 d [247]. Bound-state β-decay can also dramatically modify the terrestrial half-lives of ^{187}Re and of ^{205}Pb. It has recently been confirmed by another GSI storage-ring experiment that the fully-ionized ^{187}Re^{+75} has indeed a half-life of 34 y [249], which is more than 10^9 times shorter than the value for the neutral atoms, and in fair agreement with the theoretical prediction of 12 y [247]. Several studies have enlightened the astrophysical importance of those three nuclides and of their bound-state β-decay. In particular, that mechanism is expected to have a considerable impact on the ^{187}Re - ^{187}Os cosmochronology (Sect.8.2.3). On the other hand, bound-state β-decay may be used as a tool to determine unknown β-decay matrix elements influencing the design of a ^{205}Tl neutrino detector [250, 251], and perhaps even to set some meaningful limits on the electron neutrino mass [248, 252].

Finally, it has to be stressed that the evaluation of the bound-state β-decay rate in stellar plasmas is far from being straightforward, even if the relevant nuclear matrix elements are known. The problems relate in particular to electron screening effects, which have been estimated so far from a finite-temperature Thomas-Fermi model [147].

7.3. Charged-particle induced reactions: Experiments

We have already stressed that much dedicated and heroic effort has been devoted to the measurement of the rates of a wealth of thermonuclear reactions in order to put the astrophysical models on a safer footing. In many instances, such an experimental activity has been the trigger of new and exciting technological or physical ideas. The difficulty of providing data in quest and the vast diversity of the problems to be tackled have always made it unavoidable to use the most sophisticated experimental techniques of nuclear physics, or even to develop novel approaches. In that adventure, practically all types of accelerators have been used, from the electrostatic ones delivering energies in the few keV range to high energy heavy-ion accelerators.

As also stressed earlier, the problems that experimentalists are facing when they try to measure cross sections for astrophysics (mostly proton- and α-particle-induced reactions, a substantial fraction of them being of the radiative capture type) are of different natures, depending in particular on the non-explosive or explosive character of the sites where the considered thermonuclear reactions are expected to take place. More specifically, non-explosive conditions necessitate the knowledge of extremely small cross sections inferred by the relevant very low energies. Except in some cases, existing techniques have been able to provide measurements only at higher energies, so that a theoretical guide is required to extrapolate the data down to the energies of astrophysical interest. On the other hand, explosive situations make the energy problem less acute, but very often require cross sections to be known on unstable species.

In order to obtain thermonuclear reaction rates, various experimental techniques have been used, which can be classified into “direct” and “indirect.”

7.3.1. Direct cross-section measurements Direct measurements concern reactions that really take place in astrophysical sites. Strictly speaking, they would also have to be conducted at the stellar energies (referred to in the following as the “Gamow window”). This is very seldom the case, especially in non-explosive situations, in view of the very low energies involved.

Direct methods have been, and still are, widely utilized in the case of stable targets, all efforts being directed towards the development of techniques permitting to reach smaller and smaller cross sections and/or higher and higher accuracies ([23, 253]). Typically, use is made of a dedicated accelerator delivering for several weeks low-energy ion beams of high intensity (1 mA) on a target that is able to withstand the heavy beam load (hundreds of watts), and that is also of high chemical and isotopic purity. A few per mil atoms of impurity can indeed be responsible for a noise exceeding the expected signal. In the case of the commonly used inverse kinematics geometry, a heavy-ion accelerator is often used in conjunction with a windowless gas target of the static or supersonic jet type. Detectors have generally been the same as those used in classical nuclear physics. This will probably remain true in the future. In particular, new generations of detector systems and pulse-processing electronics that have primarily been developed for nuclear structure studies will certainly be most welcome in the attempt to measure sub-picobarn cross sections (Chap. 3.5 of [254]). However, in a few instances, new detector types (e.g. a D_2O detector [23]) have been developed specifically for nuclear astrophysics experiments.

It has to be emphasized that the particular conditions of astrophysical interest require special considerations that are not encountered in ordinary nuclear physics. This concerns namely the necessity of frequent checks of the purity and stochiometry of the targets, the beam intensity determination with calorimeters, or the cosmic-ray shielding. This last requirement becomes of major importance as the experiments get more and more performing as to be able to provide good quality data at lower and lower energies. As the cosmic-ray background may become a deterrent limiting factor, underground experiments have started to be conducted with a 50 kV accelerator installed in the Gran Sasso Laboratory. Remarkable results have already been obtained for the ^{3}He(^{3}He,2p)^{4}He cross sections down to centre-of-mass energies of about 20 keV, which are right within the Gamow window corresponding to the central regions of the Sun [255]. Plans exist to extent this underground facility in order to conduct very low energy measurements of other reactions involved in the various cold H-burning modes [166]. Another type of background of beam-induced origin may also hamper the measurement of very low energy cross sections. High-granularity detectors will certainly be of great help in limiting the inconvenience of this type of noise ([256, 257]).

It is impossible to cite here the myriad of direct cross-section measurements performed for astrophysical purposes. The NACRE compilation [165] may give the reader a flavour of the volume of dedicated experiments of this type.

In the case of unstable targets, two different direct approaches are envisioned, depending upon the lifetimes of the nuclides involved in the entrance channel ([23]). The radioactive *target* technique appears most profitable for radio-active nuclides with lifetimes in excess of about one hour. It has been applied in particular to ^{22}Na(p,γ)^{23}Mg and ^{26}Al^{g}(p,γ)^{27}Si (NACRE [165]). In contrast, the radioactive *beam* method is appropriate for shorter-lived species, and has without doubt to be seen as a new frontier in nuclear physics and astrophysics. Two basic techniques can be used to produce the high-intensity, high-purity radioactive beams that are required for the study of the low-energy resonances or non-resonant contributions of astrophysical interest: the ISOLDE post-accelerator scheme, and the projectile fragmentation method ([203] - [205], [207]). Some examples of the pioneering application of those techniques are presented below.

ISOLDE post-acceleration type experiments A major breakthrough in experimental nuclear astrophysics has been the first direct and successful measurement in inverse kinematics of the resonant ^{13}N(p,γ)^{14}O rate using the ISOLDE post-acceleration scheme at the Belgian Radioactive Ion Beam facility of Louvain-la-Neuve. (See [258] for details about this facility and its various developments, and [259] for the experimental problems – beam and target preparation, detection methods – raised by the measurement of proton captures induced by radioactive beams.)

The ^{13}N(p,γ)^{14}O measurement has been made possible thanks to a pure and intense ($\approx 10^8$ pps) ^{13}N ion beam impinging on a polyethylene $(CH_2)_n$ target, the capture γ-ray being observed with an array of efficient Ge detectors [260]. The data obtained in such a way are in good agreement with indirect measurements using the Coulomb break-up technique, as well as with predictions based on a microscopic model (see below). These resonance data have been complemented with the evaluation of the interfering non-resonant direct-capture contribution to the ^{13}N(p,γ)^{14}O rate based on the investigation of the ^{13}N(d,n)^{14}O excitation function [261].

More recently, direct experiments have also been conducted on ^{18}F(p,α)^{15}O [262] and ^{19}Ne(p,γ)^{20}Na [263] with the use of ^{18}F and ^{19}Ne beams. Preliminary measurements exist for ^{18}Ne(α,p)^{20}Na [264]. All these reactions are of interest for the development of the rp- or αp-process.

fragmentation technique An interesting alternative and complement to the above method is to directly use medium-energy or relativistic radioactive ion beams from projectile fragmentation. This technique has been developed at Berkeley, and then used at GANIL, RIKEN and GSI. In particular, it has been applied at RIKEN to the direct measurement of ^{8}Li(α,n)^{11}B [265], which has been predicted to be of interest in an inhomogeneous Big Bang model.

7.3.2. Indirect cross-section measurements The indirect methods are a very important complement, or even an inevitable alternative, to the direct measurements concerning reactions on stable as well as unstable targets. They will certainly continue to play a leading role in the future ([266]). This situation relates in particular to the extreme smallness of the cross sections of astrophysical interest, or to the incapability of setting up radioactive beams of the required purity and intensity.

Different indirect approaches have been developed and applied to a more or less large extent, like (1) the use of transfer reactions, (2) the study of the inverse reactions, or (3) measurements relating to the decay of radioactive beams.

transfer reactions In cases where resonances near or below the reaction threshold can contribute significantly to the reaction rate, extrapolations of the rates from high energies to the Gamow window may fail. In such conditions, the Breit–Wigner parameters (energy, angular momentum, partial and total widths, and decay modes) of the involved resonances must be determined independently. In nuclear structure studies, this information is typically obtained via transfer reactions. This approach is also widely in use for nuclear astrophysics purposes ([192, 266, 267]; [16, 20]).

The successful application of this technique requires particle beams with good energy resolution (provided by e.g. tandem accelerators) coupled with high resolution spectrometers (Q3D, split-pole). Transfer reactions are also well suited for investigations using radioactive beams or targets. For example, it is planned to study the important $^{15}\mathrm{O}\,(\alpha\,,\gamma)\,^{19}\mathrm{Ne}$ reaction through experiments on $\mathrm{d}(^{18}\mathrm{Ne},^{19}\mathrm{Ne}^*)\mathrm{p}$ using a $^{18}\mathrm{Ne}$ beam [264].

Inverse reactions: the example of the Coulomb break–up Direct experiments on radiative captures require the observation of very low γ-ray yields in the presence of intense backgrounds. This problem can become unsurmountable in experiments with radioactive beams. In such difficult cases, experiments on inverse reactions, which relate to the forward transformations by the principle of detailed balance, may be considered as an alternative. For example, instead of measuring the $\mathrm{A(b,}\gamma\mathrm{)X}$ reaction cross section, experiments can be conducted on the inverse $\mathrm{X(}\gamma\mathrm{,b)A}$ reaction. The γ–flux is provided by the virtual photons of the Coulomb field, which are seen by nucleus X when passing at a suitable distance from a heavy target. This Coulomb break-up technique has the advantage that the cross sections to be measured are larger than those of the direct process because of the high density of virtual photons. Of course, it requires the availability of heavy-ion beams of sufficient energy (several tens to several hundreds of MeV/u) ([268, 269]).

That method has been successfully applied, among others, to the important $^{12}\mathrm{C}\,(\alpha\,,\gamma)\,^{16}\mathrm{O}$ reaction [270]. With radioactive beams produced by the fragmentation of energetic heavy-ions, the Coulomb break-ups of $^{14}\mathrm{O}$, $^{12}\mathrm{N}$ and $^{8}\mathrm{B}$ have been used to study the reactions $^{13}\mathrm{N(p,}\gamma)^{14}\mathrm{O}$ [271, 272], $^{11}\mathrm{C(p,}\gamma)^{12}\mathrm{N}$ [273], and $^{7}\mathrm{Be(p,}\gamma)^{8}\mathrm{B}$ [269, 274].

Decay of radioactive beams In certain cases, radioactive decays may offer an interesting alternative to transfer reactions for exploring nuclear levels of astrophysical importance.

For example, the β-decay of ^{20}Mg has been studied in order to improve the knowledge of the ^{20}Na level structure above the ^{19}Ne + p threshold, and concomitantly of the $^{19}\mathrm{Ne}\,(\mathrm{p}\,,\gamma)\,^{20}\mathrm{Na}$ break-out reaction from the hot CNO cycle [275].

Similarly, $^{12}\mathrm{C}(\alpha,\gamma)^{16}\mathrm{O}$ has been investigated through the β-delayed α-emission from ^{16}N [276] - [278], and through the β-delayed proton emission from ^{17}N [279]. These experiments provide information on the E1 and E2 contributions to the rate, respectively.

7.4. Neutron capture reactions: Experiments

Neutron captures or reverse (γ, n) photodisintegrations are essential reactions in the s-, r- and p-processes of heavy element production. The experiments on (n,γ) reactions for astrophysical purposes first require the availability of neutrons with energies in the keV range. The capture cross sections are then measured through the detection of prompt capture γ-rays in combination with a time-of-flight (TOF) technique for neutron energy determination, or through the use of activation methods. These different experimental approaches are only very briefly sketched here (Chap. 4.2 of [254] for details).

Various methods can be used for the production of keV neutrons, and can be seen as complementary. They are (i) nuclear reactions in combination with low-energy particle accelerators, where the limitations in available neutron fluxes can be compensated to some extent by relatively short neutron flight paths, (ii) the bombardment of heavy-metal targets by beams of typically 50 MeV electrons from a linear accelerator, producing high intensities of energetic neutrons which are slowed down in a moderator, or (iii) spallation reactions, which can produce the highest available fluxes of keV neutrons.

The TOF techniques can be applied to the measurement of neutron captures by most of the stable nuclei, but require a pulsed neutron source [e.g. $^{7}\mathrm{Li}\,(\mathrm{p}\,,\mathrm{n})\,^{7}\mathrm{Be}$ with a pulsed proton beam] to determine the neutron energy via the TOF between target and detector. Though that technique is always applicable, it suffers from certain limitations owing to the decreasing flux along the neutron flight path. The corresponding loss in sensitivity is, to some extent, compensated by the development of detectors covering a solid angle of almost 4π. An example of such a setup is provided by the $4\pi\mathrm{BaF}_2$ detector at the Karlsruhe Van de Graaff. Such detectors allow for an accuracy of about 1% for the astrophysical rates, compared with the typical 3 to 8% uncertainties inherent to other techniques. This accuracy is especially welcome for those nuclides that can be produced exclusively by the s-process. Those "s-only" isotopes indeed serve as the normalization that is necessary to evaluate the relative s- and r-process contributions to the (solar-system) abundances of all the other stable heavy nuclides. They also help defining the stellar conditions of operation of the s-process (Sect. 8). At this point, one has to remember, however, that the remarkable experimental accuracy mentioned above clearly concerns the capture of neutrons by nuclei in their ground states, and is spoiled by the contribution to the reaction of target excited states, which can be evaluated by theory only.

When neutron capture leads to an unstable nucleus, the activation technique can serve as an alternative method for measuring stellar (n,γ) cross sections. Experiments can be conducted with neutrons e.g. from ^{7}Li(p,n)^{7}Be, the spectrum of which very closely resembles the thermalized (Maxwellian) stellar spectra in typical s-process conditions. This technique does not require a pulsed beam for neutron production, and the samples can be placed directly onto the neutron target, so that a neutron flux about 10^6 times higher than in the direct detection method can be obtained. This makes the activation technique clearly superior where a good sensitivity is required. It allows, for example, measurements of extremely small (n,γ) cross sections in the μbarn range, which can be of importance in various astrophysical situations e.g. the s-process in low-metallicity stars (Sect. 8.1.5), as well as the determination of cross sections of radioactive isotopes, where extremely small samples have to be used in order to keep the radiation hazard and the sample-induced backgrounds manageable. The limitation of the activation technique to cases in which neutron capture produces an unstable isotope could in principle be overcome by analyzing the irradiated samples via accelerator mass spectroscopy. However, this technique requires extremely pure samples, which are presently not available.

By 1992, experimental neutron-capture cross sections were available for more than 90% of the (approximately 240) stable $A \gtrsim 56$ nuclides involved in the s-process. In 15% of those cases, the obtained accuracy was better than $\pm 4\%$ [280]. Since that time, new high-precision data have become available ([281] - [283]). These data have been complemented with the measurements of relatively small (n,γ) cross sections on various light nuclides ([284, 285]), as well as of some (n,p) and (n,α) rates ([286] - [288]). Further improvement is called for, particularly concerning neutron-capture cross sections on the unstable nuclides that can be involved in the s-process branchings (Sect. 8.1). Such experimental data are now available in a few cases only ([254]) because the samples are difficult to prepare, and as a result of the sample activity itself. They concern the long-lived radionuclides ^{93}Zr, ^{99}Tc, ^{107}Pd and ^{129}I. For shorter-lived species, the activation technique has been found to be especially well suited, as demonstrated by experiments carried out with ^{155}Eu ($t_{1/2} = 5$ y).

Of course, the knowledge of the rate of the neutron captures of relevance to the p- and r-processes is by far less satisfactory, the vast majority of them involving unstable targets. As a consequence, the rates entering the astrophysical modelling come almost exclusively from calculations. Although the measurement of a sizable fraction of the relevant cross sections cannot be imagined in any foreseeable future, experimental efforts devoted to a cleverly selected sample of those reactions would be of the highest importance, particularly in order to help improving the reliability of global reaction rate models.

7.5. Thermonuclear reaction rates: Models

In a variety of astrophysical situations, and especially during the hydrostatic burning stages of stars, charged-particle induced reactions proceed at such low energies that a direct cross-section measurement is often not possible with existing techniques. Hence extrapolations down to the stellar energies of the cross sections measured at the lowest possible energies in the laboratory are the usual procedures to apply. To be trustworthy, such extrapolations should have as strong a theoretical foundation as possible. Theory is even more mandatory when excited nuclei are involved in the entrance channel, or when unstable very neutron-rich or neutron-deficient nuclides (many of them being even impossible to produce with present-day experimental techniques) have to be considered. Such situations are often encountered in the modelling of explosive astrophysical scenarios.

Various models have been developed in order to complement the experimental information. Broadly speaking, they can be divided into "non-statistical" and "statistical" models, with the former one having different variants ([289]). Each of these models has its own advantages, drawbacks, and domains of applicability. Unfortunately, the important question of the evaluation of their reliability is often very difficult to answer. Non-statistical and statistical models are appropriate for systems involving, respectively, low and high densities of participating nuclear levels. In more practical terms, the applicability of the statistical models is limited to reactions involving targets with mass numbers $A \gtrsim 20$ if they lie close to the line of nuclear stability. This mass limit has to be increased more and more when moving farther and farther away from stability. Indeed, the nucleon or α-particle separation energies decrease to such an extent that the number of available nuclear states becomes insufficient to validate a statistical description of the reaction mechanism. As far as the non-statistical models are concerned, one has to distinguish (i) those involving adjustable parameters, such as the R- or K-matrix methods, or (ii) the "ab initio" descriptions, like the potential model, the Distorted Wave Born Approximation (DWBA), or the microscopic models. The first family of models is applicable only when enough cross-section data are available above the Gamow window for a reliable extrapolation to lower energies. In contrast, the second one is useful even in absence of such information, and requires merely an experimentally based nucleus-nucleus or nucleon-nucleon interaction.

7.5.1. Microscopic models In recent years the "microscopic cluster model," based on a first-principle approach, has become an established tool to perform low-energy cross-section extrapolations for both radiative captures and transfer reactions ([290]). In this model, the nucleons are grouped into clusters. Keeping the internal cluster degrees of freedom fixed, the totally antisymmetrized relative wave functions between the various clusters are determined by solving the Schrödinger equation for a many-body Hamiltonian with an effective nucleon-nucleon interaction. When compared with most others, this approach has the major advantage of providing a consistent, unified and successful description of the bound, resonant, and scattering states of a nuclear system. Various improvements of the model have been made ([289]).

In spite of its virtues, the microscopic cluster model cannot, in general, reproduce available experimental data as accurately as often desired for the astrophysically required extrapolations. A higher level of reliability of these extrapolations is usually obtained by adjusting the parameters of the nucleon-nucleon interaction. It should be stressed, however, that these manipulations represent only minor corrections, and do not influence the description of the physics of the reaction process in any major way. In particular, the model retains its predictive power, and remains superior to other frequently used extrapolation procedures. Its major drawback lies in its rather difficult handling, and in its time-consuming computations.

The microscopic model has been applied to many important reactions involving light systems, and in particular to the various p-p chain reactions ([291]). The available experimental data can generally be well reporduced. The microscopic cluster model or its variant (the microscopic potential model) has also made an important contribution to the understanding of the key $^{12}C(\alpha,\gamma)^{16}O$ reaction rate ([292]).

7.5.2. The potential and DWBA models The potential model has been known for a long time to be a useful tool in the description of radiative capture reactions. It assumes that the physically important degrees of freedom are the relative motion between the (structure-less) fragment nuclei in the entrance and exit channels, and that the fragments themselves are just accounted for approximately by the introduction of spectroscopic factors and strength factors in the optical potential. The associated drawbacks are that the nucleus-nucleus potentials adopted for calculating the initial and final wave functions from the Schrödinger equation cannot be unambiguously defined, and that the spectroscopic factors cannot be derived from first principles. They have instead to be obtained from more or less rough "educated guesses."

The potential model has been applied, for example, to the p-p chain $^{3}He\,(\alpha\,,\gamma)\,^{7}Be$ reaction [289]. Another interesting application is to a systematic calculation of the non-statistical "direct capture (DC)" contribution to the ensemble of (n,γ) reactions on neutron-rich targets that may be involved in the r-process ([293]). The direct captures may contribute to the total (statistical + DC) (n,γ) cross sections significantly, and in some cases overwhelmingly, particularly in very neutron rich nuclei.

On the other hand, the Distorted Wave Born Approximation (DWBA) has become the standard model to describe nuclear transfer reactions. Recently, it has been applied to astrophysics by constructing an effective nucleon-nucleon interaction folded by the nuclear densities of the collision partners, with the overall strength of the nucleus-nucleus potentials being adjusted in order to reproduce experimental data ([294]).

7.5.3. Parameter fits Reaction rates dominated by the contributions from a few resonant or bound states are often extrapolated in terms of R- or K-matrix fits, which rely on quite similar strategies. The appeal of these methods rests on the fact that analytical expressions which allow for a rather simple parametrization of the data can be derived from underlying formal reaction theories. However, the link between the parameters of the R-matrix model and the experimental data (resonance energies and widths) is only quite indirect. The K-matrix formalism solves this problem, but suffers from other drawbacks ([295]).

The R- and K-matrix models have been applied to a variety of reactions, and in particular to the analysis of the $^{12}\mathrm{C}\,(\alpha\,,\gamma)\,^{16}\mathrm{O}$ reaction rate ([296, 297]).

7.5.4. The statistical models Many astrophysical scenarios involve a wealth of reactions on intermediate-mass or heavy nuclei. This concerns the non-explosive or explosive burning of C, Ne, O and Si, as well as the s-, r- and p-process nucleosynthesis. Fortunately, a large fraction of the reactions of interest proceed through compound systems that exhibit high enough level densities for statistical methods to provide a reliable description of the reaction mechanism. In this respect, the Hauser-Feshbach (HF) model has been widely used with considerable success.

A version of the model that has recently been applied to astrophysical calculations is described in [298]. It features in particular a new global α-nucleus optical potential [299], which is one of the least-known physical ingredients of the HF model, as well as an approximation of the soft dipole mode that may be of special importance when considering very neutron-rich nuclei. When dealing with such nuclei, it has to be remembered that both direct and statistical components may contribute to the (n,γ) capture. Eventually, the evaluation of an (n,γ) rate necessitates a proper combination of the DC and HF (interfering) contributions. No model to-date performs this superposition in a reliable way for a very large sample of nuclei, as the one of relevance to the r-process.

8. Selected topics

We pick here three topics that have in previous sections evaded clear definitions and/or the systematized discussions they deserve for their specific or general nuclear astrophysics interest: the s- and r-process synthesis of heavy elements, cosmochronology, and the current understanding of the Type-II supernova mechanism.

8.1. Heavy-element nucleosynthesis by the s- and r-processes of neutron captures

We have in several occasions referred to the s- and r-processes, which are invoked for the synthesis of the vast majority of the naturally-occurring nuclides heavier than the "Fe-group." For the sake of clarity, as well as for the benefit of non-expert readers, we now go back to their definitions, and give a brief summary of the nuclear and astrophysical problems they incur.

8.1.1. Defining the s-process The "slow" neutron-capture process relies on the assumption that pre-existing ("seed") nuclei are exposed to a flux of neutrons that is weak enough for allowing a β-unstable nucleus produced by a (n,γ) reaction to decay promptly, except perhaps for very long-lived isotopes which may instead capture a neutron. This definition [8, 300] does not make any reference to the very origin of the required neutrons, or to a specific astrophysical site. The nuclear flow associated with the s-process (the "s-process path") has then to develop in the close vicinity of the line of β-stability. The endpoint of this path is ^{209}Bi, at which the ^{209}Bi(n,γ)^{210}Bi(β^-) ^{210}Po(α)^{206}Pb chain leads to some cycling of the material in this mass region.

In a steady-flow regime, which is a good approximation at least locally in mass number A, the relative abundances of the synthesized nuclides are inversely proportional to their stellar neutron-capture rates. Since a nucleus with a closed neutron shell has a quite low neutron-capture probability because of the relatively low neutron-separation energy of the $N+1$ isotope, the flow staggers there, resulting in an abundance peak at a magic number such as $N = 82$ or 126. This translates in Fig. 6 as solar-system abundance maxima at $A = 138$ or 208, respectively. If (n,γ) rates dictate the relative abundances along the path, the intervening β-decay rates determine the speed of the nuclear flow, and consequently the s-process time-scale.

It is conceivable that some complications may arise at specific locations of the s-process path because of the possible competition between β^--decays and neutron captures. Even continuum-e$^-$ captures may come into play. As illustrated in Fig. 14, such a situation translates into "branching points" in the s-process path, which constitute an important ingredient of the s-process ([302, 303]). The handling of these branches necessitates the knowledge of the stellar β-decay rates, as well as of the probabilities of neutron captures by unstable nuclei close to the line of stability.

In general, the competition between neutron captures (whose rates depend on temperature and neutron density) and β-decays (which are mainly temperature-dependent) is incorporated in semi-empirical analyses of the s-process abundances to impose some constraints, particularly on the neutron density and the temperature for the s-process ([254, 303]). The meaningfulness of these branching point constraints of course relates directly to the reliability of the (n,γ) and β-decay rate input. Additional nuclear data about the rates of the neutron-producing reactions [mainly ^{13}C (α , n) ^{16}O and ^{22}Ne (α , n) ^{25}Mg] and of some (n,p) and (n,α) reactions are also required when the s-processing is followed in the framework of "realistic" stellar models.

8.1.2. Defining the r-process In contrast to the s-process the "rapid" neutron-capture process, or r-process, is based on the hypothesis that the neutron density is so high that neutron captures are always faster than β-decays. The pre-existing isotopes of each element are converted by successive neutron captures into very neutron-rich ones, whose neutron separation energies $S_{\rm n}$ are low enough for allowing the inverse (γ,n) reactions to occur efficiently and impede further progression. In the simplest picture of the r-process [8, 300], an (n,γ) $\leftrightarrow$ (γ,n) equilibrium is reached in each isotopic chain starting

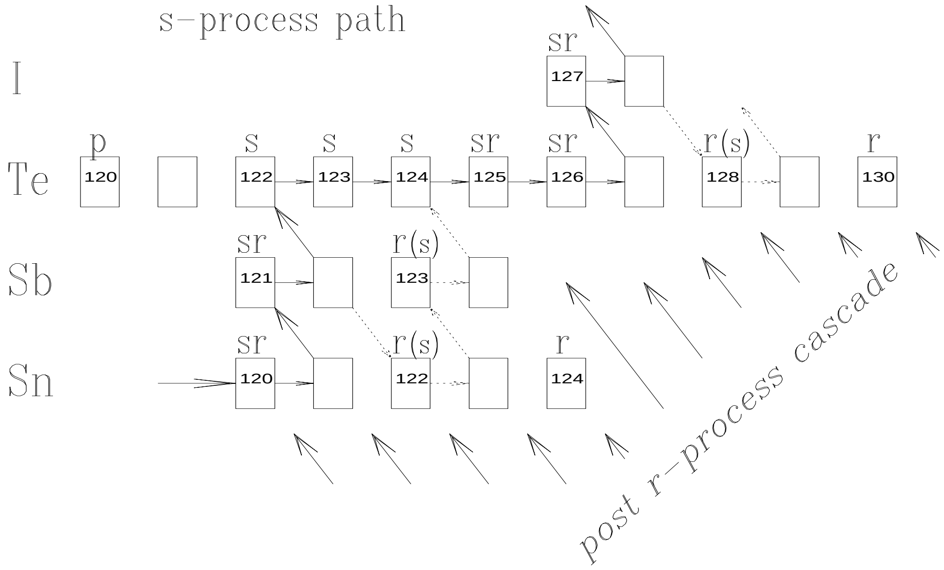

Figure 14. A typical s-process path in the $120 \leq A \leq 128$ region, with some possible branches resulting from the competition between neutron captures (*horizontal*), β^- decays (*upward* arrows) and continuum-e$^-$ captures (*downward* arrows) (taken from [301]). The stable isotopes are indicated by their mass numbers in squares, while the open squares identify the β-unstable isotopes. The β^--decay cascade from the r-process path (Fig. 15) towards the line of stability after the r-process neutron irradiation is also schematized. The stable neutron-rich nuclides ^{124}Sn and ^{130}Te are the end-points of the post-r-process cascade, and stay away from the s-process path. Such nuclides are referred to as "r-only" products (labels "r"). In contrast, ^{122}Te, ^{123}Te and ^{124}Te are located on the s-process flow, but are "shielded" from the r-process. They are thus "s-only" nuclides (labels "s"). Other nuclides are located on both the s-process path and the post r-process cascade, this situation being in some cases the direct result of s-process path branchings. The prediction of the relative s- and r-process contributions to the solar abundances of those nuclides of a mixed origin necessitates, in principle, the build-up of detailed models for the neutron capture processes. The notation "sr" is used when the s- and r-processes are expected to contribute almost equally to the abundance, while the label "r(s)" indicates that the r-process contribution dominates. The neutron-deficient nuclide ^{120}Te is produced by neither of the neutron capture processes, and is classified as a "p-only" nucleus (label "p")

at iron ($Z = 26$).‡ In such conditions, the isotopic abundance distribution for a given Z is independent of (n,γ) or (γ,n) cross sections, and is governed instead by the laws of statistical mechanics. More specifically, the isotopic abundances obey a Maxwellian distribution, and thus depend mainly on $S_{\rm n}$, temperature T and neutron density $n_{\rm n}$ (and weakly on nuclear partition functions). Once distributed in such a way, the isotopes then "wait" for β^--decays to occur (the "waiting point approximation"), and to transport the material from one (Z) isotopic chain to the next ($Z + 1$). Beta-decays thus govern the speed of the nuclear flow (the "r-process path"). If T and $n_{\rm n}$ were kept constant in

‡ This simplification is validated by the fact that the r-process has traditionally been assigned to the Fe-rich inner core of a massive star supernova

time, the nuclear flow would follow an iso-S_n line in the (N,Z) plane. The location of this line depends on T and n_n. More specifically, it corresponds to S_n-values increasing with T and decreasing with increasing n_n [300]: higher n_n-values indeed tend to push material farther away from stability, while higher temperatures have the reverse effect, as they speed up the (γ,n) photodisintegrations. It is thus conceivable that the r-process path could approach the neutron drip line if high enough n_n can be obtained in an astrophysical site at low enough temperatures. Some complication arises if enough neutrons are available and if the neutron irradiation time is long enough for the r-process path to reach the trans-actinide region, where neutron-induced (or β-delayed) fissions could interrupt the flow to higher Z-values, and could be responsible for a cycling-back of the material to lower-mass nuclei.

In the simplest picture of the r-process the neutron flux and the temperature are assumed to go abruptly to zero, as are the (n,γ) and (γ,n) rates, after a given irradiation time. As a result, the very neutron-rich unstable nuclides on the r-process path start to cascade through β^--decays back to the line of stability. This cascade may be complicated by β-delayed fission or neutron emissions (in the simplest models, the re-captures of the emitted neutrons are neglected).

The basic nuclear data needed for the modelling of the r-process in the simple framework described above are masses and β-decay rates of very neutron-rich nuclei. Their fission barriers are also required. Various classes of more sophisticated r-process models have also been constructed. Some still make use of schematic parametrized astrophysical conditions, but avoid simplifications like the waiting point approximation ([304]), the sudden freeze-out of the neutron captures and inverse photodisintegrations or the neglect of the re-capture of delayed neutrons ([305, 306]). These approaches require the solution of very large nuclear-reaction networks for the derivation of the abundances. The build-up of these networks necessitates the knowledge of neutron capture rates and of their inverse photodisintegration rates on top of the nuclear data already needed by the simple model. Even some neutrino-interaction rates may have to be considered [307]. Other complementary approaches have explored in greater detail more realistic astrophysical conditions for the development of the r-process, and the possibility for the α-process to be the progenitor of the r-process. Figure 15 illustrates possible paths of an α- and subsequent r-process.

8.1.3. The s- and r-process contributions to the solar-system composition ¿From the above definitions, one can guess qualitatively which of the s- or/and r process(es) was (were) responsible for the production of a given heavy nuclide in the solar system. The basic principles underlying such an identification are depicted in Fig. 14. A more quantitative modelling of the s- (and to a lesser extent r-) process makes it possible to split the solar abundance curve beyond the Fe peak region into an s- and an r- (as well as a p-) component. The results are shown in Fig. 16. It has to be noted that this decomposition is affected by uncertainties of various natures ([310]). Some of them are of cosmochemical and nuclear origins, and others are of more purely astronomical

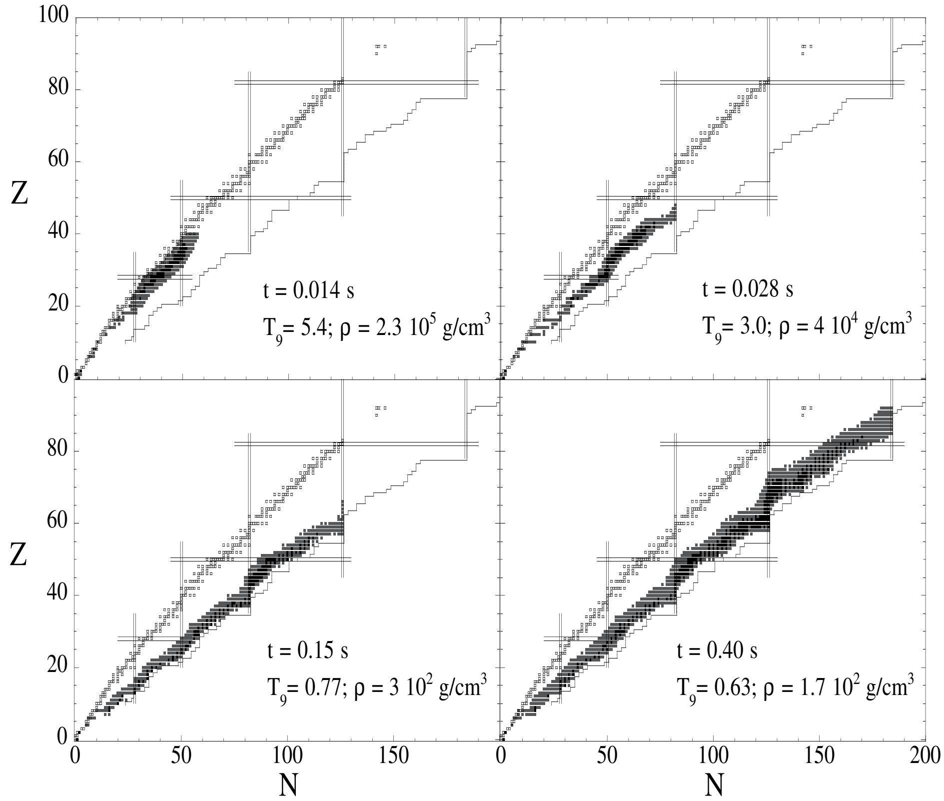

Figure 15. An example of the development of α- and r-process paths in sequence of time (t), represented by *strips* comprising synthesized nuclides between the valley of stability (*boxes*) and the neutron drip line (*stairs*), with *double-lines* running along the neutron and proton magic numbers (from [308]). The evolution of a hot-bubble material is followed with the use of a generic model for its dynamics [309] with a slight modification, and of a detailed nuclear network. The model parameters are adjusted so as to induce the r-process (see Sect. 8.3.2). The initial values of the temperature (displayed in units of 10^9 K, T_9) and density (ρ) are 10×10^9 K and 1.6×10^6 g/cm^3, respectively. In the beginning, the α-process synthesizes nuclides near the line of stability, and even beyond the "Fe-peak." With the temperature decrease, it "freezes out." Neutron captures then bring the path into the more neutron-rich region, and to more massive nuclides as (relatively slow) β-decays intervene

venue. In this respect, one has to keep in mind that the "solar s- and r-abundances" of Fig. 16 rely on semi-empirical analyses (particularly of the s-process) that are far from being rooted in realistic astrophysical models.

8.1.4. Astrophysical sites for the s- and r-processes The results displayed in Fig. 16 do not help much in the attempt to identify precisely the astrophysical (stellar) s-, r- and p-process sites, particularly because the solar-system bulk material is a mixture of a large number of nucleosynthesis events that have taken place in the Galaxy before the isolation of the solar nebula. At best, this mixture can provide a useful guide in the problem at hand. The observation of the contamination of the surface of certain stars by heavy elements (mainly s-nuclides) produced in their interiors may be of more help, as the data

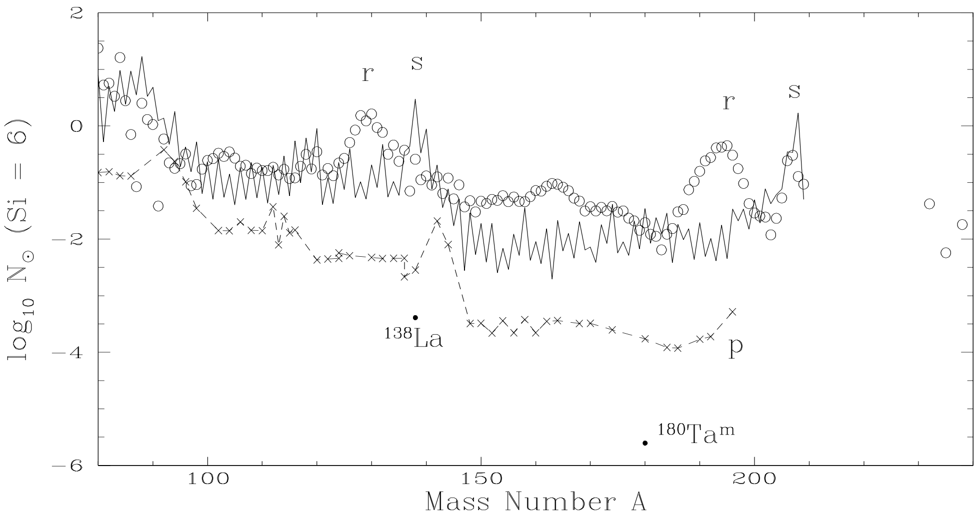

Figure 16. Decomposition of the solar abundances of heavy nuclides into an s-process (*solid line*), an r-process (*open circles*) and a p-process (*crosses*) contributions [301] (based on [303]). The procedure of the decomposition is as follows: First, the abundances of the "s-only" nuclei are fitted with the help of a semi-empirical s-process model. This fit requires a suitable distribution of neutron doses. The model predictions are then used to evaluate the s-process contributions to the other nuclides. The subtraction of these s-process contributions from the observed solar abundances leaves for each isotope a residual abundance that represents the r-process (if neutron-rich) or p-process (if neutron-deficient) contribution. Normally, the "r-only" nuclides do not have to be subjected to this procedure. Such analyses come to the conclusion that about half of the heavy nuclei in the solar material come from the s-process, and the other half from the r-process, whereas the p-process is responsible for the production of the remaining low-abundance nuclides. The rarest naturally-occurring nuclide, ^{180}Ta^m (indeed an isomeric state) is probably produced by the s- and p-processes in relative quantities that have yet to be determined precisely. It has been speculated that ^{138}La may be synthesized by the ν-process or by spallation reactions.

refer to a single event. This is also the case with some isotopically-anomalous meteoritic grains of suspected circumstellar origin, in which the precise isotopic composition is known for a variety of heavy elements.§ The application of the semi-empirical s-process model outlined above leads to the conclusion that the s-component displayed in Fig. 16 can be fitted quite satisfactorily if the neutron density is of about 10^8 cm^{-3} and if the temperature lies in the $(1 \sim 3) \times 10^8$ K for some 10 to 100 y. In order to account for the r-component, strikingly different conditions are required. More specifically, neutron densities well over 10^{20} cm^{-3} have to be maintained at temperatures $\gtrsim 10^9$ K up to a second or so. The best fits to the observations (mainly of s-nuclides) at the surfaces of individual chemically-peculiar stars generally necessitates conditions that differ to some extent from those derived from the consideration of the solar-system abundances.

§ In contrast to stellar spectroscopy, the grain analysis can provide very precise isotopic compositions, even for heavy elements ([311]). The drawback of these studies is that the precise characteristics of the stars from which the grains may originate are unknown

One of the most tantalizing problems in stellar physics and nuclear astrophysics is to obtain the development of the heavy element nucleosynthesis processes able to account for the observations as a *natural* consequence of stellar evolution on the basis of realistic models of various stars (with different initial masses and metallicities), and of the best possible nuclear-physics input. This requirement is clearly most difficult to meet for the r-process, but also raises serious problems for the s-process, while the situation for the p-process is seemingly less severe.

In what follows we sketch the current status of the continued search of the s- and r-process sites, which is far from being satisfactory ([312]).

s-Process sites As demonstrated by many observations, the surfaces of a variety of low-mass ($M \lesssim 3$ $M_\odot$) asymptotic-giant-branch (AGB) stars are enriched with certain "s-elements,"‖ implying that they have been synthesized in the interiors of their own and dredged-up. These observations also make it plausible that AGB stars eject part of their synthesized s-nuclides into the ISM through their winds, and thus contribute to the galactic, and in particular solar-system, s-nuclide enrichment. As dust particles are known from astronomical observations to form in their ejecta, AGB stars could also be the source of certain anomalous meteoritic grains containing various heavy elements with an s-process isotopic pattern.

The s-process in AGB stars is thought to occur in their He-burning shell surrounding a nuclearly inert C-O core, either during recurrent and short convective episodes ("thermal pulses"), or in between these pulses. A fraction of the produced s-nuclides (along with other He-burning products) could then be brought by convection to the surface shortly after each pulse. A similar scenario might develop in intermediate-mass (3 - 8 $M_\odot$) AGB stars, even if this possibility does not receive a strong observational support ([89, 313]).

It is generally considered that the necessary neutrons for the development of the AGB s-process are mainly provided by $^{13}\mathrm{C}(\alpha,\mathrm{n})^{16}\mathrm{O}$, which can operate at temperatures around $(1 \sim 1.5) \times 10^8$ K. In contrast, the $^{22}\mathrm{Ne}(\alpha,\mathrm{n})^{25}\mathrm{Mg}$ could at best only slightly contribute because the AGB He shell does not appear to reach the necessary temperatures ($T \gtrsim 3 \times 10^8$ K) for ^{22}Ne to burn. This situation is at the origin of the most acute problem raised by the AGB star s-process. If ^{22}Ne finds a natural origin in the classical $^{14}\mathrm{N}(\alpha,\gamma)^{18}\mathrm{F}(\beta)^{18}\mathrm{O}(\alpha,\gamma)^{22}\mathrm{Ne}$ burning of the ^{14}N produced in the preceding CNO cycle, the ^{13}C originating from this cycle is by far not abundant enough for providing the amount of neutrons necessary for a full s-process to develop. An additional ^{13}C source is thus mandatory. It has been proposed that, under certain conditions, protons and ^{12}C could be brought together at high enough temperatures for ^{13}C to be produced by $^{12}\mathrm{C}(\mathrm{p},\gamma)^{13}\mathrm{N}(\beta^+)^{13}\mathrm{C}$. Then, standard stellar models, which do

‖ An element that has an overwhelming either s- or r-component in its solar-system abundance is customarily referred to as an s- or r-element. For example, Ba is an s-element, whereas Eu is an r-element. This naming may not always properly reflect the true origin of an element outside the solar system, as exemplified for Ba in Sect. 8.1.5

not provide any such source, have to be modified in some *ad hoc* manner ([89]).

The dredge-up of the produced s-nuclides to the AGB star surfaces (as demanded by the observations) is also far from being well understood. This subject is in fact a matter of debate, different recent models reaching in some cases quite different conclusions concerning the characteristics, and even the very existence, of this transport episode ([89, 314, 315]).

The AGB star s-process has been widely discussed in attempts to explain the spectroscopic ([316]) and meteoritic ([313]) data referred to above, as well as to account for the $A \gtrsim 100$ solar-system distribution of s-nuclides ([317]). In these studies, essential quantities, like the amount of available ^{13}C, and thus the neutron density, or the efficiency of the assumed dredge-up are treated as adjustable parameters.

Massive stars, and more specifically their He-burning cores, are also predicted to be s-nuclide producers through the operation of the $^{22}\mathrm{Ne}\,(\alpha\,,\mathrm{n})\,^{25}\mathrm{Mg}$. This neutron source can indeed be active in these locations as their central regions are hotter than the He shell of AGB stars. Many calculations performed in the framework of realistic stellar models demonstrate that this site is responsible for a substantial production of the $A \lesssim 100$ s-nuclides, and can in particular account for the solar-system abundances of these species ([318]). This success does not have to hide some difficulties, however. Uncertainties in the efficiency of this s-process relate directly to remaining nuclear physics uncertainties in the ^{22}Ne burning rate [173] or in (n,γ) rates, as well as to stellar model uncertainties, even if they may appear less severe than in the AGB star case. In this respect, it may be of interest to note that the Ba enhancement derived [319] from the early spectra of the supernova SN1987A could not be explained by a core He-burning s-process model [320]. This difficulty may lie in the uncertainty in the spectroscopic analyses [321], or in the adopted astrophysical model.

r-Process sites The search for astrophysical sites for the r-process has been quite unsuccessful despite the fact that many possibilities have been suggested. Of course, this search does not receive any really useful guidance from the direct observation of an object where r-nuclides are produced *in situ*. On the theoretical side, all attempts have just revealed more or less severe shortcomings ([312]). The supernova scenarios are no exception, even if their Type-II supernova hot-bubble version has at first raised a lot of optimistic excitement, and remains an adequate site for the α-process (Sect. 8.3).

The quite old speculation that the r-process might develop in the mergence of two neutron stars, or of a neutron star and a black hole ([322]) has recently become fashionable again in relation with the demonstrated capabilities of performing multi-dimensional hydrodynamical simulations of the merging phenomena, and with the potentiality of these systems to be detectable gravitational wave, neutrino or γ-ray burst emitters ([323]). That these events are certainly less frequent than Type-II supernovae would be compensated by the presumably larger masses of the ejecta, and thus possibly of the r-process yields, than in the hot-bubble case.

Several speculative aspects of the conditions under which an r-process might accompany a neutron star merger ([156], [324] - [326]) remain to be worked out in detail. Some models might show some similarity with the hot bubble scenario. Others emphasize the role of a neutron star heating by the β-decays or fissions of extremely neutron-rich "nuclei" beyond the neutron-drip line that may populate the very cold high-density neutron star crusts. In such a situation, a reliable nuclear EOS is required to set the initial conditions for the nucleosynthesis, and the weak interaction rates of nuclei in highly exotic configurations are needed.

All in all, much remains to be explored before confirming or disregarding neutron star mergers as possible sites of the r-process (or, in fact, of any other form of nucleosynthesis). We add here that the outcome of the hydrodynamical simulations is sensitive to information that is still statistically missing, like the initial masses and spins of the mergers ([327]). Further complications might arise from the necessity of performing the calculations in a general relativity framework ([328, 329]), as opposed to a Newtonian scheme largely adopted so far. Preliminary attempts lead to the conclusion that interacting neutron stars, instead of merging, might well transform into individual black holes [329], in which case the hope to make an r-process would of course vanish, again.

8.1.5. Heavy elements in low-metallicity stars The search for the astrophysical sites for the s- and r-processes may be helped by the rapidly-accumulating observational data on the surface abundances of heavy elements in metal-poor stars ([43]). Such analyses attempt to correlate the observed abundances of "typical s- or r-elements" with the stellar metallicities, which may or may not be theoretically explained in terms of a possible impact of the initial compositions on the heavy-element yields in a given scenario. Of course, the sometimes large scatters in abundances observed at one metallicity endanger too naive interpretations of the observations ([330]).

¿From the observation that the Galaxy may have been enriched with r-elements earlier than with s-elements ([43]), it is classically inferred that the bulk galactic content of r-nuclides comes from more massive, shorter-lived, stars than the bulk s-nuclides. A metallicity change in a star of a given mass may also modify the number of neutrons made available for the production of trans-iron nuclei through variations in the amounts of both the produced neutrons and the neutrons captured by light (even as light as oxygen) poisons. This may affect the global efficiency of a neutron-capture process and the relative yields of heavy elements ([318]).

As a word of caution, we recall that the classical terminology of "s-element" or "r-element" refers in fact to the solar-system composition, and may be quite misleading when one deals with low-metallicity objects. An interesting illustration of this danger concerns recent attempts to analyze the isotopic composition of Ba in metal-poor stars. The Ba observed in the classical metal-poor subgiant HD140283 was on one hand claimed [331] to be of s-process venue in concordance with the conventional classification of Ba as an s-element. On the other hand, just the opposite conclusion was reached [332] in that its isotopic composition was consistent with an r-process origin. The development of spectroscopic techniques enabling the measurement of the isotopic composition of a variety of heavy elements is obviously of major interest for the theory of nucleosynthesis.

8.2. Cosmochronometry

The dating of the Universe and of its various constituents is another tantalizing task in modern science, referred to as "cosmochronology." This field is in fact concerned with different ages, each of which corresponding to an epoch-making event in the past ([333]). They are in particular the age of the Universe $T_{\rm U}$, of the globular clusters $T_{\rm GC}$, of the Galaxy [as (a typical?) one of many galaxies] $T_{\rm G}$, of the galactic disc $T_{\rm disc}$, and of the non-primordial nuclides in the disc $T_{\rm nuc}$, with $T_{\rm U} \gtrsim T_{\rm GC} \approx (\gtrsim ?)\ T_{\rm G} \gtrsim T_{\rm disc} \approx T_{\rm nuc}$. As a consequence, cosmochronology involves not only cosmological models and observations, but also various other astronomical and astrophysical studies, and even invokes some nuclear physics information.

The cosmological models can help determining $T_{\rm U}$, as well as $T_{\rm GC}$ and $T_{\rm disc}$, at least to some extent ([52] - [54] for brief accounts). The HRD has also been used quite extensively in order to evaluate $T_{\rm GC}$. In short, the method relies on the confrontation between stellar evolution predictions and the position of the turnoff point (TOP) of the MS, complemented with the largest possible ensemble of observed properties of the HRD of globular clusters (including in particular the magnitude difference between the TOP and the location of the HB) ([37, 334]). The HRD technique has also been applied to the determination of $T_{\rm disc}$. So-called "luminosity functions," which provide the total number of stars per absolute magnitude interval as a function of absolute magnitudes, have also been used to evaluate $T_{\rm GC}$, as well as $T_{\rm disc}$. The luminosity function of white-dwarf stars has also been proposed as $T_{\rm disc}$ evaluators. These stars, the end products of the evolution of the very abundant single or binary low- and intermediate-mass stars, are supposedly the oldest stars in the galactic disc. In very short, the method relies on a confrontation between the observed sharp fall-off in the number of WDs with a luminosity lower than a given value and the predicted times taken by WDs to cool enough for being so weakly luminous.

Each of those methods has advantages and weaknesses of its own ([54]). The age estimates they provide are sketched in a synopsis form in Fig. 17, which also displays the limits derived from the nucleo-cosmochronology discussed below.

8.2.1. Nucleo-cosmochronology: generalities The dating method that most directly relates to nuclear astrophysics is referred to as "nucleo-cosmochronology." It primarily aims at determining the age $T_{\rm nuc}$ of the nuclides in the galactic disc through the use of the observed bulk (meteoritic) abundances of radionuclides with lifetimes commensurable with presumed $T_{\rm disc}$ values. Consequently, it is hoped to provide at least a lower limit to $T_{\rm disc}$. The most studied chronometries, and some of their main characteristics, are summarized elsewhere [343]. The discovery of isotopic anomalies attributed to the *in situ* decay in some meteoritic material of radionuclides with half-lives in the approximate

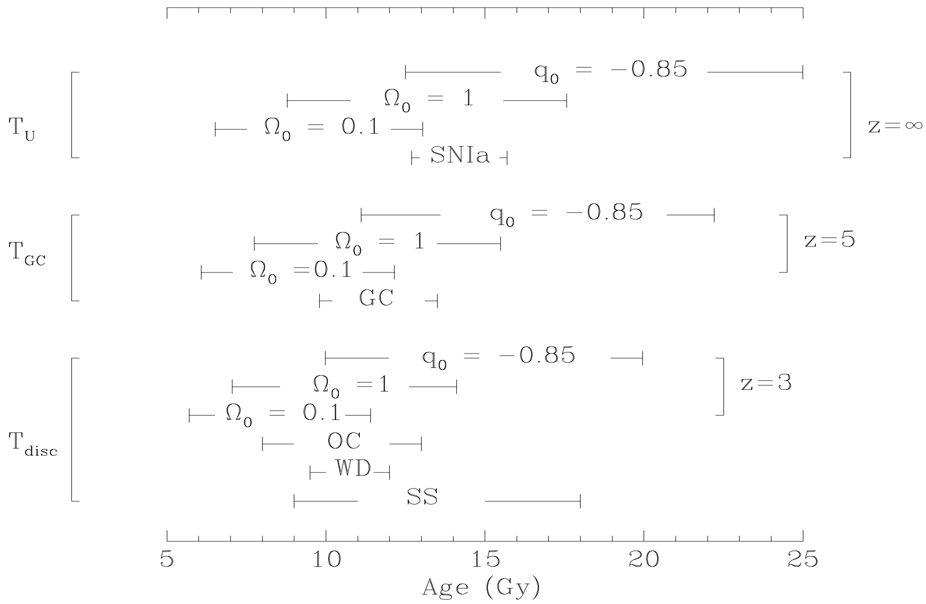

Figure 17. Ages of the Universe (T_U), of galactic globular clusters (T_{GC}) and of the galactic disc (T_{disc}). Estimates from cosmological models are specified by Ω_0 values for the Standard Model, and by $q_0 = \Omega_0/2 - \lambda_0 = 3\Omega_0/2 - 1$ in the $\Lambda \neq 0$, $k = 0$ Model. In both cases, the displayed ranges correspond to $100 \geq H_0$(km/s/Mpc)≥ 50. The adopted z (redshift) values are in no way meant to be precise. (Note, for instance, that a galaxy with $z = 5.34$ has recently been reported [335].) The label SNIa defines the age limits derived from values of those cosmological model parameters that are determined with the use of Type-Ia supernovae as standardized candles ([336, 337]). The ages derived from HRD analyses of globular clusters [38, 338] or open clusters [339, 340] are in the ranges labelled GC and OC, respectively. The predictions based on white dwarf luminosity functions are noted WD [341, 342], while the nucleo-cosmochronological evaluations of the age T_{nuc} of the nuclides in the solar system are marked with the label SS

$10^5 \lesssim t_{1/2} \lesssim 10^8$ y range has broadened the original scope of nucleo-cosmochronology. It likely provides some information on discrete nucleosynthesis events that presumably contaminated the solar system at times between about 10^5 and 10^8 y prior to the isolation of the solar material from the general galactic material, as well as constraints on the chronology of nebular and planetary events in the early solar system. This chronometry using short-lived radionuclides ([67, 86]) is not reviewed here.

If indeed the bulk solar-system composition witnesses the operation of the galactic blender, a reliable evaluation of T_{nuc} requires: (i) the build-up of models for the evolution of nuclides in the Galaxy, primarily in the solar neighbourhood, that account for as many astronomical data as possible; (ii) the construction of nucleosynthesis models that are able to provide the isotopic or elemental yields for the nuclides involved in the chronometry; as well as (iii) high quality data for the meteoritic abundances of the relevant nuclides. All these requirements clearly make the chronometric task especially demanding.

8.2.2. The trans-actinide clocks The most familiar long-lived chronometers are the ^{232}Th-^{238}U and ^{235}U-^{238}U pairs [344] developed on grounds of the present meteoritic content of these nuclides. Their use as reliable nuclear clocks raises major problems, however, as it depends heavily, among others, on the availability of precise production ratios. Such predictions are out of reach at the present time. One is indeed dealing with nuclides that can be produced by the r-process only, which suffers from very many astrophysics and nuclear physics problems, as we have emphasized in many occasions. In addition, these nuclides are the only naturally-occurring ones beyond ^{209}Bi, so that any extrapolation relying on semi-empirical analyses and fits of the solar r-process abundance curve is in danger of being especially unreliable. The difficulty is further reinforced by the fact that most of the r-process precursors of U and Th are nuclei that are unknown in the laboratory, and will remain so for a long time to come. Theoretical predictions of properties of relevance, like masses, β-decay strength functions and fission barriers, are extremely difficult, particularly as essentially no calibrating points exist. This problem would linger even if a realistic r-process model were given. Last but not least, most of the huge amount of work devoted in the past to the trans-actinide chronometry ([345]) has adopted simple functionals for the time dependence of the r-process nucleosynthesis rate (a.k.a. "Mickey Mouse Models" coined by Pagel [346]) with little consideration of the chemical evolution in the solar neighbourhood.

The so-called Th-chronometry [347] attempts to use the relative abundances of Th and Eu (which is presumed to be dominantly produced by the r-process) observed at the surface of stars with various metallicities.¶ Under the assumption, which may sound reasonable but has not at all to be taken for granted, that any r-processes in the past have produced Th and Eu with a constant ratio, the age determination is reduced to the problem of mapping the metallicity on time through a chemical evolution model. High-quality observational Th/Eu abundance data in stars of various metallicities are accumulating [349] - [351]. Though some attempts have already been made [352, 353], much remains to be done in the difficult task of deriving $T_{\rm nuc}$ from some of these observations.

The Th-chronometry could be put on safer grounds if the Th/U ratios would be known in a variety of stars with a high enough accuracy ([353] regarding the current status of the U abundance determination in a metal-poor star). These nuclides are indeed likely to be produced simultaneously, so that one may hope to be able to predict their production ratios more accurately than Th/Eu. Even in such relatively favourable circumstances, one would still face the severe question of whether Th and U were produced in exactly the same ratio in presumably a few r-process events (a single one?) that have contaminated the material from which metal-poor stars formed. Even if this ratio would turn out to be the same indeed, its precise value remains to be calculated (see [343] for an illustration of the dramatic impact of a variation in the predicted Th/U ratio on predicted ages).

¶ Originally, an attempt was made to use the observed Th/Nd ratios [348], albeit the disadvantage of Nd being possibly produced also by the s-process

8.2.3. The ^{187}Re - ^{187}Os chronometry First introduced by Clayton [354], the chronometry using the ^{187}Re - ^{187}Os pair is able to avoid the difficulties related to the r-process modelling. True, ^{187}Re is an r-nuclide. However, ^{187}Os is not produced directly by the r-process, but indirectly via the β^--decay of ^{187}Re ($t_{1/2} \approx 43$ Gy) over the galactic lifetime. This makes it in principle possible to derive a lower bound for $T_{\rm nuc}$ from the mother-daughter abundance ratio, provided that the "cosmogenic" ^{187}Os component is deduced from the solar abundance by subtracting its s-process contribution. This chronometry is thus in the first instance reduced to a question concerning the s-process. Other good news come from the recent progress made in the measurement of the abundances of the concerned nuclides in meteorites ([355] for references). This input is indeed essential for the establishment of a reliable chronometry.

Although the s-process is better understood than the r-process, this chronometry is facing specific problems. They may be summarized as follows ([356]): 1) the evaluation of the ^{187}Os s-process component from the ratio of its production to that of the s-only nuclide ^{186}Os is not a trivial matter, even in the simple local steady-flow approximation (constancy of the product of the abundances by the stellar neutron capture rates over a restricted A-range). The difficulty relates to the fact that the ^{187}Os 9.75 keV excited state can contribute significantly to the stellar neutron-capture rate because of its thermal population in s-process conditions ($T \gtrsim 10^8$ K) [357, 358]. The ground-state capture rate measured in the laboratory has thus to be modified by a theoretical correction. In addition, the possible branchings of the s-process path in the $184 \leq A \leq 188$ region may be responsible of a departure from the steady-flow predictions for the ^{187}Os/^{186}Os production ratio [359, 360]); and 2) at the high temperatures, and thus high ionization states, ^{187}Re may experience in stellar interiors, its β-decay rate may be considerably, and sometimes enormously, enhanced over the laboratory value by the bound-state β-decay of its ground state to the 9.75 keV excited state of ^{187}Os [147, 361]. Such an enhancement has recently been beautifully confirmed by the measurement of the decay of fully-ionized ^{187}Re at the GSI storage ring [249, 362]. The inverse transformation of ^{187}Os via free-electron captures is certainly responsible for further corrections to the stellar ^{187}Re/^{187}Os abundance ratio [361, 363]. Further complications arise because these two nuclides can be concomitantly destroyed by neutron captures [361].

All the above effects have been studied in the framework of realistic evolution models for $1 \lesssim M \lesssim 50$ M$_\odot$ stars [356, 364]. The range of ages labelled SS in Fig. 17 gives the plausible upper limit on $T_{\rm nuc}$ derived from ^{187}Re - ^{187}Os within a galactic chemical evolution model that is constrained by observational data in the solar neighbourhood [364]. This work, which is an up-date of [361] with regards to meteoritic abundances, nuclear input data, stellar evolution models and observational constraints, leads to a lower limit of about 11.5 Gy for $T_{\rm nuc}$. However, as even lower values cannot conclusively be excluded within the remaining uncertainties in the chemical evolution model parameters, the lower limit adopted for the SS range in Fig. 17 is given by the so-called "model independent approach" [365] -[367]. These results may imply that the ^{187}Re - ^{187}Os chronometry has not yet much helped narrowing the age range. There is

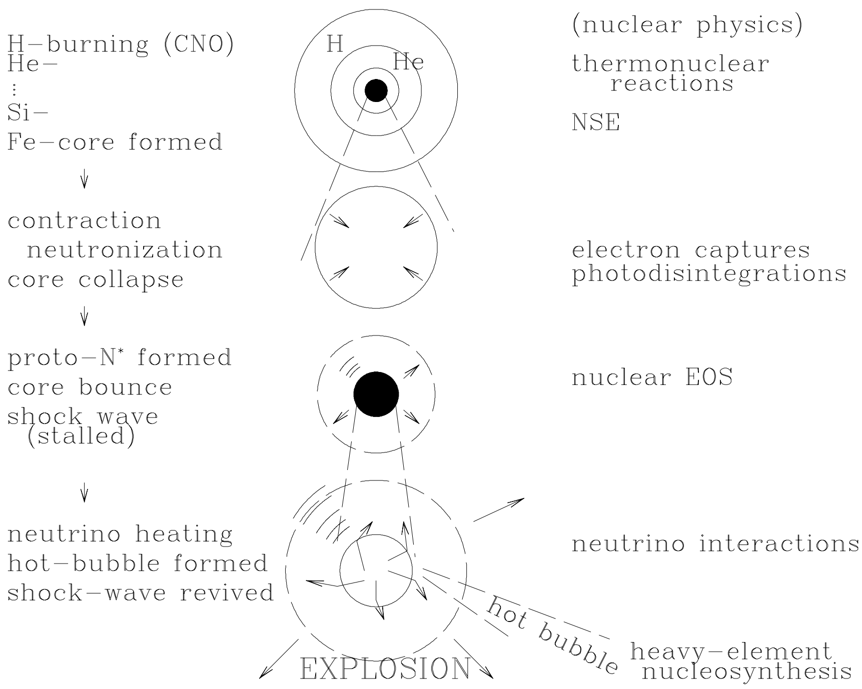

Figure 18. Schematic description of the evolution of a massive star towards a supernova explosion

still ample room for improvements, however, and it is reasonably hoped that the Re - Os chronometry will be able to set some meaningful limits on $T_{\rm nuc}$ in a near future, and independently of other methods.

8.3. Type-II supernovae

A star more massive than about 10 $M_\odot$ is expected to end its life as a Type-II supernova explosion with a neutron star left behind as its "residue." We have discussed bit by bit the nuclear physics involved during the evolution of such stars. Let us gather here all these pieces of information to try understanding Type-II supernovae. These objects are indeed the most remarkable astrophysical events in terms of the diversity of the nuclear physics questions which play a decisive role in a sequential manner before reaching the explosion stage. For simplicity, we consider only spherically symmetric models ([132] - [135]), except for some limited considerations about a recent study of convective motions by multi-dimensional hydrodynamical simulations ([88]).

8.3.1. Evolution of massive stars leading to neutrino-driven supernovae Figure 18 depicts schematically the evolution of a massive star towards a Type-II supernova. The time sequence (running from top to bottom) is labelled with some nuclear physics phenomena that are decisive at each major epoch: 1) After having experienced various burning phases governed by thermonuclear reactions, the star exhibits an "onion-skin" structure with an "iron" core in its central region, this "Fe peak" composition being dictated by the laws of statistical mechanics (NSE). The nuclear physics raised in these phases is already discussed in several of the previous sections, and is not repeated here; 2) As the nuclear fuel is exhausted in the core (any possible nuclear transformation of its iron content is endothermic), it starts to contract (as usual when not enough nuclear energy is available for covering the star energy losses). The resulting increase of density and temperature near the centre makes possible free electron captures on protons and some heavy nuclei, as well as the photodisintegration of heavy nuclei. Both of these nuclear processes reduce the pressure, and thus accelerate the contraction. The nuclear physics of interest at this stage is somehow under control, except perhaps the evaluation of free-e^- capture rates on heavy nuclei; 3) As its mass nears the "Chandrasekhar mass" of about 1.2 to 1.5 $M_\odot$, the core undergoes a gravitational collapse to form a proto-neutron star.[+] After a sufficient increase in density, the pressure from the (non-relativistic) nucleons dominates the (relativistic) electron pressure, so that the EOS becomes "stiffer" (as mentioned earlier, there are tremendous difficulties in constructing "the" EOS and in evaluating its stiffness in particular.) The mechanical equilibrium is restored in the innermost parts of the core, which stop collapsing, leading to the formation of a hot nascent neutron star. An outward moving shock develops at the interface of this configuration and the outermost "infall" material. Numerical simulations show, however, that the shock stalls before it really reaches the outer edge of the initial Fe core, meaning no "prompt" (i.e. on hydrodynamical time-scales) destruction of the star; 4) Various kinds of (anti-)neutrinos are produced very near the centre of the nascent hot neutron star through various mechanisms which have been well studied. Because of the high matter densities, those neutrinos cannot escape freely (like in most previous evolutionary stages), but are gradually transported towards the periphery of the nascent neutron star. The simulation of this neutrino transport is a difficult task, particularly if one attempts to describe the process by solving the Boltzmann transport equations. An additional huge nuclear-physics complication arises in connection with the required evaluation of neutrino-nucleus interaction cross sections, which necessitates the careful treatment of various many-body effects ([141] - [143]). Those streaming neutrinos interact with the material near the surface of the nascent neutron star that consists by then of neutrons and protons. Very important, energy is deposited mainly by the absorptions of ν_e by neutrons and of $\bar{\nu_e}$ by protons, leading a portion of that material to be expelled in the form of a "neutrino(-energized) wind." A rapidly expanding high-temperature and low-density region results, the "hot bubble." Several hydrodynamical simulations support the idea that the neutrino energy deposition of as little as 1% of the approximate 10^{53} erg of the gravitational potential energy of the forming neutron star is sufficient for reviving the stalled shock wave, and

[+] The Chandrasekhar mass is the limiting mass of a configuration whose mechanical equilibrium is obtained by the compensation of the gravitational forces by the pressure exerted by fully degenerate electrons make it drive an explosion. The nuclear uncertainties associated with this stage largely reflect those affecting the earlier phase, and in particular those concerning the neutrino energy spectra.

8.3.2. Nucleosynthesis in the hot bubble: Can the r-process occur ? The expelled material, or "neutrino wind," is made of neutrons and protons. By the time the expansion has cooled the material below about (10 to 7)$\times 10^9$ K, the weak interaction processes have largely ceased, leading to a somewhat fixed neutron/proton ratio n/p in excess of unity* and to a somewhat fixed entropy s. The entropy is essentially determined by the contributions from photons, electrons and positrons, and is very high because of the high temperatures and low densities. The expansion of this material favours the recombination of the nucleons into heavier and heavier species starting with α-particles and ending with nuclei heavier than iron when the temperatures have reached values slightly in excess of about 10^9 K, at which point the charged-particle induced reactions essentially freeze-out. A nuclear flow associated with these transformations, termed the α-process, is depicted in Fig. 15 for a generic hot-bubble model.

There has been much hope that the captures of the neutrons left at the time of the freeze-out would switch the α-process into an r-process [195]. For this to happen, and for the neutron-capture flow to possibly reach the trans-actinide region, about $100 \sim 150$ neutrons have to be available per seed nuclei produced by the α-process. This translates into the requirement of either very high s, low $Y_{\rm e}$, short expansion time scale $\tau_{\rm exp}$, or of any combination thereof ([196, 368, 369]). For example, the model used to derive Fig. 15 assumes a set of parameter values leading to a very short $\tau_{\rm exp}$, even if the assumed $s = 200k$ per baryon (k is the Boltzmann constant) and $Y_{\rm e} = 0.4$ are not unthinkable.

Save a claim of success [370], it has become a general consensus that the currently available hydrodynamical simulations of the hot bubble are unable to provide suitable conditions for the occurrence of the r-process ([309, 368, 371]). The situation gets even more unfavourable when considering the possible destruction of α-particles by neutrinos via the neutral current of weak interaction [307]. It remains, however, that a twist of $s, Y_{\rm e}$ or $\tau_{\rm exp}$ from the model values can lead to an r-process that very well matches the solar r-process abundance curve [372]. In this respect, further scrutiny of the neutrino wind conditions (especially the neutrino energy spectra) at the onset of nucleosynthesis may still be of value.

8.3.3. Signatures of a large-scale mixing of nucleosynthesis products The revived shock wave ejects into the ISM the nucleosynthesis products available at the pre-supernova stage, save the possible modification of some of their abundances by the "explosive nucleosynthesis" associated with the brief period of shock re-heating of the expelled layers. Here we pick an example illustrating how observed nuclear imprints

* The "electron concentration" $Y_{\rm e} = 1/(n/p + 1)$ is often used instead of n/p

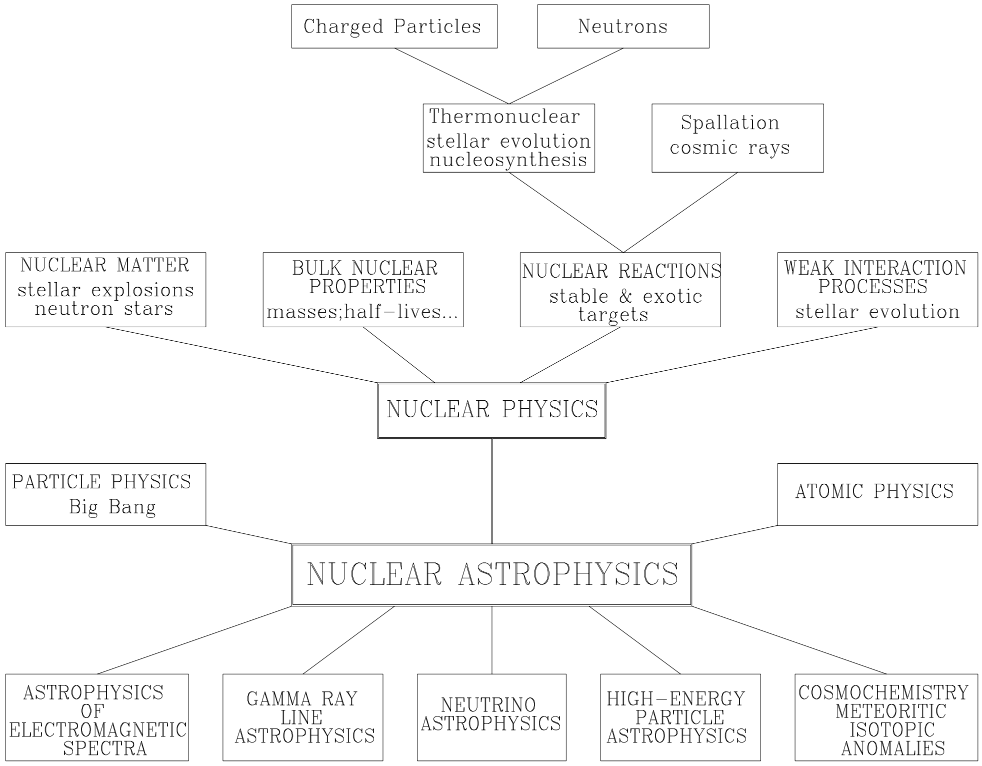

Figure 19. Diagrammatic presentation of possible connections of nuclear astrophysics with other major fields of physics, and with various main astrophysics subfields [373]

in supernova remnants could help deepening (or at least, challenging to deepen) our understanding of the very mechanism of the explosion.

Several observations in SN1987A (early detection of X- and γ-rays, and strongly Doppler-shifted broad infrared emission lines, particularly of Fe and Ni) suggest that some portion of the nuclides have been transported to the outer hydrogen envelope from as deep as close to the surface of the nascent neutron star much more quickly than expected ([88]). The unpredicted short mixing time-scale was attested in particular by the observation rather soon after the explosion of the γ-ray lines emitted following the decay of the ^{56}Ni and ^{57}Co synthesized deep in the interior. Along with other symptoms, such as the clumps and anisotropies in the remnant, the above observations have prompted multi-dimensional hydrodynamical simulations which indeed predict large-scale convective motions in the post-shock region [88]. This makes it technically difficult, if not impossible, to predict the fate of the nucleosynthesis products in the material expelled from a Type-II supernova. We add here that the same simulations lead to nearly spherical hot-bubbles after the cease of these convective motions.

9. Summary

Nuclear astrophysics is without any doubt vastly interdisciplinary. As schematized in Fig. 19, it is in fact intimately connected with a huge variety of different and complementary research fields that are essential in our understanding of a large diversity of classes of problems. As such, the nuclear astrophysics quest identifies itself to the everlasting search for an El Dorado, and opens up at the same time a Pandora Box of scientific questions. This makes the field especially exciting, but at the same time remarkably demanding. This review has obviously not been able to go beyond a quite limited overview of some of the many connections drawn in Fig. 19.

One of our goals has been to demonstrate that nuclear physics and astrophysics bring their share to the common adventure of understanding the ever-growing body of observations concerning the structure and composition of the Universe and of its various constituents, ranging from sub-millimetre grains in meteorites to galaxies at different redshifts. At all these scales, observational data obtained with the help of an impressive panoply of advanced techniques identify the strong imprints of the properties of atomic nuclei, and of their interactions. In such conditions, careful and dedicated experimental and theoretical studies of a large variety of nuclear processes are indispensable tools for the modelling of ultra-macroscopic systems such as stars.

A major common challenge to modern nuclear physics and to nuclear astrophysics is the exploration of *terra incognita* located on the sides of the chart of the nuclides well away from the valley of nuclear stability (and/or at moderately-high nuclear excitation). When Marie and Pierre Curie discovered a century ago the mysterious phenomenon of radioactivity, they certainly could not have imagined that they had just opened the way to a better understanding of the Universe. Despite the impressive experimental as well as theoretical progress having been made since that time, much obviously remains to be done in order to meet the unusual request from astrophysics regarding the exploration of the nuclear exoticism. Even along the valley of nuclear stability, nuclear astrophysics has a lot of scientific ebullience in store. There, astrophysics forces to enter the world of "almost no event," and to look for a needle in a haystack. Indeed, the charged-particle induced reaction cross sections of astrophysical interest are without doubt among the smallest one may ever dream measuring in the laboratory. This has led nuclear experimentalists to start going deep underground to do astrophysics, in the search for a "background noise deterrent," as vividly witnessed by the advent of neutrino astrophysics.

Where nuclear astrophysics will stand after a century from now is hard to imagine. For sure, however, a closer collaboration and an improved mutual understanding between the nuclear- and astro-physics communities would carry success in promoting further excitements in the field of nuclear astrophysics in the coming millennium.

References

[1] Barrow J D 1992 *Cosmology and Elementary Particles* Altschuler D R *et al.* (eds) (Singapore: World Sceintific) pp. 171-214
[2] Russell H N 1919 *Pub. Astron. Soc. Pac.* **31** 205-11
[3] Perrin J 1920 *Scientia* **30** 355-70
[4] Schatzmann E and Praderie F 1993 *The Stars* (Berlin: Springer-Verlag)
[5] Alpher R A and Herman R C 1953 *Ann. Rev. Nucl. Sci.* **2** 1-40
[6] Merrill P W 1952 *Astrophys. J.* **116** 21-6
[7] Hoyle F 1946 *Mon. Not. Roy. Astron. Soc.* **106** 343-83
[8] Burbidge E M *et al.* 1957 *Rev. Mod. Phys.* **29** 547-650
[9] Öpik E J 1951 *Proc. Roy. Irish Acad.* **A54** 49-77
[10] Salpeter E E 1952 *Astrophys. J.* **115** 326-8
[11] Hoyle F *et al* 1953 *Bull. Amer. Phys. Soc.* **28**/5 23
[12] Dunbar D N F *et al.* 1953 *Phys. Rev.* **92** 649-50
[13] Hoyle F 1954 *Astrophys. J. Suppl.* **1** 121-46
[14] Käppeler F and Wisshak K (eds) 1992 *Nuclei in the Cosmos II* (Bristol: Inst. Phys. Pub.)
[15] Busso M, Gallino R and Raiteri C M (eds) 1995 *Nuclei in the Cosmos III* [AIP Conf. Proc. **327**] (New York: Amer. Inst. Phys.)
[16] Görres J *et al.* (eds) 1997 *Nuclei in the Cosmos IV* [*Nucl. Phys.* **A621**]
[17] Prantzos N, Vangioni-Flam E and Cassé M (eds) 1993 *Origin and Evolution of the Elements* (Cambridge: Cambridge Univ. Press)
[18] Kajino T, Kubono S and Yoshi Y (eds) 1997 *Origin of Matter and Evolution of Galaxies* (Singapore: World Scientific)
[19] Arnould M *et al.* (eds) 1998 *Tours Symposium on Nuclear Physics III* [AIP Conf. Proc. **425**] (New York: Amer. Inst. Phys.)
[20] Buballa M *et al.* (eds) 1998 *Nuclear Astrophysics* (Darmstadt: Gesellschaft f. Schwerionenforschung) [*unpublished*]
[21] Hillebrandt W and Müller E (eds) 1998 *Nuclear Astrophysics 9* [MPA-report P10] (Garching: Max-Planck-Institut f. Astrophysik) [*unpublished*]
[22] Clayton D D 1968 *Principles of Stellar Evolution and Nucleosynthesis* (New York: MacGraw-Hill)
[23] Rolfs C E and Rodney W S 1988 *Cauldrons in the Cosmos* (Chicago: Univ. Chicago Press)
[24] Arnett W D 1996 *Supernovae and Nucleosynthesis* (Princeton: Princeton Univ. Press)
[25] Pagel B E J 1997 *Nucleosynthesis and Chemical Evolution of Galaxies* (Cambridge: Cambridge Univ. Press)
[26] Léna P 1988 *Observational Astrophysics* (Berlin: Springer-Verlag)
[27] Böhm-Vitense E 1989 *Introduction to Stellar Astrophysics* Vol. **1** (Cambridge: Cambridge Univ. Press)
[28] Glies W 1969 *Catalogue of Nearby Stars* [Veröff. Astron. Rech. Inst. Heidelberg Nr. 22] (Karlsruhe: Verlag G. Braun)
[29] Perryman M A C (sci. coordinator) and the Hipparcos Science Team 1997 *The Hipparcos and Tycho Catalogues* (Noordwijk: ESA Pub. Div., ESTEC)
[30] Johnson H L and Mitchell R I 1958 *Astrophys. J.* **128** 31-40
[31] Hazlehurst J and Thomas H C 1970 *Mon. Not. Roy. Astron. Soc.* **128** 311-23
[32] Durrell P R and Harris W E 1993 *Astron. J.* **105** 1420-40
[33] Chiosi C, Bertelli G and Bressan A 1992 *Ann. Rev. Astron. Astrophys.* **30** 235-85
[34] Cox J P and Giuli R T 1968 *Principles of Stellar Structure* (New York: Gordon and Breach)
[35] Kawaler S D 1997 *Stellar Remnants* Meynet G and Schaerer D (eds) [Saas-Fee Advanced Course **25**] (Berlin: Springer-Verlag) pp. 1-95
[36] Schwarzschild M 1958 *Structure and Evolution of the Stars* (New York: Dover Pub. Inc.)
[37] VandenBerg D A, Bolte M and Stetson P B 1996 *Ann. Rev. Astron. Astrophys.* **34** 461-510
[38] Chaboyer B *et al.* 1998 *Astrophys. J.* **494** 96-110
[39] Sandage A 1988 *Calibration of Stellar Ages* Philip A G D (ed) (Schenectady: L. Davis Press) pp.

43-58
[40] Anders E and Grevesse N 1989 *Geochim. Cosmochim. Acta* **53** 197-214
[41] Gilmore G, Wyse R F G and Kuijken K 1989 *Ann. Rev. Astron. Astrophys.* **27** 555-627
[42] Reeves H 1994 *Rev. Mod. Phys.* **66** 193-216
[43] McWilliam A 1997 *Ann. Rev. Astron. Astrophys.* **35** 503-56
[44] Magain P 1989 *Astron. Astrophys.* **209** 211-25
[45] Gratton R G and Sneden C 1991 *Astron. Astrophys.* **241** 501-25
[46] Edvardsson B *et al.* 1993 *Astron. Astrophys.* **275** 101-52
[47] Nissen P E *et al.* 1994 *Astron. Astrophys.* **285** 440-50
[48] Smith V V 1997 *Nuclei in the Cosmos IV* loc. cit. [16] pp. 3c-9c
[49] Kahane C. 1995 *Nuclei in the Cosmos III* loc. cit. [15] pp. 19-30
[50] Savage B D and Sembach K R 1996 *Ann. Rev. Astron. Astrophys.* **34** 279-329
[51] Lu L *et al.* 1996 *Astrophys. J. Suppl.* **107** 475-519
[52] Tayler R J 1986 *Q. Jl. R. astr. Soc.* **27** 367-82
[53] Fowler W A and Meisl C C 1986 *Cosmogonical Processes* Arnett W D *et al.* (eds) 1986 (Utrecht: VNU Sci. Press) pp. 83-100
[54] Arnould M and Takahashi K 1990 *New Windows to the Universe* Sanchez F and Vazquez M (eds) (Cambridge: Cambridge Univ. Press) pp. 355-74
[55] Smith V V 1989 *Cosmic Abundances of Matter* [AIP Conf. Proc. **183**] Waddington C J (ed) (New York: Amer. Inst. Phys.) pp. 200-23
[56] Denissenkov P A *et al.* 1998 *Astron. Astrophys.* **333** 926-41
[57] Kraft R P *et al.* 1998 *Astron. J.* **115** 1500-15
[58] Gehrz R D *et al.* 1998 *Pub. Astron. Soc. Pac.* **110** 3-26
[59] Filippenko A V 1997 *Ann. Rev. Astron. Astrophys.* **35** 309-55
[60] Vauclair S and Vauclair G 1982 *Ann. Rev. Astron. Astrophys.* **20** 37-60
[61] Prantzos N and Diehl R 1996 *Phys. Rep.* **267** 1-69
[62] Diehl R 1998 *Nuclear Astrophysics* loc. cit. [20] pp. 234-41
[63] Diehl R and Timmes F X 1998 *Pub. Astron. Soc. Pac.* **110** 637-59
[64] Grevesse N and Noels A 1993 *Origin and Evolution of the Elements* loc. cit. [17] pp. 15-25
[65] Harper C L Jr 1993 *Nuclei in the Cosmos II* loc. cit. [14] pp. 113-26
[66] Bernatowicz T J and Zinner E (eds) 1997 *Astrophysical Implications of the Laboratory Study of Presolar Materials* [AIP Conf. Proc. **402**] (New York: Amer. Inst. Phys.)
[67] Podosek F A and Nichols R H Jr 1997 *Astrophysical Implications of the Laboratory Study of Presolar Materials* loc. cit. [66] pp. 617-47
[68] Meyer J-P 1993 *Origin and Evolution of the Elements* loc. cit. [17] pp. 26-62
[69] Meyer J -P, Drury O'C and Ellison D C 1997 *Astrophys. J.* **487** 182-96
[70] Ellison D C, Drury O'C and Meyer J -P 1997 *Astrophys. J.* **487** 197-217
[71] Bionta R M *et al.* 1987 *Phys. Rev. Lett.* **58** 1494-6
[72] Hirata K S *et al.* 1987 *Phys. Rev. Lett.* **58** 1490-3
[73] Arnett W D *et al.* 1989 *Ann. Rev. Astron. Astrophys.* **27** 629-700
[74] Gaisser T K, Halzen F and Stanev T 1995 *Phys. Rep.* **258** 173-236
[75] Arnett D and Bazán G 1997 *Science* **276** 1359-62
[76] Bazán G and Arnett D 1998 *Astrophys. J.* **496** 316-32
[77] Pinsonneault M 1997 *Ann. Rev. Astron. Astrophys.* **35** 557-605
[78] Chiosi C and Maeder A 1986 *Ann. Rev. Astron. Astrophys.* **24** 329-75
[79] Dupree A K 1986 *Ann. Rev. Astron. Astrophys.* **24** 377-420
[80] Weaver T and Woosley S E 1993 *Phys. Rep.* **227** 65-96
[81] Hashimoto M 1995 *Prog. Theor. Phys.* **94** 663-736
[82] Chevalier R A 1997 *Science* **276** 1374-8
[83] Nomoto K, Iwamoto K and Kishimoto N 1997 *Science* **276** 1378-82
[84] Srinivasan G 1997 *Stellar Remnants* loc cit. [35] pp. 97-235

[85] Novikov I 1997 *Stellar Remnants* loc. cit. [35] pp. 237-334
[86] Arnould M, Meynet G and Paulus G 1997 *Astrophysical Implications of the Laboratory Study of Presolar Materials* loc. cit. [66] pp. 179-202
[87] Woosley S E, Langer N and Weaver T A 1995 *Astrophys. J.* **448** 315-38
[88] Janka H-Th and Müller E 1996 *Astron. Astrophys.* **306** 167-98
[89] Lattanzio J C and Boothroyd A I 1997 *Astrophysical Implications of the Laboratory Study of Presolar Materials* loc. cit. [66] pp. 85-114
[90] Blöcker T 1995 *Astron. Astrophys.* **297** 727-38
[91] Iben I Jr, Ritossa C and García-Berro E 1997 *Astrophys. J.* **489** 772-90
[92] Nomoto K 1987 *Astrophys. J.* **322** 206-14
[93] Portinari L, Chiosi C and Bressan A 1998 *Astron. Astrophys.* **334** 505-39
[94] Nussbaumer H and Orr A (eds) 1994 *Interacting Binaries* [Saas-Fee Advanced Course **22**] (Berlin: Springer-Verlag)
[95] DuVernois M A *et al.* 1996 *Astrophys. J.* **466** 457-72
[96] Ramaty R, Kozlovski B and Lingenfelter R E 1996 *Astrophys. J.* **456** 525-40
[97] Vangioni-Flam *et al.* 1996 *Astrophys. J.* **468** 199-206
[98] Parizot E, Cassé M and Vangioni-Flam E 1997 *Astron. Astrophys.* **328** 107-20
[99] Michel R 1998 *Tours Symposium on Nuclear Physics III* loc. cit. [19] pp. 447-56; also Lee T *et al. Astrophys. J.* **506** 898-912
[100] Sarkar S 1996 *Rep. Prog. Phys.* **59** 1493-609
[101] Hogan C J 1996 *Phys. Rev.* **D54** 112-5
[102] Penzias A A and Wilson R W 1965 *Astrophys. J.* **142** 419-21
[103] Alpher R A and Herman R 1988 *Physics Today* **41**/8 24-34
[104] White M, Scott D and Silk J 1994 *Ann. Rev. Astron. Astrophys.* **32** 319-70
[105] Burles S and Tytler D 1996 *Astrophys. J.* **460** 584-600
[106] Rugers M and Hogan C J 1996 *Astron. J.* **111** 2135-40
[107] Levshakov S A, Kegel W H and Takahara F 1998 *Astrophys. J.* **499** L1-4
[108] Olive K A and Schramm D N 1996 *Phys. Rev.* **D54** 109-11
[109] Ashman K M 1992 *Pub. Astron. Soc. Pac.* **104** 1109-38
[110] Hata N *et al.* 1995 *Phys. Rev. Lett.* **75** 3977-80
[111] Malaney R A and Mathews G J 1993 *Phys. Rep.* **229** 145-219
[112] Shore S N 1997 *Nuclei in the Cosmos IV* loc. cit. [16] pp. 535c-47c
[113] Truran J W and Timmes F X 1997 *Nuclei in the Cosmos IV* loc. cit. [16] pp. 548c-57c
[114] Prantzos N 1997 *Nuclei in the Cosmos IV* loc. cit. [16] pp. 558c-65c
[115] Nørgaard H and Fricke K 1976 *Astron. Astrophys.* **49** 337-42
[116] Ferrara A 1998 *Astrophys. J.* **499** L17-20
[117] Montmerle T 1977 *Astrophys. J.* **217** 878-82
[118] Scalo J M 1986 *Fund. Cosmic Phys.* **11** 1-278
[119] Miller G E and Scalo J M 1979 *Astrophys. J. Suppl.* **41** 513-47
[120] Horiguchi T, Tachibana T and Katakura J 1996 *Chart of the Nuclides 1996* (Tokai-mura: Jap. Atom. Energy Res. Inst.) [*unpublished*]
[121] Bohlen H G and Von Oertzen W 1995 *Nuclear News* **5**/1 26-8
[122] Heßberger F P *et al.* 1998 *Tours Symposium on Nuclear Physics III* loc. cit. [19] pp. 3-15
[123] Coc A and Porquet M-G 1998 *Tours Symposium on Nuclear Physics III* loc. cit. [19] pp. 457-64
[124] Klay N *et al.* 1991 *Phys. Rev.* **C44** 2839-49
[125] Lesko K T *et al.* 1991 *Phys. Rev.* **C44** 2850-64
[126] Hillebrandt 1991 *High-Pressure Equations of State: Theory and Applications* Eliezer S and Ricci R A (eds) ["Enrico Fermi" Course **113**] (Amsterdam: North-Holland Pub.) pp. 399-437
[127] Pethick C J and Ravenhall D G 1995 *Ann. Rev. Nucl. Part. Sci.* **45** 429-84
[128] Grotz K and Klapdor H V 1990 *The Weak Interaction in Nuclear, Particle and Astrophysics* (Bristol: Adam Hilger)

[129] Bravo E *et al.* 1983 *Astron. Astrophys.* **124** 39-42
[130] Hashimoto M *et al.* 1986 *Astrophys. J.* **307** 687-93
[131] Hashimoto M, Iwamoto K and Nomoto K 1993 *Astrophys. J.* **414** L105-8
[132] Bethe H A 1990 *Rev. Mod. Phys.* **62** 801-66
[133] Mayle R W 1990 *Supernovae* Petschek A G (ed) (New York: Springer) pp. 267-89
[134] Bruenn S W and Haxton W C 1991 *Astrophys. J.* **376** 678-700
[135] Janka H-Th 1993 *Frontier Objects in Astrophysics and Particle Physics*, Giovannelli F and Mannocchi G (eds) (Bologna: Società Italiana di Fisica) pp. 345-74
[136] Woosley S E *et al.* 1990 *Astrophys. J.* **356** 272-301
[137] Nadyozhin D K 1991 *Nuclear Astrophysics 6* Hillebrandt W and Müller E (eds) [MPA-report P5] (Garching: Max-Planck-Institut f. Astrophysik) pp. 118-22 [*unpublished*]
[138] Konopinski E J 1966 *The Theory of Beta Radioactivity* (Oxford: Clarendon Press)
[139] Tubbs D L and Schramm D N 1975 *Astrophys. J.* **201** 467-88
[140] Bruenn S W 1985 *Astrophys. J. Suppl.* **58** 771-841
[141] Raffelt G, Seckel D and Sigl G 1996 *Phys. Rev.* **D54** 2784-92
[142] Barrows A and Sawyer R F 1998 *Phys. Rev.* **C58** 554-71
[143] Yamada S 1998 *Nuclear Astrophysics 9* loc. cit. [21] pp. 115-8
[144] Takahashi K, Mathews G J and Bloom S D 1986 *Phys. Rev.* **C33** 296-302
[145] Daudel R *et al.* 1947 *C. R. Acad. Sci.* **224** 1427-9
[146] Takahashi K and Yokoi K 1981 *Nuclei Far from Stability* [CERN-report 81-09] Hansen P G and Nielsen O B (eds) (Genève: CERN) pp. 351-8 [*unpublished*]
[147] Takahashi K and Yokoi K 1983 *Nucl. Phys.* **A404** 578-98
[148] Takahashi K and Yokoi K 1987 *Atm. Nucl. Data Tables* **36** 375-409
[149] Simpson J A and Garcia-Munoz M 1988 *Space Sci. Rev.* **46** 205-24
[150] Cassé M 1973 *Astrophys. J.* **180** 623-9
[151] Simpson J A and Connell J J 1998 *Astrophys. J.* **497** L85-8
[152] Ahmad I *et al.* 1998 *Phys. Rev. Lett.* **80** 2550-3
[153] Görres J *et al.* 1998 *Phys. Rev. Lett.* **80** 2554-7
[154] Norman E B *et al.* 1998 *Phys. Rev.* **C57** 2010-6
[155] Mochizuki Y *et al.* 1999 *Astron. Astrophys.* submitted
[156] Sumiyoshi K *et al.* 1998 *Astron. Astrophys.* **334** 159-68
[157] Perrone F A and Clayton D D 1971 *Astrophys. Space Sci.* **11** 451-62
[158] Rolfs C 1993 *Origin and Evolution of the Elements* loc. cit. [17] pp. 66-76
[159] Angulo C *et al.* 1992 *Nuclei in the Cosmos II* loc. cit. [14] pp. 147-52
[160] Angulo C *et al.* 1993 *Z. Phys.* **A345** 231-42
[161] Dzitko H *et al.* 1993 *Origin and Evolution of the Elements* loc.cit. [17] pp. 388-91
[162] Haxton W C 1995 *Ann. Rev. Astron. Astrophys.* **33** 459-503
[163] Bahcall J N, Krastev P I and Smirnov A Yu 1998 *Phys. Rev.* **D58** 096016 1-22
[164] Castellani V *et al.* 1997 *Phys. Rep.* **281** 309 - 98
[165] Angulo C *et al.* (NACRE Collaboration) 1998 *Nucl. Phys.* in press
[166] Junker M 1998 *Nuclear Astrophysics* loc. cit. [20] pp. 271-78
[167] Taddeucci I N *et al.* 1987 *Nucl. Phys.* **A469** 125-72
[168] Bahcall J N and Ulrich R K 1988 *Rev. Mod. Phys.* **60** 297-372
[169] Iben I Jr 1991 *Astrophys. J. Suppl.* **76** 55-114
[170] Arnould M, Mowlavi N and Champagne A 1995 *Stellar Evolution: What Should be Done* Noels A *et al.* (eds) (Liège: Inst. Astrophys. Univ. Liège) pp. 17-29 [*unpublished*]
[171] Arnould M, Goriely S and Jorissen A 1998 *Astron. Astrophys.* in press
[172] Drotleff H W *et al.* 1993 *Astrophys. J.* **414** 735-9
[173] Meynet G and Arnould M 1992 *Nuclei in the Cosmos II* loc.cit. [14] pp. 487-92
[174] Arnould M and Howard W M 1976 *Nucl. Phys.* **A274** 295-332
[175] Descouvemont P. 1989 *Nucl. Phys.* **A504** 193-204

[176] Hammer J W 1998 *Nuclear Astrophysics* loc. cit. [20] pp. 370-7
[177] Knee H *et al.* 1993 *Origin and Evolution of the Elements* loc. cit. [17] pp. 81-5
[178] Descouvemont P and Baye D 1987 *Nucl. Phys.* **A475** 219-32
[179] Woosley S E, Arnett W D and Clayton D D 1973 *Astrophys. J. Suppl.* **26** 231-312
[180] Arnould M 1992 *Nucleus-Nucleus Collisions IV* Toki H, Tanihata I and Kamitsubo H (eds) [*Nucl. Phys.* **A538**] pp. 493c-504c
[181] Arnould M 1994 *Eighth Intern. Symp. on Capture Gamma-ray Spectroscopy and Related Topics* Kern J (ed) (Singapore: World Scientific) pp. 647-59
[182] Smith M S, Kawano L H and Malaney R A 1993 *Astrophys. J. Suppl.* **85** 219-47
[183] Orito M *et al.* 1997 *Astrophys. J.* **488** 515-23
[184] Arnould M and Nørgaard H 1975 *Astron. Astrophys.* **42** 55-70
[185] Boffin H M J *et al.* 1993 *Astron. Astrophys.* **279** 173-8
[186] Arnould M, Paulus G and Jorissen A 1992 *Astron. Astrophys.* **254** L9-12
[187] Coc A *et al.* 1995 *Astron. Astrophys.* **299** 479-92
[188] Meynet G *et al.* 1997 *Astron. Astrophys.* **320** 460-8
[189] Van Wormer L. *et al.* 1994 *Astrophys. J.* **432** 326-50
[190] Schatz H *et al.* 1998 *Phys. Rep.* **294** 167-263
[191] Taam R E 1998 *Tours Symposium on Nuclear Physics III* loc. cit. [19] pp. 551-8
[192] Iliadis C *et al.* 1998 *Nuclei in the Cosmos* vol V, ed N Prantzos and S Harissopulos (Gif-sur-Yvette: Editions Frontières) pp 441-4; and *Astrophys. J.* submitted
[193] Arnould M 1995 *ENAM 95* de Saint Simon M and Sorlin O (eds) (Gif-sur-Yvette: Editions Frontières) pp. 639-48
[194] Woosley S E and Weaver T A 1995 *Astrophys. J. Suppl.* **101** 181 - 235
[195] Woosley S E and Hoffman R D 1992 *Astrophys. J.* **395** 202-39
[196] Witti J, Janka H-Th and Takahashi K 1994 *Astron. Astrophys.* **286** 841-56
[197] Arnould M, Rayet M and Hashimoto M 1998 *Tours Symposium on Nuclear Physics III* loc. cit. [19] pp. 626-36
[198] Howard W M and Meyer B S 1992 *Nuclei in the Cosmos II* loc. cit. [14] pp. 575-80
[199] Fülöp Zs *et al.* 1996 *Z. Phys.* **A355** 203-7
[200] Sauter T and Käppeler F 1997 *Phys. Rev.* **C55** 3127-38
[201] Somorjai E *et al.* 1998 *Astron. Astrophys.* **333** 1112-6
[202] Audi G *et al.* 1997 *Nucl. Phys.* **A624** 1-124
[203] Delbar Th (ed) 1992 *Radioactive Nuclear Beams II* (Bristol: Inst. Phys. Pub.)
[204] Morrisey D J (ed) 1993 *Radioactive Nuclear Beams III* (Gif-sur-Yvette: Editions Frontières)
[205] Kubono S, Kobayashi T and Tanihata I (eds) 1997 *Radioactive Nuclear Beams IV* [*Nucl. Phys.* **A616**]
[206] de Saint Simon M and Sorlin O (eds) 1995 *ENAM 95* (Gif-sur-Yvette: Editions Frontières)
[207] Åberg S *et al.* 1997 *Nuclear Physics in Europe: Highlights and Opportunities* [NuPECC Report] J Vervier *et al.* (eds) pp. 31-53 [*unpublished*]
[208] Mittig W *et al.* 1997 *Ann. Rev. Nucl. Part. Sci.* **47** 27-66
[209] Möller P *et al.* 1995 *Atm. Nucl. Data Tables* **59** 185-381
[210] Aboussir Y *et al.* 1995 *Atm. Nucl. Data Tables* **61** 127-76
[211] Patyk Z *et al.* 1997 [GSI-preprint 97-40] (Darmstadt: Gesellschaft f. Schwerionenforschung)
[212] Pearson J M *et al.* 1998 *Tours Symposium on Nuclear Physics III* loc. cit. [19] pp. 475-84
[213] Goriely S and Bouquelle V 1993 *Nuclei in the Cosmos II* loc. cit. [14] pp. 595-600
[214] Dobaczewski J *et al.* 1994 *Phys. Rev. Lett.* **72** 981-4
[215] Kratz K-L 1995 *Nuclei in the Cosmos III* loc. cit. [15] pp. 113-24
[216] Pearson J M *et al.* 1996 *Phys. Lett.* **B387** 455-9
[217] Vautherin D 1994 *Supernovae* Bludman S A, Mochkovith R and Zinn-Justin J (eds) (Amsterdam: North Holland Pub.) pp. 345-91
[218] Hillebrandt W, Nomoto K and Wolf R G 1984 *Astron. Astrophys.* **133** 175-84

[219] Shen H *et al.* 1998 *Nucl. Phys.* **A637** 435-50
[220] Ravenhall D G, Pethick C J and Wilson J R 1983 *Phys. Rev. Lett.* **50** 2066-9
[221] Laussaut M *et al.* 1987 *Astron. Astrophys.* **183** L3-6
[222] Tamagaki R 1993 *Prog. Theor. Phys. Suppl.* **112** 1-25
[223] Pines D and Alpar M A 1990 *The Structure and Evolution of Neutron Stars* Pines D, Tamagaki R and Tsuruta S (eds) (New York: Addison-Wesley) pp. 7-31
[224] Link B, Epstein R I and Van Riper K A 1992 *Nature* **359** 616-8
[225] Mochizuki Y S, Oyamatsu K and Izuyama T 1997 *Astrophys. J.* **489** 848-64
[226] Glendenning N K 1997 *Compact Stars* (New York: Springer)
[227] Petersson B 1991 *Quark Matter '90* Blaizot J P *et al.* (eds) [*Nucl. Phys.* **A525**] 237c-53c
[228] Aufderheide M B *et al.* 1994 *Astrophys. J. Suppl.* **91** 389-417
[229] El-Kateb S *et al.* 1994 *Phys. Rev.* **C49** 3129-36
[230] Williams A L *et al.* 1995 *Phys. Rev.* **C51** 1144-53
[231] Kratz K L *et al.* 1986 *Z. Phys.* **A325** 489-90
[232] Kratz K L *et al.* 1991 *Z. Phys.* **A340** 419-20
[233] Sorlin O *et al.* 1993 *Phys. Rev.* **C47** 2941-53
[234] Bernas M *et al.* 1992 *Phys. Rev. Lett.* **67** 3661-4
[235] Bernas M *et al.* 1997 *Radioactive Nuclear Beams IV* loc. cit. [205] pp. 352c-62c
[236] Ameil F *et al.* 1998 *European Phys. J.* **A1** 275-83
[237] Roeckl E 1998 *Nuclear Astrophysics* loc. cit. [20] pp. 350-5
[238] Ikeda K, Fujii S and Fujita J-I 1963 *Phys. Lett.* **3** 271-2
[239] Takahashi K 1984 *Yields and Decay Data of Fission Product Nuclides* [BNL-report 51778] (Brookhaven: Brookhaven Nat. Lab) pp. 157-87 [*unpublished*]
[240] Takahashi K 1992 *Comments Astrophys.* **16** 187-204
[241] Takahashi K, Yamada M and Kondoh T 1973 *Atm. Nucl. Data Tables* **12** 101-42
[242] Tachibana T, Nakata H and Yamada M 1998 *Tours Symposium on Nuclear Physics III* loc. cit. [19] pp. 495-504
[243] Martinez-Pinedo G and Langanke K 1998 *Nuclei in the Cosmos* vol V, ed N Prantzos and S Harissopulos (Gif-sur-Yvette: Editions Frontières) pp 248-51
[244] Koonin S E, Dean D J and Langanke K 1997 *Phys. Rep.* **278** 1-77
[245] Möller P, Nix J R and Kratz K-L 1997 *Atm. Nucl. Data Tables* **66** 131-343
[246] Borzov I and Goriely S 1998 *Nuclei in the Cosmos* vol V, ed N Prantzos and S Harissopulos (Gif-sur-Yvette: Editions Frontières) pp 303-9
[247] Takahashi K *et al.* 1987 *Phys. Rev.* **C36** 1522-8
[248] Jung M *et al.* 1992 *Phys. Rev. Lett.* **69** 2164-7
[249] Bosch F *et al.* 1996 *Phys. Rev. Lett.* **77** 5190-3
[250] Freedman M S 1988 *Nucl. Inst. Meth.* **A271** 267-76
[251] Kienle P 1988 *Nucl. Inst. Meth.* **A271** 277-9
[252] Cohen S G, Murnick D E and Raghavan 1987 *Hyperfine Interact.* **33** 1-8
[253] Greife U *et al.* 1994 *Nucl. Inst. Meth.* **A350** 327-37
[254] Käppeler F, Thielemann F-K and Wiescher M 1998 *Ann. Rev. Nucl. Part. Sci.* **48** 175-251
[255] Junker M *et al.* 1998 *Phys. Rev.* **C57** 2700-10
[256] Nolan P J, Beck F A and Fossan D B 1994 *Ann. Rev. Nucl. Part. Sci.* **44** 561-607
[257] Lutz G and Schwarz A S 1996 *Ann. Rev. Nucl. Part. Sci.* **45** 295-335
[258] Galster W 1998 *Tours Symposium on Nuclear Physics III* loc. cit. [19] pp. 327-36
[259] Leleux P 1998 *Nuclear Astrophysics* loc. cit. [20] pp. 356-63
[260] Decrock P et al. 1991 *Phys. Rev. Lett.* **67** 808-11
[261] Decrock P *et al.* 1993 *Phys. Rev.* **C48** 2057-67
[262] Graulich J-S *et al.* 1997 *Nucl. Phys.* **A626** 751-9
[263] Vancraeynest G *et al.* 1998 *Phys. Rev.* **C57** 2711-23
[264] Bradfield-Smith W *et al.* 1998 *Nuclear Astrophysics* loc. cit. [20] pp. 364-9

[265] Gu X *et al.* 1995 *Phys. Lett.* **B343** 31-5
[266] Champagne A E and Wiescher M 1992 *Ann. Rev. Nucl. Part. Sci.* **42** 39-76
[267] Bardayan D W and Smith M S 1997 *Phys. Rev.* **C56** 1647-50
[268] Bauer G, Typel S and Wolter H H 1998 *Nuclear Astrophysics* loc. cit. [20] pp. 389-93
[269] Motobayashi T 1998 *Tours Symposium on Nuclear Physics III* loc. cit. [19] pp. 362-71
[270] Tatischeff V *et al.* 1995 *Phys. Rev.* **C51** 2789-93
[271] Motobayashi T *et al.* 1991 *Phys. Lett.* **B264** 259-63
[272] Kiener J *et al.* 1993 *Nucl. Phys.* **A552** 66-81
[273] Lefebvre A *et al.* 1995 *Nucl. Phys.* **A592** 69-88
[274] Sümmerer K *et al.* 1998 *Nuclear Astrophysics* loc. cit. [20] pp. 402-6
[275] Piechaczek A *et al.* 1993 *Radioactive Nuclear Beams III* loc. cit. [204] pp. 495-9
[276] Azuma R E *et al.* 1994 *Phys. Rev.* **C50** 1194-1215
[277] France III R H *et al.* 1997 *Nuclei in the Cosmos IV* loc. cit. [16] pp. 165c-8c
[278] France III R H and Gai M 1998 *Nuclei in the Cosmos* vol V, ed N Prantzos and S Harissopulos (Gif-sur-Yvette: Editions Frontières) pp 111-4
[279] King J D *et al.* 1998 *Tours Symposium on Nuclear Physics III* loc. cit. [19] pp. 372-81
[280] Beer H *et al.* 1992 *Astrophys. J. Suppl.* **80** 403-24
[281] Käppeler F and Wisshak K 1998 *Tours Symposium on Nuclear Physics III* loc. cit. [19] pp. 408-17
[282] Wisshak K *et al.* 1998 *Nuclei in the Cosmos* vol V, ed N Prantzos and S Harissopulos (Gif-sur-Yvette: Editions Frontières) pp 211-4
[283] Wisshak K *et al.* 1998 *Phys. Rev.* **C57** 391-408
[284] Nagai Y *et al.* 1994 *Proc. 8th Intern. Symp. on Capture Gamma-ray Spectroscopy and Related Topics* J Kern (ed) (Singapore: World Scientific) pp. 734-41
[285] Nagai Y *et al.* 1998 *Tours Symposium on Nuclear Physics III* loc. cit. [19] pp. 399-407
[286] Koehler P E 1997 *Phys. Rev.* **C56** 1138-43
[287] Wagemans C *et al.* 1998 *Phys. Rev.* **C57** 1766-70
[288] Wagemans C *et al.* 1998 *Nuclei in the Cosmos* vol V, ed N Prantzos and S Harissopulos (Gif-sur-Yvette: Editions Frontières) pp 187-90
[289] Descouvemont P 1998 *Tours Symposium on Nuclear Physics III* loc. cit. [19] pp. 418-27
[290] Descouvemont P 1993 *J. Phys. G Suppl.* **19** S141-52
[291] Langanke K and Barnes C A 1996 *Advances in Nuclear Physics* **22** Negele J W and Vogt E (eds) (New York: Plenum Press) pp. 173-263
[292] Descouvemont P 1993 *Phys. Rev.* **C47** 210-5
[293] Goriely S 1998 *Tours Symposium on Nuclear Physics III* loc. cit. [19] pp. 436-44
[294] Oberhummer H and Staudt G 1991 *Nuclei in the Cosmos* Oberhummer H (ed) (Heidelberg: Springer-Verlag) pp. 29-59
[295] Barker F C 1994 *Nucl. Phys.* **A575** 361-73
[296] Azuma R E *et al.* 1995 *ENAM95* loc. cit. [206] pp. 619-28
[297] Hale G M 1997 *Nuclei in the Cosmos IV* loc. cit. [16] pp. 177c-80c
[298] Goriely S 1998 *Nuclei in the Cosmos* vol V, ed N Prantzos and S Harissopulos (Gif-sur-Yvette: Editions Frontières) pp 314-17
[299] Grama C and Goriely S 1998 *Nuclei in the Cosmos* vol V, ed N Prantzos and S Harissopulos (Gif-sur-Yvette: Editions Frontières) pp 465-8
[300] Seeger P A, Fowler W A and Clayton D D 1965 *Astrophys. J. Suppl.* **11** 121-66
[301] Takahashi K 1995 *Neutrons and Their Applications* [*SPIE* **2339**] Vourvopoulos G and Paradellis T (eds) pp. 20-37
[302] Ward R A, Newman M J and Clayton D D 1976 *Astrophys. J. Suppl.* **31** 33-59
[303] Käppeler F, Beer H and Wisshak K 1989 *Rep. Prog. Phys.* **52** 945-1013
[304] Goriely S and Arnould M 1996 *Astron. Astrophys.* **312** 327-37
[305] Meyer B S 1993 *Origin and Evolution of the Elements* loc. cit. [17] pp. 444-8
[306] Howard W M *et al.* 1993 *Astrophys. J.* **417** 713-24

[307] Meyer B S 1995 *Astrophys. J.* **449** L55-8
[308] Goriely S [*private communication*]
[309] Takahashi K and Janka H-Th 1997 *Origin of Matter and Evolution of Galaxies* loc. cit. [18] pp. 213-27
[310] Goriely S 1998 *Nuclear Astrophysics* ed Buballa M *et al.* (Darmstadt: Gesellschaft f. Schwerionenforschung) pp. 320-5; see also [298]
[311] Hoppe P and Ott U 1997 *Astrophysical Implications of the Laboratory Study of Presolar Materials* loc. cit. [66] pp. 27-58
[312] Meyer B S 1994 *Ann. Rev. Astron. Astrophys.* **32** 153-90
[313] Gallino R *et al.* 1997 *Astrophysical Implications of the Laboratory Study of Presolar Materials* loc. cit. [66] pp. 115-53
[314] Straniero O *et al.* 1997 *Astrophys. J.* **478** 332-9
[315] Mowlavi N 1998 *Nuclei in the Cosmos* vol V, ed N Prantzos and S Harissopulos (Gif-sur-Yvette: Editions Frontières) pp 170-3, and *Astron. Astrophys.* submitted
[316] Busso M *et al.* 1992 *Astrophys. J.* **399** 218-30
[317] Käppeler F *et al.* 1990 *Astrophys. J.* **354** 630-43
[318] Rayet M and Hashimoto M 1998 *Tours Symposium on Nuclear Physics III* loc. cit. [19] pp. 605-15
[319] Höflich P *Proc. Astron. Soc. Aust.* **7** 434-42
[320] Prantzos N, Arnould M and Cassé M 1988 *Astrophys. J.* **331** L15-9
[321] Mazalli P A, Lucy L B and Butler K *Astron. Astrophys.* **258** 399-411
[322] Schramm D N 1982 *Essays in Nuclear Astrophysics* Barnes C A, Clayton D D and Schramm D N (eds) (Cambridge: Cambridge Univ. Press) pp. 325-53
[323] Ruffert M and Janka H-Th 1998 *Astron. Astrophys.* **338** 535-55
[324] Latimer J M *et al.* 1977 *Astrophys. J.* **213** 225-33
[325] Meyer B S 1989 *Astrophys. J.* **343** 254-76
[326] Ruffert M *et al.* 1997 *Astron. Astrophys.* **319** 122-53
[327] Ruffert M, Janka H-Th and Schäffer G 1996 *Astron. Astrophys.* **311** 532-66
[328] Shibata M 1997 *Phys. Rev.* **D55** 6019-29
[329] Wilson J R, Mathews G J and Maronetti P 1996 *Phys. Rev.* **D54** 1317-31
[330] Baraffe I and Takahashi K 1993 *Astron. Astrophys.* **280** 476-85
[331] Magain P 1995 *Astron. Astrophys.* **297** 686-94
[332] Gacquer W 1999 *Cosmic Chemical Evolution (IAU Symp. 187)* ed J W Truran and K Nomoto (Dordrecht: Kluwer) in press
[333] Vangioni-Flam E *et al.* (eds) 1990 *Astrophysical Ages and Dating Methods* (Gif-sur-Yvette: Editions Frontières)
[334] Jimenez R 1998 *From Quantum Fluctuations to Cosmological Structures* [APS Conf. Ser. **126**] pp. 411-26
[335] Dey A *et al.* 1998 *Astrophys. J.* **498** L93-7
[336] Riess A G *et al.* 1998 *Astron. J.* **116** 1009-38
[337] Tripp R 1997 *Astron. Astrophys.* **325** 871-6
[338] Chaboyer B 1998 *Phys. Rep.* **307** 23-30
[339] Grenon M 1990 *Astrophysical Ages and Dating Methods* loc. cit. [333] pp. 153-70
[340] Phelps R L 1997 *Astrophys. J.* **483** 826-36
[341] Hernanz M *et al.* 1994 *Astrophys. J.* **434** 652-61
[342] Oswalt T D *et al.* 1996 *Nature* **382** 692-4
[343] Arnould M and Takahashi K 1990 *Astrophysical Ages and Dating Methods* loc. cit. [333] pp. 325-48
[344] Fowler W A and Hoyle F 1960 *Ann. Phys.* **10** 280-302
[345] Cowan J J, Thielemann F-K and Truran J W 1991 *Phys. Rep.* **208** 267-394
[346] Pagel B E J 1990 *Astrophysical Ages and Dating Methods* loc. cit. [333] pp. 493-502
[347] Pagel B E J 1989 *Evolutionary Phenomena in Galaxies* Beckman J and Pagel B E J (eds)

(Cambridge: Cambridge Univ. Press) pp. 201-23
[348] Butcher H R 1987 *Nature* **328** 127-31
[349] da Silva L, de la Reza R and Dore de Magalhães S 1990 *Astrophysical Ages and Dating Methods* loc. cit. [333] pp. 419-26
[350] François P, Spite M and Spite F 1993 *Astron. Astrophys.* **274** 821-4
[351] Sneden C A *et al.* 1996 *Astrophys. J.* **467** 819-40
[352] Cowan J J *et al.* 1997 *Astrophys. J.* **480** 246-54
[353] Pfeiffer B *et al.* 1998 *Nuclear Astrophysics 9* loc.cit. [21] pp. 168-71
[354] Clayton D D 1964 *Astrophys. J.* **139** 637-63
[355] Faestermann T 1998 *Nuclear Astrophysics 9* loc. cit. [21] pp. 172-4
[356] Takahashi K 1998 *Tours Symposium on Nuclear Physics III* loc. cit. [19] pp. 616-25
[357] Woosley S E and Fowler W A 1979 *Astrophys. J.* **233** 411-7
[358] Winters R A *et al.* 1986 *Phys. Rev.* **C34** 840-9
[359] Arnould M, Takahashi K and Yokoi K 1984 *Astron. Astrophys.* **137** 51-7
[360] Käppeler F *et al.* 1991 *Astrophys. J.* **366** 605-16
[361] Yokoi K, Takahashi K and Arnould M 1983 *Astron. Astrophys.* **117** 65-82
[362] Kienle *et al.* 1998 *Nuclear Astrophysics 9* loc. cit. [21] pp. 180-6
[363] Arnould M 1972 *Astron. Astrophys.* **21** 401-12
[364] Takahashi *et al.* 1998 *Nuclear Astrophysics 9* loc. cit. [21] pp. 175-9
[365] Schramm D N and G J Wasserburg 1970 *Astrophys. J.* **162** 57-69
[366] Meyer B S and Schramm D N 1986 *Astrophys. J.* **311** 406-17
[367] Schramm D N 1990 *Astrophysical Ages and Dating Methods* loc. cit. [333] pp. 365-83
[368] Hoffman R D, Woosley S E and Qian Y-Z 1997 *Astrophys. J.* **482** 951-62
[369] Meyer B S and Brown J S 1997 *Astrophys. J. Suppl.* **112** 199-220
[370] Woosley S E *et al.* 1994 *Astrophys. J.* **433** 229-46
[371] Qian Y-Z and Woosley S E 1996 *Astrophys. J.* **471** 331-51
[372] Takahashi K, Janka H-Th and Witti J 1994 *Astron. Astrophys.* **286** 857-69
[373] Arnould M *et al.* 1994 *Impact and Applications of Nuclear Science in Europe* van der Woude A *et al.* (eds) [NuPECC-report] pp. 157-77 [*unpublished*]
[374] Fukuda Y *et al.* 1998 *Phys. Rev. Lett.* **81** 1158-62