NuPECC
REPORT*

DECEMBER 1994

IMPACT AND APPLICATIONS OF NUCLEAR SCIENCE IN EUROPE: OPPORTUNITIES AND PERSPECTIVES

edited by:

Adriaan van der Woude, Juha Äystö, Sydney Galès,
Björn Jonson and Gabriele-Elisabeth Körner

* Sponsored by CEC DGXII

NuPECC is an Associated Committee of the European Science Foundation

IMPACT AND APPLICATIONS OF NUCLEAR SCIENCE IN EUROPE:

Nuclear Astrophysics

M. Arnould (Convener)[1], P. Aguer[2], J. Cugnon[3], F. Käppeler[4], A.C. Mueller[5],
C. Rolfs[6], V. Schönfelder[7], K. Takahashi[8], B. Jonson (NuPECC Liaison)[9]

[1]Université Libre de Bruxelles, Belgium
[2]CSNSM, Orsay, France
[3]Université de Liège, Belgium
[4]Kernforschungszentrum Karlsruhe, Germany
[5]IPN, Orsay, France
[6]Ruhr-Universität Bochum, Germany
[7]MPE, Garching, Germany
[8]MPI für Astrophysik, Garching, Germany
[9]Chalmers University of Technology, Göteborg, Sweden

1. Introduction

Astrophysics, the union of astronomy and physics, applies physical laws investigated on earth to the vast and diverse laboratory of space. As such, it is essentially an interdisciplinary field. In particular, cosmology, every branch of astronomy, astronautics, elementary particle, nuclear, atomic and molecular physics, geo- and cosmochemistry have to bring their share to the common adventure of understanding the macro-structure of the Universe and of its various constituents. Very often, the macroscopic properties of those objects are derived from the micro-physics of the elementary particles or nuclei making up the matter.

This chapter deals with the very special interplay between nuclear physics and astrophysics that is embodied into a field commonly referred to as *Nuclear Astrophysics*. The pioneering works of Gamow, Bethe, Hoyle and others, as well as the famed article by Burbidge, Burbidge, Fowler and Hoyle [254] have set the bases of this field, which has advanced since that early epoch of research at a remarkable pace, and has in fact achieved such an impressive record of success that it is now widely recognised as a major keystone in modern physics and astrophysics (see e.g. [255] for a general account of the current situation). Factors contributing to these rapid developments include progress in experimental and theoretical nuclear physics, as well as in (ground-based or space) astronomical observations and astrophysical modelings. In spite of that success, major problems and puzzles remain, which challenge continuously the nuclear astrophysics concepts and findings. To put them on a safer footing requires in particular a deeper and more precise understanding of the many nuclear physics processes operating in the astrophysical environments. Therefore, the acquisition of new nuclear physics data has not to be seen as a fine tuning activity or a sort of cleaning-up work. It truly represents an essential and continuing step in the unravelling of many and highly diverse astrophysical phenomena.

Although initially motivated by astrophysics, some experimental and theoretical nuclear physics efforts have provided on many occasions unexpected intellectual rewards in nuclear physics itself. Thus, nuclear physics studies directed towards astrophysics have not to be seen in the reduced way of just a service activity to astrophysics, but instead as a mature and exciting field of its own.

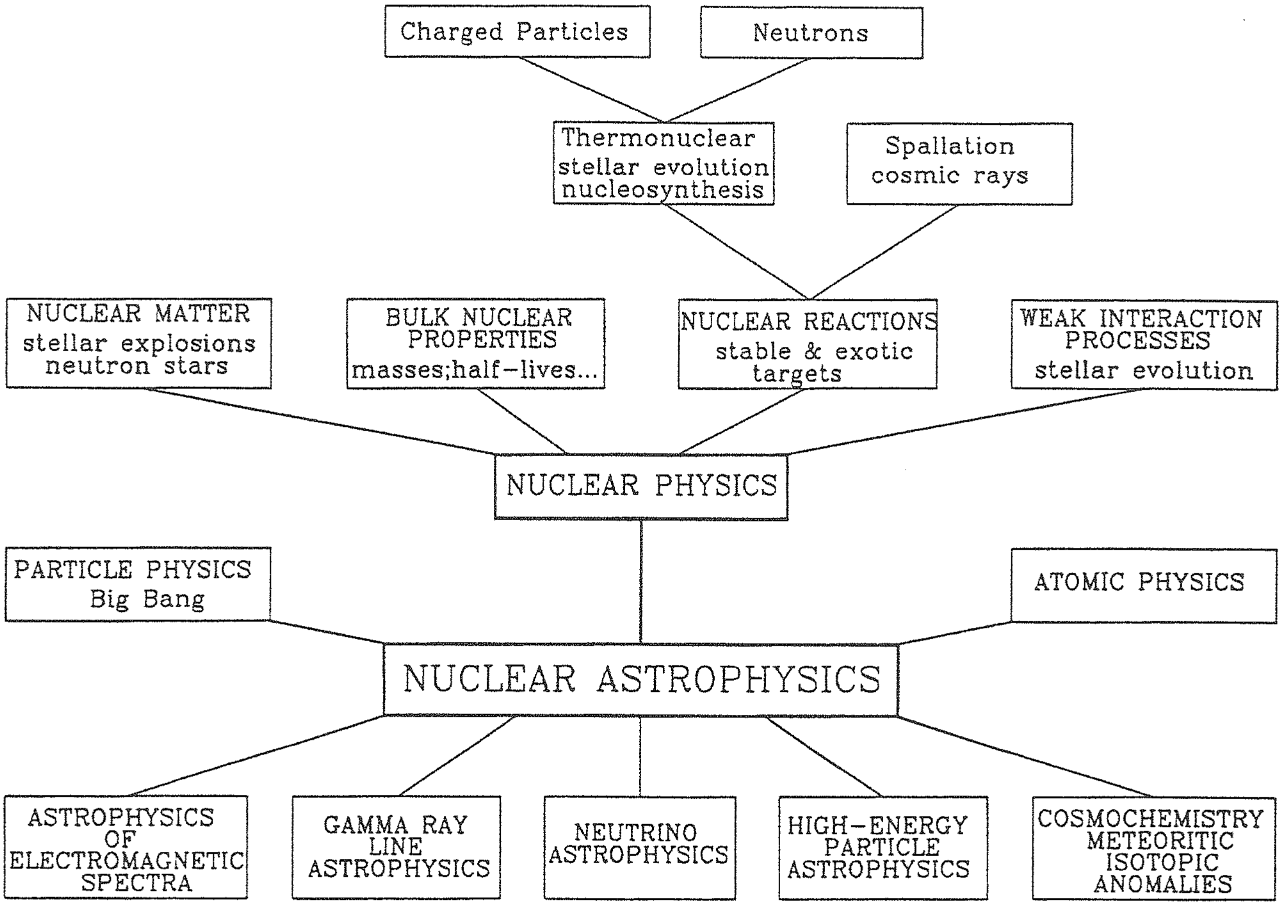

Figure 56: Diagramatic representation of possible connections of nuclear astrophysics with other major fields of physics, as well as with various main astrophysics subfields. Details about some of those connections are described in the main text.

As briefly schematised in Figure 56, the nuclear astrophysics quest is vastly interdisciplinary. It is in fact intimately connected with a large variety of different and complementary research fields that are essential in our understanding of a large diversity of classes of problems. It is impossible to discuss all of them in full detail here. This chapter will focus instead on a short discussion of the following questions:

- the role of nuclear reactions as a major source of energy in, and as a key to the evolution of a large variety of astrophysical objects
- the "nucleosynthesis" resulting from the operation of nuclear reactions that have started to take place at the cosmological level at the birth of the Universe (Big Bang), and have continued to operate in stars or in the interstellar medium since the beginning of the galaxies. As such, they are the key to the understanding of the observed surface composition of the stars, of the evolution of the nuclidic content of the galaxies, as well as of the composition of the solar system, to which much nuclear astrophysics effort is devoted[1]
- the description through an equation of state of the stellar matter, even in such extreme conditions as encountered in supernova explosions or in neutron stars
- the neutrino properties that can have impacts on the structure and characteristics of certain

---

[1] It has to be noted that the problem of the very origin of hydrogen is outside the realm of the nucleosynthesis models. It is instead a question which is addressed by astrophysicists and particle physicists building up „baryosynthesis" models

astrophysical objects, like supernovae or neutron stars.

The nuclear physics studies that are required in order to tackle these problems are of both experimental and theoretical nature, and concern by necessity an impressive variety of questions, some of them being reviewed in this chapter.[2]

2. Observational Foundation of Nuclear Astrophysics

Observationally, nuclear astrophysics relies on a large body of information that dramatically grows and also diversifies itself with time.

The most traditional source of information (referred to as the "astrophysics of the electromagnetic spectra" in Figure 56) consists of the analysis of the electromagnetic radiation at all wavelengths ranging from radiofrequencies to ultra-hard photons (up to the TeV and PeV domain) that originate from a large diversity of emitting locations (galaxies, interstellar medium, stars of various types, including exploding objects like supernovae), and possibly even from the early Universe. That unprecedented vision of the sky at all wavelengths results from recent progress in optical astronomy paralleled by the advent of a variety of "new" (especially infrared, UV, X, and γ-ray) astronomies, the dramatic advances of which are very often directly related to those of the space technologies (e.g. [256] for a general discussion).

Schematically speaking, the analysis of the electromagnetic radiation from astrophysical sites relates to nuclear astrophysics in two complementary ways. First of all, it provides the surface characteristics of stars that are necessary for the construction of the Hertzsprung-Russell diagram, generally considered as the "Rosetta stone" of stellar evolution. As such, that diagram and its specific topology directly relate to the production of nuclear energy in stars. Second, the electromagnetic radiation is the privileged (and often only) witness of the temporal evolution of the composition of the Universe and of its various constituents, and thus represents an essential source of information on the operation of nuclear reactions in astrophysical sites. Myriads of elemental and isotopic abundance data have been gathered. They range from the "traditional" information provided by the analysis of stellar spectra to the recent discovery of γ-ray line emission from the interstellar medium (esp. ^{26}Al) or from individual supernovae (esp. from the $^{56}\mathrm{Ni} \rightarrow {}^{56}\mathrm{Co} \rightarrow {}^{56}\mathrm{Fe}$ chain and from the $^{57}\mathrm{Co} \rightarrow {}^{57}\mathrm{Fe}$ decay emitted in the Large Magellanic Cloud supernova SN1987A; also from the ^{44}Ti decay in the young Cas-A supernova remnant). These abundance data 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 is the clearest and most direct demonstration of the operation of explosive nucleosynthesis processes. It is also worth mentioning that γ-rays from nuclear interactions of cosmic rays with the ambient interstellar matter have recently been identified in the Orion complex as γ-rays from $^{12}\mathrm{C}^*$ and $^{16}\mathrm{O}^*$.

Important data of relevance to nuclear astrophysics also come from the study of the very minute amount of the matter of the Universe accessible to man. That matter is comprised for its very largest part in the solar system itself (planets, meteorites). The rest is in the form of galactic cosmic rays, or of solar energetic particles.

The painstaking determination by a large body of cosmochemical studies (often made with the help of nuclear instrumentation) of the nuclidic composition of the material from which the solar system formed some $4.6 \cdot 10^9$ years ago, complemented with detailed evaluations of the composition of the solar surface, has clearly represented a milestone in the development of nuclear astrophysics. This relates directly to the fact that the solar system is by far the object in the Universe that provides the most complete set of high-quality abundance data, especially concerning isotopic compositions. The quality and completeness of those data have provided the demonstration that a close correlation exists between solar system abundances and nuclear properties. As a simple example, a nuclide is

---

[2] In view of the nature of the present chapter and of the limited space available for it, references will be made to a few textbooks, publications that have a review character, or to proceedings of recent conferences

observed to be more abundant than the neighbouring ones if it is nuclearly more stable. An intense nuclear astrophysics activity has been devoted to the unravelling of the details of the "alchemy" that has led to that nuclear imprint.

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. Those "isotopic anomalies" are identified in specific inclusions of "primitive" meteorites, as well as in grains that are very likely of circumstellar origin and have found their way into the meteorites. There is a very exciting connection between those discoveries and nuclear astrophysics, which tries to identify the nature of the stars that may be responsible for the production of the isotopically anomalous material. Some of the anomalies are identified as resulting from the decay within the solar system itself of radionuclides with periods in excess of about 10^5 yr. This is in particular the case for ^{26}Al. The possible presence of such radioactive nuclides has far reaching consequences for the understanding of the early solar system history, as well as for the nuclear astrophysical modelling of their stellar origins.

As for the galactic cosmic rays or solar energetic particles, much progress has been made in the knowledge of their elemental or isotopic compositions. Those accumulated data have had significant impact on our understanding of the possible sources of cosmic rays and of their composition. Concomitantly, they have triggered some nuclear astrophysics activities.

Finally, neutrino astrophysics, which has for years just been concerned with the famed solar neutrino puzzle, has entered a new era with the detection by the IMB and Kamiokande II collaborations of a neutrino burst from SN1987A. This remarkable observation seems to validate standard models of neutrino emission from supernovae. (e.g. [257]).

Clearly, progress in our understanding of the Universe and its constituents through the various astrophysical or cosmochemical approaches sketched above (and summarised in Figure 56) requires progress in a large variety of observational or experimental devices. In very many instances, it also goes through experimental and theoretical improvements in nuclear astrophysics, as briefly described in the following sections.

3. Nuclear Reactions in Astrophysics: Generalities

In astrophysics, the nuclear reactions of interest are of thermonuclear or "spallative" nature. The former ones have developed at the cosmological level (Big Bang), and continue to take place in stars. They are of pivotal importance for the stellar energy budget, as well as for the bulk composition of the galaxies and for the "peculiar" abundances observed at the surface of stars of certain classes. The spallation reactions act in low temperature and density media through the interaction of non-thermally accelerated particles with the interstellar medium, or with the material (gas or grains) at stellar surfaces or in circumstellar shells. A more specific example concerns the bombardment of the interplanetary material by solar energetic particles. Those reactions are responsible for the bulk galactic (and solar system) content of rare species (like Li, Be, B), as well as for the composition of stellar (solar) flares, or for the spallogenic components observed in solar system solid bodies. We will not deal here with spallation reactions, and will concentrate instead on some problems raised by thermonuclear reactions in astrophysical plasmas.

The thermonuclear reactions involved in astrophysical scenarios concern mainly the capture of nucleons or α-particles by stable, neutron-deficient or neutron-rich nuclides in the whole mass range. A limited number of fusion reactions involving light heavy ions (^{12}C, ^{16}O) are also of great importance. The rates of many of those reactions, even the ones involving stable targets, are still very uncertain at the energies of relevance to astrophysics, and their reliable knowledge clearly requires much dedicated experimental and theoretical work.

4. Thermonuclear Reactions in Non-Explosive Events

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 (e.g. [255]).

The energy region of "almost no events"

The experimental difficulties mentioned above relate directly to the fact that the energies of astrophysical interest for charged-particle induced reactions are much lower than the Coulomb barrier energies. As a consequence, the corresponding cross sections can dive into the nanobarn to picobarn abysses.

Thanks to their impressive skill and painstaking efforts, experimentalists 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 to reach the astrophysically relevant region of "almost no events" at experimentalists' timescales. Theoreticians are thus requested to supply reliable extrapolations from the experimental data obtained at the lowest possible energies.

Electron screening corrections

As if the problem of deriving 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. As a result, the situation appears even more intricate than previously imagined, necessitating a multistep process in order to go from laboratory data to stellar rates: before applying the usual electron screening corrections relevant to the stellar plasma conditions, it is indeed required to first 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 modelings that have already been dedicated to that question, 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 in certain regimes, and may impede an accurate enough treatment of some specific problems, as exemplified in the following section.

4.1 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 known as 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 (by a factor of about 3) than the one predicted by the solar modelings. That puzzle has led to a flurry of theoretical and experimental activities, and namely to three new neutrino detection collaborations (Kamiokande II, and the SAGE and GALLEX gallium detector experiments). The relative levels of "responsibility" of particle physics, nuclear physics or astrophysics in that discrepancy have also continued to be warmly debated. Detailed reviews have recently been devoted to all those questions (e.g. [258]). In what follows, we concentrate our discussion only on some questions that concern nuclear physics more 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. In spite of that, serious problems remain concerning the astrophysical rates of some of the involved reactions. This is especially the case for ^{7}Be(p,γ)^{8}B, which provides the main neutrino flux detectable by the chlorine detector, and the only one to which the Kamiokande experiment is sensitive. Traditionally, the experiments involve a hydrogen beam bombarding a ^{7}Be target. Recently, a Coulomb dissociation experiment (6.2) using a ^{8}B beam has been conducted, allowing to distinguish between conflicting experiments. More specifically, that experiment predicts a $^7Be(p,\gamma)^8B$ rate at solar energies that is consistent with the lower values measured most recently by the ^7Be target technique. It would be of prime interest to complement the cross section information derived up to now by experiments conducted with a radioactive ^7Be beam. Measurements at energies where the counting rate is still healthily large (e.g. 400 or 500 keV) could be sufficient as a first step in order to determine the possible extent of systematic errors in the ^7Be target experiments. Improved low-energy data are also required for a variety of reactions, like $^3He(^3He,2p)^4He$. They would also provide additional information on the laboratory electron screening question mentioned above. Since the present very low-energy measurements are predominantly hampered by the cosmic-ray background, improved data could be obtained by underground measurements. This is the aim of the installation of a 50 keV accelerator at the Gran Sasso laboratory within the pilot Italian-German project LUNA (Laboratory Underground for Nuclear Astrophysics).

Another nuclear physics activity that has an important bearing on the solar neutrino problem concerns the calibration through (p,n) reaction studies of the transition matrix elements involved in the rates of neutrino captures to excited states of ^{71}Ge, which are responsible for the largest uncertainties in the SAGE and GALLEX gallium experiments. Much more experimental and theoretical work is required on the relation between (p,n) cross sections and weak-interaction matrix elements in order to reduce those uncertainties.

4.2 Non-Explosive Stellar Evolution and Related Nucleosynthesis

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 a broad range of values (essentially between about 1 $M_\odot$ and 100 $M_\odot$, as well as of the concomitant nucleosynthesis.

In short, 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 and lead to composition changes. In massive enough stars ($M \gtrsim 8\ M_\odot$), the time sequence of nuclear stages comprises fuels (H, He, C, Ne, O and Si) with increasing charge number Z that burn as temperatures increase from several 10^6 K to roughly $4 \cdot 10^9$ K. Correspondingly, the duration of the successive nuclear burning phases decreases dramatically. In fact, all those general trends are quite intimately correlated. It has also to be noted 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. Less massive stars ($M \lesssim 8\ M_\odot$) do not experience the full sequence of burning phases, their nuclear history ending after completion of central He burning.

If a star can experience Si burning, it is expected to develop an iron core that is lacking further nuclear fuels. This situation may lead through a very complex chain of physical events to a catastrophic supernova explosion.

Hydrogen burning

In addition to the p-p chains that operate in solar-type stars (4.1), energy production by hydrogen burning can also occur non-explosively through the "cold" CNO cycle. Some hydrogen can also be consumed by the NeNa and MgAl chains. These burning modes most likely play only a minor role in the stellar energy budget. In contrast, they are of significance in the production of the Na to Al isotopes, especially in massive stars. Most important, the MgAl chain might synthesise ^{26}Al, which is a very interesting radionuclide for γ-ray astronomy and cosmochemistry.

Much experimental and theoretical effort has been devoted recently to various key reactions involved in those burning modes. In spite of that, many uncertainties remain. As an example, the $^{17}O(p,\alpha)^{14}N$ reaction rate is still very poorly known, which hampers any detailed confrontation between predictions and observational data concerning the oxygen isotopic composition at the surface of certain stars.

Helium burning and the s-process

The main reactions involved in the He burning stage have been discussed in many places. Of very special and dramatic importance for the theories of stellar evolution and of nucleosynthesis is the reaction $^{12}C(\alpha,\gamma)^{16}O$, which has been the subject of a recent flurry of experimental investigations (6.2), as well as theoretical efforts (8.1; 8.3). In spite of that, the remaining uncertainties preclude certain nuclear astrophysics predictions to be made at a satisfactory level.

Other α-particle induced reactions are of special importance, and have been the subject of recent dedicated experimental and theoretical work. This is in particular the case for $^{13}C(\alpha,n)^{16}O$ and $^{22}Ne(\alpha,n)^{25}Mg$. These reactions are considered as the main neutron sources for the s-process nucleosynthesis, which is called for in order to account for the existence of the stable nuclides heavier than iron that are located at the bottom of the valley of nuclear stability, as well as of some lighter stable species. In spite of much experimental effort, a further reduction of the remaining uncertainties would be highly desirable. With the present technology, and as in the case of the reactions involved in the p-p chains (4.1), that could be achieved only through a reduction of the cosmic background.

The proper treatment of the s-process also requires the knowledge of a host of neutron capture cross sections at typical energies in the $10 \lesssim kT \lesssim 100$ 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 is especially the case when unstable targets close to the valley of nuclear stability are involved, for which experiments are eagerly awaited (7). In these cases, the knowledge of the neutron capture cross sections has of course to be complemented by the astrophysical rates of the competing β-decays. The evaluation of those rates raises some complication (9.1). It has also to be emphasised that a special β-decay mechanism, referred to as bound-state β-decay, could also come into play for ionised atoms, and could significantly affect the production of some specific s-nuclides (9.1).

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 $^{12}C + {}^{12}C$ fusion cross section at low energies. The experimental and theoretical work that has already been devoted to that question does not provide fully satisfactory solutions.

Neon, oxygen, and silicon burning

The neon burning phase is initiated by $^{20}Ne(\gamma,\alpha)^{16}O$. The rate of the inverse $^{16}O(\alpha,\gamma)^{20}Ne$ reaction that is used in order to evaluate the ^{20}Ne photodisintegration rate through the detailed balance has recently been examined both experimentally, and in the framework of a microscopic model (8.1). A microscopic three-cluster model has also been used to study the $^{20}Ne(\alpha,\gamma)^{24}Mg$ reaction, but it fails to reproduce an astrophysically important resonance in ^{24}Mg.

The $^{16}O + {}^{16}O$ fusion reaction that governs the oxygen burning phase does not exhibit intricacies comparable to those encountered with the $^{12}C + {}^{12}C$ system. Yet, much has still to be learned about heavy-ion reaction mechanisms at low energy, and about the way to extrapolate the yields to astrophysically interesting energy regions.

Silicon burning comprises a very complex pattern of nuclear reactions, and evolves into a nuclear statistical equilibrium regime when the remaining Si has sufficiently low abundances. Much effort has been devoted over the years to the measurement of α- or p-capture rates of interest in that burning phase. This experimental work is also important for evaluating the virtues of statistical model calculations (8.4) that have to be used in order to calculate the host of unmeasured reaction rates involved in the Si burning modelling.

5. Thermonuclear Reactions in Explosive Events

In stellar (nova, 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 those 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 problem gets even more complicated as the targets can exist in excited states in the very hot explosive environments. In such conditions, a large resort to theory is mandatory in order to predict reaction rates, even in the case of stable (in their ground state) targets.

5.1 Big Bang Nucleosynthesis

As reviewed recently in great detail [259], dedicated experimental and theoretical efforts have been devoted to the determination of the rates of the reactions involved in the standard Big Bang nucleosynthesis model. They 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.

It has been proposed recently that deviations from the standard model could have existed in the form of inhomogeneities in the hadronic matter at the epoch of Big Bang nucleosynthesis. That speculation has raised much excitement, particularly in view of its cosmological, astrophysical and compositional consequences. In order to be able to evaluate the latter as reliably as possible, much experimental and theoretical effort has been devoted to some reactions identified as keys, or at least as being able to play a role, in the inhomogeneous Big Bang nuclear flows. Some of them, like (d,n) or (t,n), are not encountered at the stellar level, and most of them involve unstable nuclei in the entrance channel.

A remarkable example of such a reaction is provided by ^{8}Li(α,n)^{11}B, which has been studied in the framework of a microscopic model (8.1) before being investigated experimentally through various direct or indirect methods (6). Much nuclear physics effort has also been directed towards the reactions that could lead to the cosmological synthesis of ^{9}Be. A reliable evaluation of that production can indeed provide stringent tests of the validity of the inhomogeneous Big Bang model through a confrontation with the measured abundances of that nuclide at the surface of very old stars. Such measurements have started recently.

The interest of pursuing specific nuclear studies of importance for the inhomogeneous Big Bang clearly depends on the outcome of the investigations concerning in particular the very nature of the transition from unconfined quark-gluon plasma to normal hadronic matter, which is a critical component of the scenario. In fact, the envisioned inhomogeneous Big Bang can be valid only if that transition was first order. While the early predictions from finite-temperature Monte-Carlo lattice QCD calculations seemed to support this possibility, the most recent results from dedicated special purpose machines are by far less optimistic, even if they cannot entirely rule out the possibility of a weakly first-order transition (e.g. [260]).

In any case, it has to be stressed that the strong interplay between nuclear physics and the Big Bang models is not limited to the question of the composition of the early galaxies. It also has many far-reaching astrophysical and cosmological implications. They concern the possible existence of baryonic dark matter and of non-baryonic (exotic) matter. They also relate to constraints imposed on the physics of new particles, on the leptonic number of the Universe, on the cosmic entropy increase since the Big Bang nucleosynthesis era, and even on the constancy of the "constants" of physics (e.g. [260]).

5.2 The Hot Modes of Hydrogen Burning

While hydrogen burns through "cold" modes in non-explosive stellar situations, it can be destroyed in various astrophysical events of explosive nature by "hot" burning modes involving a large variety of unstable nuclei.

The hot p-p mode

This mode 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. Several of the corresponding rates have recently been scrutinised both theoretically and through indirect experimental techniques (6.2). Let us note in particular that the $^{11}C(p,\gamma)^{12}N$ rate has been measured recently through a Coulomb break-up experiment (6.2), the results of which differ quite substantially from the predictions of a microscopic model. Such a model has also been used to predict the rate of $^{8}B(p,\gamma)^{9}C$, which can also be of astrophysical importance.

The hot CNO and NeNa-MgAl chains

A major change in the cold CNO cycle occurs when $^{13}N(p,\gamma)^{14}O$ becomes faster than the ^{13}N β-decay. In such a case, a hot CNO cycle is initiated. The cold NeNa and MgAl chains of reactions could also switch into a hot mode for temperatures that appear to be quite similar to the operating conditions for the hot CNO chain. In fact, novae could be favourable sites for the development of both the hot CNO and NeNa-MgAl chains.

Many reactions on unstable nuclei are involved in those burning modes. Much theoretical and experimental effort has been devoted to a reliable determination of the astrophysical 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. They are rather evaluated from experimental spectroscopic information on individual level properties, this approach leading to some inherent uncertainties. There are, however, some noticeable exceptions to this situation. In particular, the resonant contribution to the $^{13}N(p,\gamma)^{14}O$ rate has been measured *directly* at the Belgian Radioactive Ion Beam facility (6.1). This represents a major breakthrough in experimental nuclear astrophysics. The data obtained in such a way are in agreement with very interesting indirect measurements using the Coulomb break-up technique (6.2), as well as with predictions based on a microscopic model (8.1). These data have been complemented recently with the evaluation of the non-resonant direct capture contribution to the $^{13}N(p,\gamma)\ ^{14}O$ rate based on the investigation of the $^{13}N(d,n)^{14}O$ excitation function. The astrophysical consequences of those measurements have been analysed in detail. From this, it can be concluded that our knowledge of the $^{13}N(p,\gamma)^{14}O$ rate is now good enough for practical astrophysical purposes.

Other examples of directly measured rates concern the proton captures by the relatively long-lived and astrophysically very interesting ^{22}Na and $^{26}Al^{g}$ radionuclides. In fact, the experimental investigation of the rates of $^{22}Na(p,\gamma)^{23}Mg$ and $^{26}Al^{g}(p,\gamma)^{27}Si$ provides a very interesting illustration of the use of the radioactive target technique (6.1). The direct experiments on $^{22}Na(p,\gamma)^{23}Mg$ and on $^{26}Al^{g}(p,\gamma)^{27}Si$ have been complemented by an indirect search for low-lying resonances using the $^{22}Na(^{3}He,d)^{23}Mg$ and $^{26}Al^{g}(^{3}He,d)^{27}Si$ reactions, respectively.

Those 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 and the one prevailing in the mid-eighties. Note that large uncertainties still remain in the $^{26}Al^{g}(p,\gamma)^{27}Si$ 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. On the other hand, in conditions where the ^{26}Al^{m} isomeric state can be thermally populated to a significant level, the contribution of the proton capture by ^{26}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 (8.4). Its direct experimental determination would require the development of a ^{26}Al^{m} beam, which obviously represents an interesting technological challenge.

rp- and αp-processes

The hot CNO and NeNa-MgAl modes can transform into the so-called rp- or αp-processes especially when ^{15}O(α,γ)^{19} Ne or ^{14}O(α,p)^{17}F become faster than the corresponding β-decays. This could occur in certain Type I supernovae, or in X-ray bursts 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 (p,γ), (γ,p), and β^+-decays. This chain of transformations has been termed the rp-process. It could transform into an αp-process at temperatures that are high enough for (α,p) reactions to play a leading role.

A host of reactions on unstable neutron-deficient nuclei up to the iron region are involved in the rp- or αp-process, some of them already partaking in the hot CNO and NeNa-MgAl chains. A direct measurement of a significant fraction of all those potentially important reactions is difficult. In fact, much of what is known on reaction rates involved in the rp-process results from indirect nuclear spectroscopy, or from the use of a global statistical model (8.4), which appears to be adequate except for low Q-value reactions implying relatively low nuclear level densities.

Here, we just want to comment on the key ^{15}O(α,γ)^{19}Ne(p,γ)^{20}Na reaction chain, which can be responsible for a leakage out of the CNO region to higher masses. The ^{19}Ne(p,γ)^{20}Na reaction has been recently, and still is, the subject of a flurry of activity. The experimental investigations aim at improving the knowledge of the ^{20}Na level structure above the ^{19}Ne + p threshold through the use of various indirect methods, like (^{3}He,t) or (p,n) reactions on ^{20}Ne, or β-decay of ^{20}Mg. The availability of a ^{19}Ne beam at the Belgian Radioactive Ion Beam facility opens up new possibilities to investigate in detail the spectroscopy of ^{20}Na. The use of such a beam may even make the direct measurement of the ^{19}Ne(p,γ)^{20}Na rate feasible in the near future. Some theoretical work has also been devoted to that reaction.

In spite of the experiments and calculations dedicated to ^{19}Ne(p,γ)^{20}Na, its rate remains uncertain. The same is true for the ^{15}O(α,γ)^{19}Ne rate, even if it is sometimes claimed that it is "fairly well understood", or just "uncertain by approximately a factor of 2" for temperatures $T \leq 5 \cdot 10^8$ K. In reality, that rate, determined through indirect techniques, is still quite uncertain at various temperatures of interest.

Irrespective of the uncertainties remaining in both the ^{19}Ne(p,γ)^{20}Na and ^{15}O(α,γ)^{19}Ne rates, it is most likely that the latter transformation is slower than the former and thus really constitutes the crucial breakout path from the hot CNO to the rp-process. A more reliable determination of that α-capture rate would be most welcome, and might have to await a direct measurement requesting the challenging development of a suitable ^{15}O radioactive beam combined with an appropriate detection device.

5.3 The α-Process and the r-Process

In contrast to the s-process (4.2), the r-process, which shares the responsibility of synthesising the vast majority of the elements heavier than iron, requires a very high neutron density of about $10^{20\text{-}30}$ per cm^3. Therefore, the search for its astrophysical sites has been conducted in relation to some explosive (or catastrophic) events. Supernovae are by far the most commonly envisioned sites, but other more or less exotic scenarios have also been proposed.

In accordance with the recent development in supernova models, an interesting possibility for the r-process has been raised in connection with the so-called "hot bubble" region in Type II supernovae. It is a rapidly expanding region of high temperature and low density that is created just outside of the nascent neutron star through the energy deposition by (anti-) neutrinos streaming out from the central region of the star. Under such conditions, the major constituents become essentially α-particles and neutrons as the temperature goes down below 10^{10} K. The key reaction chain converting these particles into heavy nuclides as matter cools further is $\alpha\alpha n \rightarrow {}^{9}\mathrm{Be}(\alpha,n)^{12}\mathrm{C}$, which is followed by the dominant sequence of reactions: $^{12}\mathrm{C}(n,\gamma)^{13}\mathrm{C}(\alpha,n)^{16}\mathrm{O}(\alpha,\gamma)^{20}\mathrm{Ne}$. This kind of build-up of heavy nuclides via a series of (mostly α-capture) reactions up to, or often beyond, the iron-group elements is now referred to as the α-process. If enough neutrons are left at the freeze-out of the α-process (at about $2 \cdot 10^9$ K), the r-process may start. The numerical simulations of the hydrodynamical evolution and the accompanied nucleosynthesis have recently been performed, demonstrating the attractive feature of that r-process scenario.

A major nuclear uncertainty concerning the α-process appears to have been removed by recent $^{9}\mathrm{Be}(\alpha,n)^{12}\mathrm{C}$ experiments. However, more reliable cross sections for many α-captures by intermediate to heavy mass nuclides remain to be supplied. The r-process modelling is also suffering from many nuclear uncertainties concerning in particular the masses of β-decay half-lives of very neutron-rich nuclei (9.1), as well as their neutron capture rates (7).

It has also to be emphasised that a reliable prediction of the very occurrence of the α- and r-processes, and of the precise astrophysical conditions under which they could possibly develop are still hampered by many uncertainties, like the neutrino properties or the equation of state of the supernova core (9.3).

5.4 The p-Process

It seems now astrophysically plausible that the production of the stable neutron-deficient isotopes of the elements with charge number $Z \geq 34$ (classically referred to as the p-nuclei) occurs in the oxygen/neon layers of highly evolved massive stars during their pre-supernova phase or during their explosion. At the temperatures of about $2\text{-}3 \cdot 10^9$ K that can be reached in those layers, the p-nuclei may be synthesised by the (γ,n) photodisintegrations of pre-existing more neutron-rich species (especially s-nuclei), possibly followed by cascades of (γ,p) and/or (γ,α) reactions. It has also been proposed that those nuclear transformations could take place in the C-rich zone of Type Ia supernovae as well. This alternative model remains, however, to be scrutinised on grounds of more realistic explosion models, particularly with regard to the p-process seed abundance distribution.

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 in a few cases, no experimental data are available, and resort is classically made to statistical model predictions (8.4).

6. Charged-Particle Induced Reactions: Experiments

The previous sections have already made it clear that much dedicated and heroic effort has been devoted to the measurement of the rates of a wealth of astrophysically important 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 astrophysically relevant data and the vast diversity of the problems to be tackled have always made it necessary 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 accelerators delivering energies in the few keV range to high-energy heavy-ion accelerators.

As stressed in Sects. 4 and 5, 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 implied 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.

Various experimental nuclear physics techniques, which can be classified into "direct" and "indirect" methods, have been used in order to obtain astrophysically relevant reaction rates.

6.1 Direct Cross Section Measurements

Direct measurements concern the reactions that really take place in stellar sites. Strictly speaking, they would also have to be conducted at the stellar energies, which is very seldom the case, as emphasised previously, especially in non-explosive situations.

Direct methods have been widely utilised in the case of stable targets. 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 quite common 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 are generally the same as those used in classical nuclear physics. However, some new detector types have been developed specifically for nuclear astrophysics experiments.

It has to be emphasised 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 at lower and lower energies. As the cosmic-ray background may become a deterrent limiting factor, underground experiments have been planned. As an example, a 50 keV accelerator has been installed recently in the Gran Sasso Laboratory.

In the case of unstable targets, two different direct approaches are envisioned, depending upon the lifetimes of the nuclides involved. (e.g. [255], [261]). Whereas the radioactive target technique appears most profitable for radionuclides with lifetimes in excess of about one hour and has already been applied to reactions involving ^{22}Na and ^{26}Al (5.2), 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. As discussed in great detail recently, two basic techniques can be used to produce the necessary high-intensity radioactive beams: the ISOL post-accelerator scheme, and the projectile fragmentation method. Examples of the pioneering application of those techniques are presented below. Projects exist in various countries to upgrade existing radioactive ion beam facilities, or to build new ones.

ISOL post-acceleration experiments

The first direct and successful measurement of a capture reaction using the ISOL post-acceleration scheme has been carried out on ^{13}N(p,γ)^{14}O at the Belgian national facility of Louvain-la-Neuve thanks to a pure and intense ($\approx 10^8$ pps) ^{13}N ion beam impinging on a hydrogen-plastic-foil target. The capture γ-rays have been observed with efficient Ge detectors. More recently, a ^{19}Ne beam has been developed in order to study the ^{19}Ne(p,γ)^{20}Na reaction of astrophysical interest through the measurement of the characteristics of the ^{20}Na decay. In addition, elastic scattering data have been obtained through the use of an array of large solid angle detectors.

Quite clearly, the ISOL post-acceleration technique for direct rate measurements has a bright future, and many efforts will likely be put in its development. As an illustration, let us mention the

SPIRAL facility that will become available at GANIL, even if the energies that will be delivered appear to be higher than those required for direct cross section measurements (cf. 9.1).

Fragmentation technique

A very interesting alternative and complement to experiments based on the ISOL method discussed above is to directly use medium-energy or relativistic radioactive ion beams for projectile fragmentation.

In this approach, the secondary beam particles have roughly the same velocity and direction as the primary beam. These attractive features have been used initially at Berkeley, and then at GANIL, RIKEN, MSU and GSI.

The projectile fragmentation technique has, for example, been adopted recently at RIKEN to measure the cross section of the ^{8}Li(α,n) ^{11}B reaction of interest in inhomogeneous Big Bang models (5.1). Only data at energies (> 1.5 MeV) exceeding slightly those of direct astrophysical relevance have been obtained in a first experiment. Further efforts have made possible the measurement of the cross section at the energies (around 0.75 MeV) characteristic of the Big Bang nucleosynthesis.

6.2 Indirect Cross Section Measurements

The indirect methods have been shown to be a very important complement, or even an inevitable alternative, to the direct measurements concerning reactions on stable as well as unstable targets, and will certainly continue to play a leading role in the future (e.g. [255], [261]). This situation relates in particular to the extreme smallness of the cross sections of astrophysical interest, or to the impossibility 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 (i) the use of transfer reactions; (ii) the study of the inverse reactions, a special aspect of this technique being the Coulomb break-up viewed as a radiative capture under the operation of time reversal; or (iii) measurements relating to the decay of radioactive beams. The consideration of knock-out reactions has also been envisioned.

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 those of astrophysical interest may fail completely. 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.

For example, the cross section of the reaction $A + p \to X$ proceeding through a resonating level is connected to the cross section of the reaction $A + {}^3He \to X + d$ since a proton has been transferred to nucleus A in both cases. The energy of the outgoing deuteron provides the energy of the resonating level, and a DWBA analysis can relate, within some uncertainty, a spectroscopic factor to the proton width. The same method can be applied to α-transfer [e.g. (α,γ)] reactions, but raises serious theoretical problems.

Sometimes, transfer reactions are the only way for obtaining experimental information on levels of astrophysical relevance, and have thus been widely used. They require 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.

Inverse reactions: The example of the Coulomb break-up

Direct experiments carried out on radiative captures require the observation of very low γ-ray yields in the presence of intense backgrounds. This problem can become insurmountable in experiments with radioactive beams. For 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 A(b,γ)X reaction cross section, experiments can be conducted on the inverse X(γ,b)A reaction. The γ-flux is provided by the virtual photons of the Coulomb field, which are seen by a high-energy nucleus X when passing at a suitable distance from a heavy target. This Coulomb break-up technique has the advantage that the cross section of the heavy-target break-up by the Coulomb field is larger than that 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 of MeV/u).

That method has been successfully applied to ^{4}He(d,γ)^{6}Li with a ^{6}Li beam of 26 MeV/u, and to ^{4}He(t,γ)^{7}Li. With radioactive beams produced by the fragmentation of energetic heavy-ions beams (~100 MeV/u), the Coulomb break-up of ^{14}O, ^{12}N and ^{8}B has been used to study the reactions ^{13}N(p,γ)^{14}O (5.2), ^{11}C(p,γ)^{12}N (5.2), and ^{7}Be(p,γ)^{8}B (4.1).

The decay of radioactive beams

In certain cases, radioactive decay studies may offer an interesting alternative to transfer reactions for exploring nuclear levels of astrophysical importance. For example, a recent experiment with LISE-III at GANIL has produced a clean radioactive beam of the proton drip-line isotope ^{20}Mg which was subsequently implanted into a highly efficient system for the detection of the β-p and β-γ coincidences from the radioactive decay. Indeed, the ^{20}Mg β^+-decay populates excited states in ^{20}Na which decay through γ-radiation or, above threshold, through proton emission. Thus, such an experiment becomes part of the investigation of the ^{19}Ne(p,γ)^{20}Na break-out reaction from the hot CNO cycle (5.2), which critically depends on the poorly understood states of ^{20}Na.

Similarly, the key ^{12}C(α,γ)^{16}O reaction has been investigated recently at the TISOL facility at TRIUMF and at the MSU-NSCL through the β-delayed α-emission from ^{16}N.

The availability of other clean radioactive beams and the benefits from detector developments for charged particle and photon detection will certainly warrant further studies along these lines.

7. Neutron Capture Reactions: Experimental Approaches

Neutron captures or reverse (γ,n) photodisintegrations are essential reactions in the s-, r- and p-processes of nucleosynthesis.

The measurement of (n,γ) cross sections at relevant stellar energies requires the detection of the prompt capture γ-rays in combination with a time-of-flight technique for neutron energy determination. Though that technique is always applicable, it suffers from certain limitations due 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 set-up is provided by the 4π BaF_2 detector at the Karlsruhe Van de Graaff. In this case, neutrons are produced via the ^{7}Li(p,n)^{7}Be reaction in exactly the energy range of interest (1 to 250 keV). Since 4π detectors can be operated as calorimeters with well-defined efficiency, they allow for an accuracy of ~1% for the Maxwellian-averaged cross sections 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 normalisation's that are 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.

Neutrons in the keV range can be produced with even larger intensities at electron linear accelerators via (γ,n) reactions using electron beams of typically 50 MeV. A further increase in energy is obtained by spallation reactions from intense proton beams of ~1 GeV energy. Among other differences, all these neutron sources exhibit a moderated spectrum ranging from thermal energies beyond the energy of the bombarding particle beam, giving rise to different experimental conditions, in contrast to the situation encountered with electrostatic accelerators. Hence, the different neutron sources show complementary features for the measurement of stellar cross sections.

When neutron capture leads to an unstable nucleus, the activation technique can serve as an alternative method for measuring stellar (n,γ) cross sections. This possibility results from the fact that the ^{7}Li(p,n)^{7}Be reaction can be used to produce almost exactly the neutron spectrum required to determine the proper Maxwellian-averaged cross sections in typical helium burning conditions. On the other hand, 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 $\approx 10^6$ 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. Big Bang nucleosynthesis), 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.

In principle, the restriction of the activation technique to cases in which neutron capture produces an unstable isotope could be overcome by analysing the irradiated samples via accelerator mass spectroscopy. However, this technique requires extremely pure samples.

Experimental neutron capture cross sections are now available for more than 90% of the (≈240) stable nuclides involved in the s-process. In 15% of those cases, the obtained accuracy is better than ± 4%. These data have been complemented with the measurements of the relatively small (n,γ) cross sections on various stable isotopes of C and N, as well as of some (n,p) and (n,α) rates. Further improvement is called for, particularly concerning neutron capture cross sections on the unstable nuclides that can be involved in the s-process. Such experimental data are now largely missing.

Of course, the knowledge of the rate of the neutron captures or (γ,n) reactions 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 modelings come almost exclusively from calculations. Even if 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 (8.4).

8. Thermonuclear Reaction Rates: Models

In a variety of astrophysical situations, and especially during the hydrostatic burning stages of stars (4), charged-particle induced reactions proceed at such low energies that a cross section measurement is often not possible with existing techniques. Hence extrapolations down to the stellar energies of the cross sections measured at energies where a reaction can be studied in the laboratory are the usually necessary procedures. To be trustworthy, such extrapolations should have a strong theoretical foundation. Theory is even more mandatory when excited nuclei are involved in the entrance channel, or when unstable very neutron-rich or neutron-deficient nuclides (some 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 (5).

Various models have been developed in order to complement the experimental information when necessary (e.g. [262]). Broadly speaking, they can be divided into “non-statistical” (8.1 – 8.3) and “statistical” (8.4) models appropriate to systems involving, respectively, low and high densities of participating nuclear levels.

8.1 Microscopic Models

In recent years, the *microscopic cluster model*, based on a first-principle approach, has become an established tool to perform the necessary extrapolations mentioned above.

In that model, the nucleons are grouped into clusters. Keeping the internal cluster degrees of freedom fixed, the totally antisymmetrised 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.

In spite of its virtues, the microscopic cluster model cannot, in general, reproduce available experimental data as accurately as often desired for the extrapolation of astrophysically important reactions. A higher level of reliability of the 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.

The microscopic cluster model has been applied to many astrophysically important reactions involving light systems, and in particular to all the reactions of the p-p chains (but the p + p reaction itself). In all those cases, the available experimental data have been nicely reproduced. This remarkable success gives some confidence in the extrapolation to the energies of astrophysical (solar) interest. Various reactions of key importance for the inhomogeneous Big Bang model or for the hot CNO cycle have also been studied within the microscopic cluster model. As highlights, these calculations have made *predictions* for the Big Bang reactions ^{8}Li(α,n)^{11}B and t(α,γ)^{7}Li that have subsequently been verified by experiments.

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(α,γ)^{16}O reaction rate.

8.2 The Potential Model

The potential model has been known for a long time to be a useful tool in nuclear astrophysics. It assumes that the physically important degrees of freedom are the relative motion between the (structureless) 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.

Based on these principles, the Distorted Wave Born Approximation (DWBA) has become the standard model to describe nuclear transfer reactions. Recently, that model has been more specifically adapted to astrophysics requirements. It is based on an effective nucleon-nucleon interaction folded with the nuclear densities of the collision partners, the overall strength of the nucleus-nucleus potentials being adjusted in order to reproduce experimental data. That approach has been successfully applied to astrophysically important (p,α) or (p,d) reactions.

The potential model might also be applied to radiative captures if the scattering states in the entrance channel and the final bound states are well approximated by the same nuclear fragmentation. This is the case for several astrophysically important radiative captures by light nuclei [e.g. ^{3}He(α,γ)^{7}Be] which have recently been studied successfully.

8.3 Parameter Fits

Reaction rate data dominated by the contributions from a few resonant or bound states are often extrapolated in terms of R-matrix 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 parametrisation of the data can be derived from underlying formal reaction theories. The parameter values can be obtained from experimentally measured properties of the identified levels, or from best fits to relevant data (cross sections, phase shifts, etc.). Both methods lack, however, a rigorous way of parametrising possible non-resonant (background) contributions.

In recent years it has become apparent that the two methods differ quite considerably in their predicted extrapolations for at least the astrophysically very important ^{12}C(α,γ)^{16}O reaction. The resolution of that discrepancy is currently the subject of much theoretical research.

8.4 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 model has been widely used with considerable success.

It is felt, however, that the reliability of such a model has yet to be improved, especially for its extrapolations to highly β-unstable nuclei. This particularly concerns the evaluation of nuclear level densities which generally adopts an extrapolation of the empirical values by using the "backshifted" Fermi-gas model.

9. Other Nuclear Properties of Astrophysical Interest

The astrophysical importance of nuclear properties other than nuclear reaction rates is vividly illustrated by the s-, r- and p-processes of production of the stable nuclides heavier than iron, by the dynamics and composition of the innermost regions of pre-supernovae or supernovae, and by the structure of cooling or cold neutron stars.

9.1 Nuclear Masses and Half-Lives

As already emphasised in Sects. 5.3 and 5.4, the r- and p-processes involve very neutron-rich or neutron-deficient nuclides. No wonder then that, on top of uncertainties of purely astrophysical nature, their modelling suffers greatly from many nuclear physics uncertainties. Aside from those related to a wealth of nucleon or α-particle capture rates, they concern various nuclear properties, like masses or β-decay properties for, in principle, thousands of nuclei. This is especially acute for the r-process.

The precise evaluation of the rates of β-decays that can compete with neutron captures also raises some difficulties in the s-process, even if, in contrast to the r- and p-processes, it concerns only nuclides close to stability. This comes about because transitions from thermally-populated nuclear excited states can contribute to the β-decay rates in stellar conditions. In general (except in the case of isomeric states), that contribution cannot be measured, and the complexity of the nuclear structure makes the prediction of the required β-decay matrix elements a real challenge for nuclear theory.

In all cases, it is hoped that more reliable experimental and theoretical data on masses and half-lives may help illuminating the astrophysical conditions of development of the s-, p- and r-process.

Masses and half-lives of nuclei far off stability: experimental situation

An exhaustive experimental study of those quantities is completely out of reach with the present experimental tools, and many nuclides of interest for the r-process will not be produced in the laboratory in the foreseeable future. It may be hoped, however, that experimental efforts focused on certain key nuclides, and in particular magic or near-magic neutron-rich nuclei, may be of great help to improve the reliability of the nuclear models, and, at the same time, benefit greatly to nuclear astrophysics. It is in fact interesting to note that the same nuclei are of special importance to nuclear physics and astrophysics, which stresses once again the privileged interconnection between those two fields of research.

Impressive progress has been made recently in the experimental study of nuclei very far off stability that are of relevance for example to the rp- or r-processes. In particular, the development of the target technology at CERN-ISOLDE along with the use of a highly efficient neutron detection by means of a (paraffin-moderated) long-counter has made possible the study of the β-delayed neutron decay of the very neutron-rich nuclei ^{79}Cu and ^{130}Cd. These are the rare cases in which experiments have reached the region of an r-process path on the chart of nuclides that is most preferable for describing the solar r-process abundance curve, and thus greatly help reducing nuclear physics uncertainties in r-process calculations.

Another milestone has been the availability of high-intensity (up to 10^{12} pps) isotopically enriched heavy-ion beams at GANIL and, subsequently, at the MSU-NSCL. The projectile fragmentation of such beams has allowed the production of new exotic species. The spectrometer LISE-III at GANIL uses a combination of magnetic rigidity selection, energy-loss separation and a Wien-type velocity filter to single out the nuclei under investigation. This in-flight separation technique is extremely fast (< 0.5 μs), and also allows an unambiguous event-by-event identification. The combined use of LISE and of the neutron counter developed at ISOLDE has in particular made possible the measurement of the β-decay properties of the astrophysically interesting isotopes ^{44}S, and $^{45-47}$Cl.

Important measurements have also been able to provide the β-decay half-lives of neutron-rich Fe, Co, Ni and Cu isotopes of r-process interest produced in neutron-induced fission at the Grenoble ILL high-flux reactor, and via relativistic heavy-ion projectile fragmentation at the new SIS-FRS facility at GSI.

On the proton-rich side, experiments at MSU have enabled locating the proton drip-line in the As region and measuring the β-half-lives of the corresponding exotic nuclei.

The examples cited above underline the activity of the field, and further progress in decay studies may certainly be expected in the near future, thanks to projectile-fragment separators and the new ISOLDE PS-Booster. Significant advances are also most likely in direct mass measurements of nuclei far from stability. The Penning trap and (for the shortest-lived isotopes) the radio-frequency mass-spectrometer at ISOLDE, the SISSI upgrade at GANIL, and the storage ring ESR at GSI should all start measurements in a near future.

In the future, the availability of post-accelerated radioactive beams is expected to provide new experimental possibilities for the study of nuclei far from stability (e.g. [261]). Along these lines, a first European facility, SPIRAL, is presently under construction at GANIL (6.1).

Finally, it has to be noted that a very interesting experiment has been conducted on a quite exotic β-decay mode of a non-exotic nucleus. More specifically, bound-state β-decay has been observed for the first time by storing bare $^{163}_{66}\mathrm{Dy}^{66+}$ ions in the GSI heavy-ion storage ring. As recalled in Sect. 4.2, this special decay mechanism can be of importance particularly in s-process conditions. The derived experimental data confirm the theoretical expectations.

Nuclear masses: theoretical situation

The masses of very neutron-rich nuclei, a vast majority of which remain unknown despite vigorous experimental efforts, enter r-process calculations in forms of neutron separation energies and β-decay *Q*-values. Much progress has been made recently in predicting unknown masses through the continued sophistication of the Droplet Model, and through the development of a "microscopic" description of the mass surface that approximates the Hartree-Fock predictions closely. In addition, a few attempts to apply the Relativistic Mean Field Theory to mass predictions have recently been made. Despite these, some important aspects deserve further scrutiny. One of them concerns 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.

Probabilities of the various β-decay modes: theoretical situation

A general account of the weak interaction processes of astrophysical interest can be found in e.g. [263].

β^--decay: As for the masses, most of the β^--decay half-lives of those nuclei involved in the r-process are still unknown experimentally. Their prediction has been made from the statistical "Gross theory", or from nuclear shell models at the expenses of certain approximations (e.g. the so-called quasi-particle random-phase approximation).

β-delayed neutron emission and fission: Those processes have also to be included in the detailed modelling of the r-process, and raise further nuclear physics problems. This particularly concerns the absence of experimental information on the fission barriers of very neutron-rich actinides, which have been evaluated so far from droplet-type models. An effort to predict barriers from a microscopic model has also been initiated.

Bound-state β-decay: At stellar temperatures, the atoms can be highly ionised, and the probability of creating an electron in bound orbits via weak interaction may be greatly enhanced. This process, referred to as "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 ionisation. Such an effect can even lead to the decay of terrestrially stable nuclides. This is notably the case for $^{163}Dy^{66+}$, for which a recent storage-ring experiment at GSI has confirmed the theoretical expectations. Bound-state β-decay can also dramatically modify the terrestrial half-lives of ^{187}Re and of ^{205}Pb. 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, and on the estimate of the age of the galactic r-nuclides. 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, as well as to set some meaningful limits on the electron neutrino mass.

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. Those problems relate directly in particular to electron screening effects which has been estimated so far from a finite-temperature Thomas-Fermi model.

9.2 Neutronisation of Presupernova Cores

One of the keys to the final fate of massive stars lies in the level of neutronisation of the presupernova configuration through the captures of highly degenerate electrons on protons, as well as on iron-group nuclides.

The evaluation of those capture rates basically requires the knowledge of the β^+ Gamow-Teller strengths in an energy range that is often out of reach of standard β-decay experiments. As the information from intermediate-energy (n,p) reactions is so far limited, one has to rely heavily on theoretical estimates. A few attempts have been made in the framework of truncated nuclear shell models. Migdal's Theory of Finite Fermi Systems may turn out to be a good tool for tackling the problem.

Other weak interaction processes are of crucial importance in supernovae. In particular, the production of various kinds of neutrinos at the centre of a nascent (hot) neutron star, and certain reaction cross sections that determine their transport rate to its surface play a pivotal role in the current modelings of Type II supernova explosions (5.3).

9.3 Nuclear Equation of State in Supernovae and Neutron Stars

One of the most important ingredients for both supernova and neutron star models is the equation of state (EOS), which provides the energy density and pressure as functions of temperature, density and of composition (e.g. [257]). In particular, the "stiffness" of the nuclear EOS at densities near and up to a few times the nuclear matter density determines to a large extent the possibility for a star to explode. On the other hand, the EOS in a wide range of densities, up to (or even beyond) ten times nuclear density, is required to study the structure of a neutron star.

In supernova or hot neutron star conditions, the entropy per nucleon is quite low, and the material is significantly neutron-rich. It is thus difficult to extract the required information from nuclear experiments such as heavy-ion collisions. Resort has thus to be made to theory.

At temperatures in excess of about $5{\cdot}10^9$ K, all nuclear species are in statistical equilibrium as far as strong and electromagnetic interactions are concerned (cf. 9.2). In such conditions, the EOS can be appropriately calculated from a Boltzmann gas approximation, at least if the densities do not exceed about one hundredth of the nuclear matter density. Such a description requires, however, the knowledge of both the binding energies and the statistical weight ("nuclear partition functions") of the very neutron-rich nuclides that are favoured by the equilibrium conditions. Those quantities are difficult to evaluate.

At higher densities, the Coulomb (lattice) and nucleon-nucleon correlations have to be properly taken into account. Some attempts have been made to apply the temperature-dependent Hartree-Fock method to the supernova problem, whereas the possibility of complicated geometrical configurations has been studied within the technically simpler Thomas-Fermi approximation. The superfluidity that could characterise the crust and outer core of a neutron star has also been investigated with the help of realistic nucleon-nucleon forces. Such studies may help understanding some puzzling phenomena, like the decrease of the rotational velocity of certain pulsars after "glitches".

Beyond nuclear density, many microscopic calculations of the EOS have been performed. As yet, most 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. Recently, the finite-temperature Hartree-Fock method with an effective nucleon-nucleon interaction has been used to study the pion condensation which might occur in the inner region of a neutron star core at a few times the nuclear density. Finally, it has to be mentioned that 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. The required conditions might also be obtained in the early Universe.

10. Conclusions and Recommendations

Over the last few years, an impressive experimental and theoretical effort has led to a substantial improvement in our knowledge of many nuclear reaction rates and of other basic nuclear quantities of astrophysical interest. In spite of that, much obviously remains to be done, particularly in order to increase the reliability of the astrophysical models dealing with a more or less large number of neutron-rich or neutron-deficient nuclides.

In order to be efficient and successful, research in nuclear astrophysics calls for a close and continuous interaction between dedicated nuclear physicists and astrophysicists. In order for such an interdisciplinary effort to be most successful and efficient, the following requirements have to be fulfilled in Europe:

- to provide a strong support to Radioactive Ion Beam facilities in view of the key importance of exotic nuclei in astrophysics

- to support the development of a new Underground Accelerator Laboratory (e.g. at Gran Sasso), the cosmic background often representing the most important limiting factor in the measurements of nuclear reaction cross sections at energies of astrophysical interest

- to give universities the necessary financial and human means to develop, by their own, novel experimental techniques to be used eventually at other facilities, and to support likewise the development of strong research groups in theoretical nuclear astrophysics.

- to reinforce the relations between nuclear astrophysics and the many fields of science that connect to it, particularly the "end members" represented by cosmology and the space technologies. The tightening of these links would obviously be highly profitable to research, but would also be most valuable at the educational level.

Under such conditions, nuclear astrophysics will certainly remain a challenging and exciting field of research for many years to come.

Acknowledgements.

Communications on specific subjects from J.N. Bahcall, R.N. Boyd, M. Cribier, W. Hillebrandt and K. Langanke are highly appreciated.

11. References

[254] Burbidge E.M. et al., "Synthesis of the elements in stars", Rev. Mod. Phys. **29** (1957) 547-650.

[255] Rolfs C.E. & Rodney W.S., Cauldrons in the Cosmos, University of Chicago Press, Chicago (1988).

[256] Léna P., Observational Astrophysics, Springer-Verlag, Berlin (1988).

[257] Bethe H.A., "Supernova mechanisms", Rev. Mod. Phys. **62** (1990) 801-866.

[258] Turck-Chièze S. et al., "The solar interior", Phys. Rep. **230** (1993) 57-235.

[259] Smith M.S. et al., "Experimental, computational, and observational analysis of primordial nucleosynthesis", Ap. J. Suppl. **85** (1993) 219-247.

[260] Reeves H., "On the origin of the light elements ($Z < 6$)", Rev. Mod. Phys. **66** (1994) 193-216.

[261] Radioactive Nuclear Beams: I. eds. W.D. Myers et al., World Scientific Pub., Singapore (1990); II. ed. Th. Delbar, IOP Pub. Ltd., Bristol (1992); III. ed. D. Morrisey, Editions Frontières, Gif-sur-Yvette (1994).

[262] Descouvemont P., "Microscopic models for nuclear reaction rates" J. Phys. G Suppl. **19** (1993) S141-152; Langanke K., in Advances in Nuclear Physics 21, eds. J.W. Negele & E. Vogt, Plenum Press, New York, to appear.

[263] Grotz K. & Klapdor H.V., The weak interaction in nuclear-, particle- and astrophysics, IOP Pub., Bristol (1990).