Nuclei in the Universe

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1 Introduction

This report summarizes some recent highlights and the present status of nuclear astrophysics and evaluates its future prospects and needs. Nuclear astrophysics has developed in the last twenty years into one of the most important subfields of 'applied' nuclear physics. It is a truly interdisciplinary field, concentrating on primordial and stellar nucleosynthesis, stellar evolution, and the interpretation of cataclysmic stellar events like novae and supernovae [1]. It combines astronomical observation and astrophysical modelling with meteoritic anomaly research and with nuclear physics measurements and theory. In fact, it is this broad scope which fascinates research in nuclear astrophysics and motivates many young researchers to start a career in this field.

The field has been tremendously stimulated by recent developments in laboratory and observational techniques. The rapid increase in satellite observations of intense galactic gamma-sources, observation and analysis of isotopic and elemental abundances in deep convective Red Giant and Asymptotic Giant Branch stars, and abundance and dynamical studies of nova ejecta and supernova remnants allow the placement of stringent limits on the various stellar and nucleosynthesis models. Also, the latest developments in modelling stars, novae, X-ray bursts, type I supernovae, and the identification of the neutrino-wind-driven shock in type II supernovae as a possible site for the r-process allow now much better predictions from nucleosynthesis calculations to be compared with the observational data. New spectroscopic capabilities have become available on the Hubble Space Telescope, and through new large telescope facilities like the VLT and the Keck. Highlights with significant public attention were the high redshift supernova search and its implication for the structure and dynamics of the Universe as well as the proof of oscillations for solar neutrinos on their way from the solar core to earth by earthbound detectors.

This solution to the solar neutrino puzzle does not only open the door to new physics beyond the standard model of particle physics, it also confirms the predictions of the solar models including their nuclear physics input. The latter included the measurement of the ^{3}He(^{3}He,2p)^{4}He reaction cross sections at the Gran Sasso low-energy underground facility. This milestone of nuclear astrophysics constitutes the first direct measurement of a reaction rate at stellar energies. Other highlights of experimental nuclear astrophysics include the development and successful use of novel neutron-time-of-flight facilities at Los Alamos and CERN, which allow to determine neutron capture cross sections for the s-process with unprecedented precision, the high-accuracy mass measurements of many unstable nuclei at GSI and GANIL, the determination of more than 30 new half-lives for neutron-rich nuclei on the r-process path, and the precision measurements of spin-isospin responses in nuclei at KVI Groningen and Osaka, which are important inputs in supernova simulations and for supernova neutrino detectors. A new era of nuclear astrophysics has started with the use of radioactive ion-beam accelerators dedicated to the measurement of astrophysically relevant nuclear reactions involving short-lived nuclides. After the pioneering work in Louvain-la-Neuve, new facilities are now operational at TRIUMF, Vancouver, Spiral/GANIL and at Rex-Isolde/CERN. They will allow to determine some of the most important reaction rates for the nuclear networks in novae and X-ray bursters. The next generation of radioactive ion-beam facilities, planned and proposed in Europe (GSI and EURISOL), in Japan and in the USA, will then allow to produce and experiment with most of the astrophysically important short-lived nuclides, promising to remove the most crucial ambiguities in nuclear astrophysics arising from nuclear physics input.

In many of the astrophysical models, nuclear theory has to bridge the gap between experimental data and astrophysical applications. Here, we clearly stand at the eve of a new era as the required step can now be taken on the basis of first-principle theoretical models rather than by empirical parametrization of the data. This should reduce the uncertainties connected with the extrapolations into yet unexplored parts of the nuclear chart in the near future, thus going timely hand-in-hand with the experimental developments.

Nuclear astrophysics has benefitted enormously from the progress in astronomical observation, astrophysical modelling and nuclear physics. But many fundamental open questions remain. Given the unique interdisciplinary nature of the field, a global understanding can only be achieved by combined and coordinated efforts in the three subfields. Clearly, nuclear physics plays a central role in this endeavour.

It is the aim of this manuscript to identify the needs and prospects of experimental and theoretical nuclear astrophysics for the next 5 years. To underline the interdisciplinary character and the supplementing role of astrophysics and nuclear physics we first identify current and future developments of astrophysical observation and modelling, which will stimulate the nuclear physics program, but also benefit from it. This program is then individually described in the major subfields of nuclear astrophysics and the future prospectives and needs are derived.

2 Stellar physics and nuclear astrophysics

2.1 Stellar physics

Over the last decades, stellar physics has evolved into a field of research that uses high-precision data obtained by new generations of ground-based and space telescopes in all wavelength bands (Fig. 1). Another basic ingredient is provided by nuclear data and detailed numerical models to study fundamental physics problems under conditions not reachable in laboratory experiments. These include the properties of neutrinos, the origin and abundances of the chemical elements, and the evolution of galaxies and of the Universe as a whole.

Structure and evolution of stars. Stars are an important component of the Universe and a major source of information about its structure and history. Recent activities mainly in the USA, Japan, and Europe have focussed on the evolution of low- and intermediate-mass stars and on massive stars. Here, in particular, due to much improved telescopes and their instrumentation, stellar properties can be measured with ever increasing precision. These advances are accompanied and completed by realistic stellar models.

One example is the highly accurate solar model produced independently by several groups. Helioseismology allows to measure the sound velocity as a function of radial position, and thus the temperature and density, to better than 1% through most of the sun's interior. The new "Standard Solar Model", constructed on the basis of standard physics input (equation of state, nuclear reactions and initial composition, opacities, mixing-length theory of convection, etc.), reproduces the results of

Figure 1: The ESO Very Large Telescope (VLT), installed at the Paranal Observatory in northern Chile, is Europe's flagship astronomical project for the early 21st century. It consists of four Unit Telescopes (UT1 - 4), each of which is equipped with an 8.2-m monolithic Zerodur mirror. Some of the main scientific tasks of the VLT are vested in the VLT Interferometer (VLTI) which, in addition to the UTs, also includes a number of smaller movable telescopes which can be placed at various positions on the observatory platform in order to form different interferometric configurations.

helioseismology extremely well, leaving little room for changes. In fact, modifications of the physics input, including nuclear reactions, must leave this agreement untouched in order to be acceptable. Therefore, the sun has become a "laboratory for fundamental physics". The recent confirmation of neutrino flavour oscillations by the Sudbury Neutrino Observatory SNO [2], making use of the sun as a well-calibrated neutrino source, is a major break-through in our basic understanding of neutrino physics.

A second example concerns the evolution of low-mass globular cluster stars [3]. Originally, the ages of globular clusters were derived from purely theoretical reasoning. This led to the so-called "age-problem", which seemed to suggest that these stars be older than the Universe. Improved stellar models, however, have now demonstrated that these objects are younger than commonly believed. This is in agreement with the HIPPARCOS parallax observations which have confirmed that globular clusters do indeed have ages of 14 Gyr or less, in agreement with expectations from cosmology.

EDDINGTON, an ESA mission to be launched in 2007, will allow to extend high precision stellar oscillation measurements to many stars in our cosmic neighborhood and to put the theory of stellar structure and evolution on a much improved empirical basis. New astrometry satellites such as DIVA and GAIA will supply information about stellar positions and velocities that reach far beyond what HIPPARCOS could do.

Some of the nuclear reaction rates needed for the stellar models still carry significant uncertainties which certainly should be removed in the future. Possible consequences for stellar models and evolution have then to be investigated.

Nuclear abundances in stars. With the ever increasing quality of stellar atmosphere models and the use of new telescopes and spectrographs, detailed abundance determinations in individual stars have become an important constrain in nuclear astrophysics.

An outstanding example are the elemental (and some times even isotopic) abundances observed in many (ultra-) metal-poor giant stars [4]. Here one avoids the complicated problem of chemical evolution and infers constrains on nucleosynthesis sites from the observed abundances in very old stars since their abundances have been polluted by only one or at most a few supernovae. Because of their low heavy element content, in particular iron, it is relatively easy to detect un-blended spectral lines of elements with mass-numbers exceeding even 50 in those stars.

It has been found that a certain class of very metal-poor stars with iron abundances of only about 10^{-3} of the sun contains no s-process material, but the r-process nuclei are sometimes over-abundant in these stars by up to a factor of 50 (relative to iron). Even more surprising, in all these cases the heavy r-process nuclei with $A > 130$ follow almost exactly the solar system pattern. On the other hand, the overall elemental abundances in these stars appear to be non-solar, even for the main components such as the CNO-group and α-capture elements.

These findings leave us with a puzzle: How can it be that old stars which formed in completely different parts of our Galaxy and received heavy r-process nuclei from at most a few different (nearby) supernovae have exactly the same r-process abundances which, moreover, resemble those of the much younger sun? One possible explanation seems to be that the heavy r-process is robust and produces always the same abundances, *independent* of the astrophysical conditions being only governed by nuclear physics, a very unexpected conclusion!

Stellar diagnostics and extragalactic stellar astronomy In the current era of 8 and 10 meter-class telescopes, it has become possible to apply precise stellar diagnostics also to external galaxies. Recently, the basic diagnostic techniques to analyze the spectra of luminous blue supergiants and other hot stars have been developed. They establish new tools to study the chemical evolution of galaxies and, in addition, provide promising new extragalactic distance indicators. Similarly, Planetary Nebulae can now be used as distance indicators and to investigate the structure of galaxies, or to determine the mass-to-light ratios and dark matter content in the outskirts of galaxies [5].

In the coming years, high-resolution spectroscopy and imaging photometry by space-based telescopes will expand the astronomical data base even further in all wavelength bands. ESA's infrared satellite HERSCHEL has the potential of discovering the earliest epoch of proto-galaxies. Its main science objectives emphasize the formation of stars and galaxies, and the interrelation between them, but also include the physics of the interstellar medium and astrochemistry. NGST, the follow-up mission of HUBBLE, is planned for launch in 2009. It will shed light on the "Dark Ages of the Universe" by observing infrared light from the first generations of stars and galaxies. XMM-Newton, already in orbit, and XEUS, with a possible launch in 2015, will give x-ray data of similar quality.

Again, the basic building blocks for interpreting these data are stars and the gas in between them. These observations will shed light on the evolution of the chemical elements over the past 12 billion years in an unprecedented way, delivering the benchmarks nucleosynthesis models will have to match.

2.2 Late Stages of Stellar Evolution and Neutrino Astrophysics

For several decades, these branches of astrophysics have been very successful areas of research. Highlights include the construction of realistic models of thermonuclear and core-collapse supernovae, detailed investigations of nuclear burning in exploding stars, and the computation of nuclear abundances of the ejecta, including those of neutron-rich isotopes of the heavy elements produced by the r-process.

This progress was driven by advances in nuclear physics (weak and strong interaction rates, nuclear equation of state, neutrino processes), high performance scientific computing (2- and 3-dimensional hydro- and magneto-hydrodynamics, neutrino and radiation transport) advanced by the development of new numerical tools and the ever increasing power of modern super-computers and, of course, by new observational facts, discovered by large ground-based telescopes and space missions, such as Compton GRO, Chandra and XMM Newton, and the Hubble Space Telescope. A few outstanding examples are reviewed in the following subsections.

Core-collapse supernovae and nucleosynthesis Despite considerable progress, the physics of core-collapse supernovae and their nucleosynthesis remains to be an active field of research in nuclear astrophysics [6]. Still open questions related to the debated explosion mechanism include the interaction cross sections of neutrinos in dense nuclear matter and the necessity to develop new methods to calculate their transport, taking into account nucleon-nucleon correlations and magnetic field effects, for multi-dimensional simulations of the events [7]. The equation of state of very neutron-rich low-entropy nuclear matter up to about five times nuclear saturation density also remains to be an open and important problem. The new discovery of unexpected element and isotopic abundances in very metal-poor stars discussed earlier present yet another puzzle. However, some confirmation of the general picture is supplied by the detection of γ-ray lines of a few radioactive isotopes in supernovae, supernova remnants and the distribution of ^{26}Al in the disk of our Milky Way galaxy (Fig. 2).

Besides the progress that can be expected from advances in computer technology and high-performance scientific computing, and from the new telescopes mentioned previously, the field will also profit from the next generation of γ-ray instruments and in particular INTEGRAL, launched on October 17, 2002. Like laboratory studies of isotopic anomalies in primitive meteorites, they will provide information about in-situ abundances of radioactive isotopes in explosive nucleosynthesis events and, thus, about the physical conditions in their deep interiors. The next generation of gravitational wave experiments either on ground (LIGO II, EURO, VIRGO) or in space (LISA) may allow us to map the dynamics of a star collapsing to a neutron star or a black hole.

γ-ray bursts Neutrinos and dense nuclear matter also play an important role in mergers of two neutron stars and of a neutron star and a black hole. In these events, dense nuclear matter is heated to tens of MeV and most of this energy is emitted in form of weakly interacting particles. It is believed that the annihilation of neutrinos into e^+e^- pairs may give rise to γ-ray bursts [8] and may explain the "weak" sub-class of the observed bursts. Of course, state-of-the-art simulations of such mergers have to be done in three spatial dimensions with all the relevant micro-physics and General Relativity included. Similarly, the collapse of rotating extremely massive stars to black holes, thought to be the cause of the class of very energetic γ-ray bursts, requires the same kind of micro-physics.

Here a combination of optical observations of γ-ray burst after-glows, carried out by robotic telescopes, X- and γ-ray observations with space-based telescopes, gravitational wave and, possibly, neutrino detections may allow us to understand these most powerful explosions in the Universe.

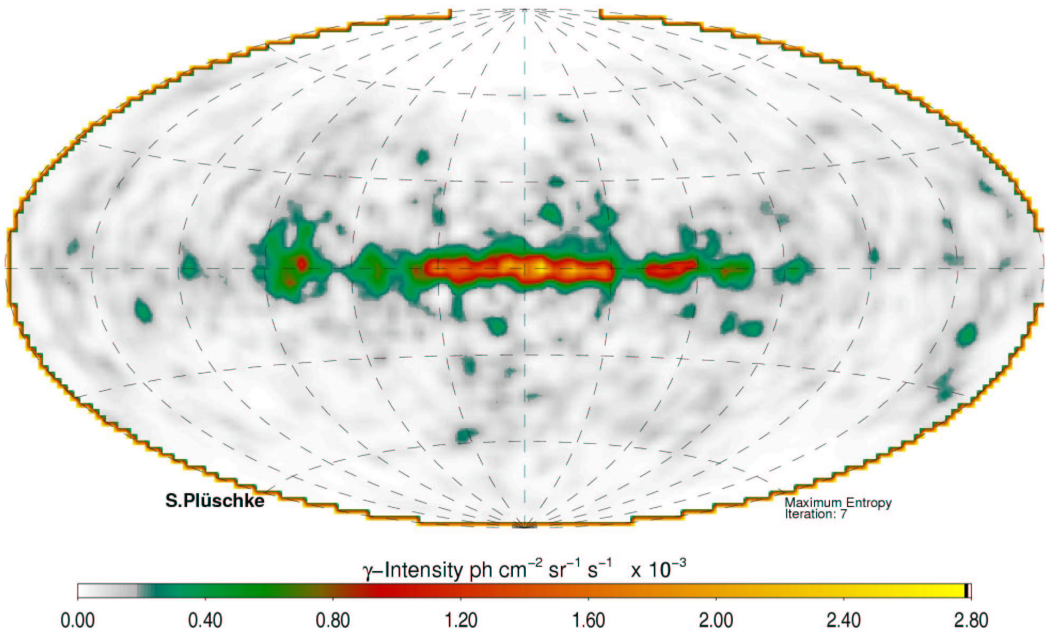

Figure 2: COMPTEL all-sky map of ^{26}Al activity. The half-life of ^{26}Al is 7×10^5 y. The observation of the characteristic γ-line from the ^{26}Al decay indicates therefore 'recent' nucleosynthesis activities. Beside an intensive ridge along the inner galaxy, a pronounced emission feature in the Cygnus region and a low intensity ridge reaching out to the Carina-Vela region are detected. Massive stars and their subsequent core-collapse supernovae are the dominant sources of interstellar ^{26}Al. (From Plüschke et al.; preprint astro-ph/0104047)

Thermonuclear flashes and explosions The most interesting applications of explosive thermonuclear burning in binary stars are novae, X-ray bursts, and (type Ia) supernovae. In the case of a nova, the essential question is how turbulent convection interacts with nuclear fusion of hydrogen on the surface of a white dwarf star. In contrast, X-ray bursts are believed to be the outcome of a thermonuclear runaway on the surface of a neutron star. In both cases the fusing matter tends to be proton-rich, many of the nuclei involved are unstable, and their reaction rates, which drive the burning, are not or only poorly known. The combined efforts of new X-ray telescopes in orbit, future radioactive ion-beam facilities, which will allow to determine reliable reaction rates of short-lived proton-rich nuclei, and improved numerical models certainly will lead to major break-throughs.

For type Ia supernovae, the main question is how a thermonuclear burning front, which fuses carbon and oxygen mostly into ^{56}Ni, propagates in the degenerate matter of a massive white dwarf [9]. Since the flame front is very narrow (only a fraction of a millimeter thick), the physical problem is very similar to that in combustion engines. As far as nuclear reactions are concerned, type Ia supernovae are fairly well understood, with the exception of certain weak rates which, however, have little impact on the explosion physics, but affect the elemental abundances of the ejecta.

However, these supernovae have attracted considerable interest since they are thought to be good tools to measure cosmological parameters such as the expansion rate and the deceleration/acceleration of the Universe. Observations of this particular class of supernovae at high redshift seem to indicate that the expansion of the Universe is accelerating, possibly due to a positive cosmological constant or a new form of "dark" energy (Fig. 3). But currently, our understanding of the supernova physics is the major systematic uncertainty of this result. Only once we understand the physics of the explosions will we be able to assess whether supernovae can reliably be used as distance indicators, and whether

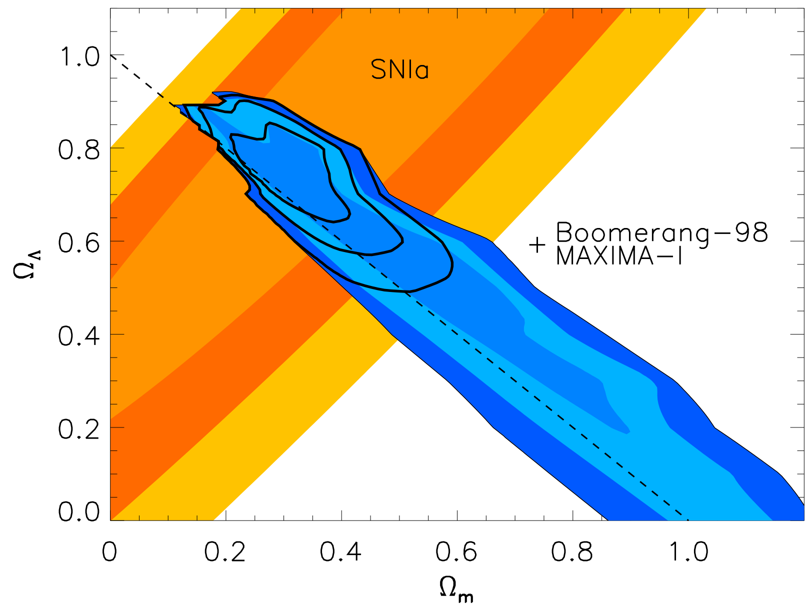

Figure 3: Constrains for the matter density Ω_m and the cosmological constant Ω_Λ of the Universe from the combined BOOMERANG and MAXIMA-I anisotropy measurements of the Cosmic Microwave Background (in blue) and from the observations of high-redshift supernovae. A consistent solution is obtained for a universe consisting of less than 30% of dark matter, between 60 and 70% dark energy, and 3 to 4% baryons only. (From Jaffe et al., Phys.Rev.Lett. 86 (2001) 3475-3479)

we have to search for new physics beyond the standard models of particle physics and cosmology.

Neutron stars Neutron stars are unique "cosmic laboratories" in which our theories of dense nuclear matter at densities exceeding 10^{15} g/cm^3 are used to construct stellar models and can then be confronted with astronomical observations. Observations by radio telescopes led to discovery of 1400 radio pulsars, which are rotating magnetized neutron stars. Hundreds of neutron stars are observed as compact X-ray and gamma-ray sources (X-ray pulsars, X-ray bursters, soft gamma repeaters etc.). Recently launched X-ray and gamma-ray observatories, such as RXTE-Rossi, AXAF-Chandra, and XMM-Newton have led to many remarkable discoveries: the kHz oscillations in low-mass X-ray binaries, numerous neutron stars in the type II supernova remnants, precise spectra of the surface radiation of solitary and binary neutron stars, and bursting millisecond pulsars. The number of observed neutron stars doubled in the last 5 years, and will soon reach two thousand. Still, this is a tiny fraction of the 10^8 neutron stars expected to exist in our Galaxy.

Precise mass determinations of neutron stars in binary systems are known since several years, the most famous being the Hulse-Taylor binary pulsar PSR 1913+16, for which the masses of both neutron stars are known to better than a few %. However, recent studies of the spectral and temporal properties of X-ray bursts observed from objects such as Cygnus X-2 with RXTE-Rossi allow for the first time to obtain also a reliable determination of the mass-radius relation of neutron stars. Similarly, masses and radii of nearby isolated X-ray sources such as RX J185635-3754 can be determined from their multi-wavelength spectral energy distribution. Finally, the near-constancy of the highest observed frequencies of the quasi-periodic oscillations of low-mass X-ray binaries, interpreted as being due to the orbital frequency of a marginally stable orbit, gives strong constrains on both masses and radii of their compact companions. All these observations and their interpretation will put our knowledge of the properties of neutron stars on a firm empirical basis.

Nuclear physics should try to explain the observed properties of neutron stars: this is our challenge. On the other hand, observations of neutron stars can be used to test and to constrain nuclear theory under extreme astrophysical conditions, which are far from the laboratory ones: these are our chances.

3 Hydrostatic burning

3.1 Nuclear processes during hydrostatic burning

Stars generate the energy, which allows them to stabilize and shine over lifetimes from millions to billions of years, by nuclear reactions in their interior. Simultaneously, the network of nuclear reactions operating in the hot, dense stellar interior is believed to be the source of nuclides of mass $A \geq 12$. The fate and evolution of stars depend strongly on their mass at birth. Stars with masses less than $\sim 8M_\odot$ reach temperature and densities in the center which only suffice to ignite the first two hydrostatic burning stages, hydrogen and helium burning. Mainly because of their enormously shorter lifetimes, massive stars (with masses exceeding about 13 $M_\odot$) were, and are still, the most efficient breeders of the heaviest elements. After helium burning, these stars go through periods of carbon, neon, oxygen, and silicon burning in their central core, before the procession of nuclear core burning stages ceases, resulting in the collapse of the stellar core and the explosion of the star as a Type II supernova.

Obviously, the star for which the best and most detailed data exist is our sun. Thus, it is natural that our general understanding of stellar structure and evolution be checked in detail against solar observations. Historically an outstanding role has been played by the detection of the neutrinos, which are generated by the various hydrogen burning chains operating in the sun's interior, and the quest to understand why the observed flux of solar neutrinos is less than predicted by the standard solar model. The solution to this famous solar neutrino puzzle was delivered by the Sudbury Neutrino Observatory (SNO) which experimentally proved the existence of oscillations for solar neutrinos [2]. Furthermore, the SNO measurements, together with the high-precision helioseismology data, confirm the predictions of the solar models and their nuclear physics inputs. This, however, does not mean that more precise determinations of the solar nuclear reaction rates are no longer needed. On the contrary, the aim is now to turn the sun into a calibrated neutrino source which allows us to convert the measured solar neutrino event rates into information about neutrino masses and mixing parameters. This requires an even more precise knowledge of the various nuclear reaction rates in the sun!

The determination of stellar fusion rates in terresterial laboratories is strongly hampered by the fact that stars, including our sun, burn their nuclear fuel at such low energies that the cross sections, due to the Coulomb repulsion of the two colliding nuclei, are extremely small. To measure such cross sections requires accelerators with very high intensities and a very efficient background suppression. Despite enormous experimental efforts in the last decades, a direct measurement of stellar cross sections has been nearly impossible, and data, obtained at higher energies than those needed in stars, have to be extrapolated down to the stellar energy range. Such a procedure can obviously have considerable uncertainties. To reduce these uncertainties or to circumvent the notorious extrapolation procedure at all, considerable efforts have been spent in recent years to push the experimental limits to lower and lower energies and, simultaneously, to develop new indirect approaches to determine the required rates at stellar energies.

The underground LUNA laboratory at the Gran Sasso is an extremely background free facility dedicated to the measurement of astrophysically important low-energy nuclear cross sections. As a milestone, it has been possible at LUNA [10] with the original 50 kV accelerator to directly determine the rates of the ^{3}He(^{3}He,2p)^{4}He and d(p,γ)^{3}He reactions at those energies at which these reactions operate in the core of the sun (Fig. 4). Following the recommendations of the last NuPECC report,

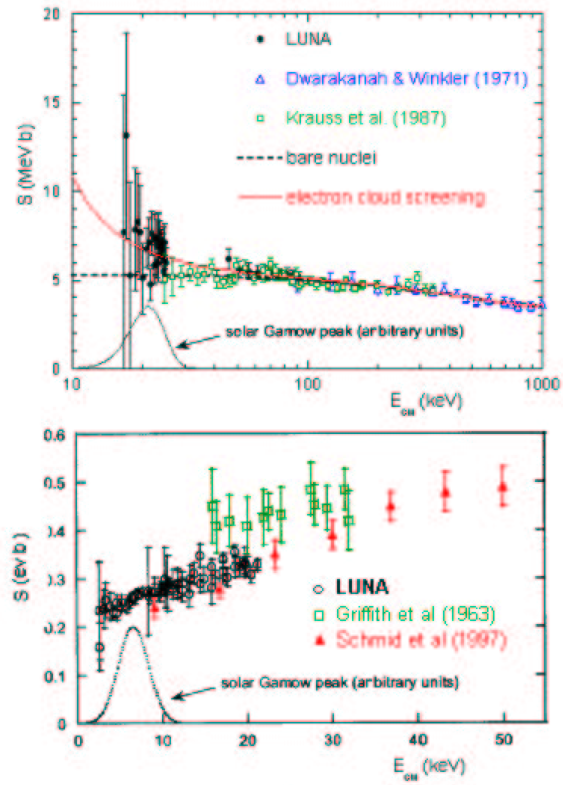

Figure 4: Reaction cross sections, expressed in terms of the astrophysical S-factor, for the ^{3}He(^{3}He,2p)^{4}He and d(p,γ)^{3}He reactions. It has been possible at the underground laboratory LUNA to directly measure these cross sections at solar energies (solar Gamow peak).

a new 400 kV accelerator, which will be dedicated solely to the study of astrophysically important fusion reactions, has recently been installed. This machine is presently used for the measurement of the ^{14}N(p,γ)^{15}O cross section, which is important for the knowledge of the neutrino flux generated by the solar CNO cycle. Direct measurements of total cross sections at energies down to 70-80 keV will soon be possible.

LUNA will determine the fusion rates of other key-reactions in quiescent stellar burning with significantly improved precision. A prominent example is the ^{3}He(^{4}He,γ)^{7}Be reaction rate which is directly proportional to the flux of the high-energy ^{8}B neutrinos from the sun and hence is essential for the analysis of the observed solar neutrino fluxes in terms of neutrino masses and mixing parameters. Detailed studies of many reactions of the NeNa and MgAl cycles, which operate during hydrogen burning in stars more massive than the sun, should be performed. In particular, a precision measurement of the ^{25}Mg(p,γ)^{26}Al cross section can contribute to the solution of the astrophysical origin of ^{26}Al. In the future, the installation of a high-current 5-MeV accelerator in the LUNA laboratory is desired. Among other important reactions, such a machine would allow the precision measurement of the rates for the ^{13}C(α,n)^{16}O and ^{12}C(α,γ)^{16}O reactions, where the first is important for studies of s-process nucleosynthesis.

The fusion of ^{4}He and ^{12}C nuclei to ^{16}O is the most important nuclear reaction in the development of massive stars. It occurs during the helium burning stage of Red Giant stars and its reaction rate decisively influences the subsequent stellar evolution, including the core collapse and the supernova explosion. Furthermore, this rate determines the abundances of the two brickstones of life, carbon and oxygen, in the Universe. Despite enormous efforts and significant progress made in several laboratories around the world in measuring the relevant low-energy elastic and capture cross sections, the stellar ^{12}C(α,γ)^{16}O rate is still not known with the required accuracy of $\approx$ 20%. Further improved measurements are needed. Besides direct measurements with a future 5-MeV accelerator at LUNA down to energies of about 500 keV (which is still higher than the energy of 300 keV, at which this reaction burns most effectively in Red Giants), crucial information to reduce the uncertainty in the rates can come from measurements in inverse kinematics or via indirect techniques like Coulomb dissociation or using high-intensity photon sources.

The determination of low-energy cross sections from the observed reaction yield requires a precise knowledge of the effective beam energy. Energy loss effects in the target as well as screening effects of the target and projectile electrons (see below) on the reaction cross section have to be well under control. This is particularly important as such effects, if inaccurately corrected, will be amplified in the required extrapolation of the data to stellar energies. Recently, unexplained effects have been reported in the low-energy measurements of stopping powers and electron screening. It is important that these effects are confirmed and understood, requiring for example precision measurements of stopping powers at energies below the Bragg peak.

In recent years several indirect methods, which can avoid some of the apparent difficulties encountered in the direct approaches to determine astrophysically important low-energy cross sections, have been proposed and developed. In the Coulomb dissociation method, which can be viewed as the inverse of a capture reaction, a nucleus is dissociated by the virtual photons created in the strong Coulomb field of a heavy nucleus. Supplemented by considerable theoretical progress in modelling the 3-body process, Coulomb dissociation experiments have contributed to reduce the uncertainty in the solar ^{7}Be(p,γ)^{8}B fusion rate. Although this method can only provide partial information about the capture process; i.e. it can only determine the radiative capture cross section to the ground state of the compound nucleus, there are several astrophysically interesting reactions where this technique can provide valuable data, in particular if it can be applied to short-lived radioactive ion-beams.

The Coulomb dissociation method or the recently developed intense real photon sources also allow inverse studies of fusion reactions involving three particles in the entrance channel like the triple-alpha reaction ^{4}He+^{4}He+^{4}He$\rightarrow^{12}$C, occuring as the first step in helium burning in Red Giants, or the ^{4}He+^{4}He+n$\rightarrow^{9}$Be reaction, which determines the dynamical flow to heavier nuclei in the neutrino-wind scenario of the r-process. First promising results have already been obtained for the later reactions. Future applications should include studies of the ^{4}He+2n $\rightarrow^{6}$He reaction, or once radioactive ion-beams are available, the 2p-capture reactions on several rp-process waiting points. Important data to derive the cross section for 3-body fusion reactions can also be obtained by indirectly populating relevant reaction states in β-decays, again requiring the availability of radioactive ion-beam facilities.

For certain non-resonant radiative capture reactions, the capture process occurs at such large separations of the fusing particles that the reaction can be viewed as an external process which is solely determined by the asymptotic behavior of the nuclear wave functions in the initial scattering and in the final bound state. Then, the only unknown required to determine the astrophysically important low-energy cross section is the asymptotic normalization coefficient (ANC) of the final bound state, which can be indirectly determined in properly chosen peripheral transfer reactions. Such an approach, called the ANC method, has been recently developed and was successfully tested and applied to several astrophysically interesting reactions [11], including the proton capture reactions on ^{16}O leading to the ground and the first excited state of ^{17}F, and the ^{12}C(n,γ)^{13}C reaction, using the ^{16}O(^{3}He,d)^{17}F and ^{12}C(d,p)^{13}C transfer reactions, respectively, to experimentally determine the ANC. The dependence of the approach on the chosen transfer reactions were investigated for the ^{13}C(p,γ)^{14}N and ^{7}Be(p,γ)^{8}B reactions and a sensitivity of the results on the chosen optical potential parametrization of the transfer reaction was observed. This aspect requires further studies and will be crucial, if the ANC method is to be applied to unstable nuclei for which the necessary optical model parameters are not known and have to be determined by suitable experiments at radioactive ion-beam facilities.

In the Trojan Horse (TH) method, an astrophysically relevant reaction a(A,B)b is studied via a three-body reaction x(A,Bb)c, in which the projectile x is well clustered into x=c+a. For appropriately chosen incident beam energies, the 3-body reaction can be viewed as a quasi-free break-up mechanism, in which the cluster c behaves like a spectator and does not affect the interaction between the fragments a+A. Under such conditions the desired a(A,B)b cross section can be deduced from the measured 3-body reaction yield. By properly balancing the Fermi motion of the cluster 'a' in the nucleus x with the incident beam energy, which can be chosen above the respective Coulomb barrier, the TH method is able to measure fusion cross sections at very low energies. Supplemented by important theoretical developments of the underlying 3-body reaction mechanism, the TH method has been successfully applied to the ^{6}Li(d,α) and ^{7}Li(p,α) reactions [12] and holds some promise for future applications (Fig. 5). One advantage of the TH approach is that it determines the cross section between bare nuclei and is, unlike direct measurements of the a(A,B)b reaction, not influenced by screening enhancements due to the presence of projectile and/or target electrons. The reported screening enhancement for most reactions studied so far are noticeably larger than theoretically expected. However, it has to be noted that these enhancements are usually deduced with respect to an experimentally yet unknown cross section for bare nuclei which has been derived by extrapolation from data at higher energies and might thus carry some uncertainty. With its ability to measure the cross section for bare nuclei, the TH method can play a key-role in unravelling the disturbing difference between observed and expected electron screening effects. Clearly the clarification of this discrepancy needs more experimental and theoretical work. Such studies might also help to improve our understanding of electron screening effects in stellar plasma, which, once the proposed accurate measurements of nuclear cross sections are achieved, represent the largest uncertainties of the respective stellar rates.

3.2 The s-Process

For the last decades, much work has been devoted to the slow neutron-capture process (or s-process) which synthesizes heavy elements by a sequence of neutron captures and β-decays, mainly processing material from seed nuclei below and near the iron peak into a wide range of nuclei extending up to Pb and Bi. As the involved neutron capture times are usually significantly longer than the competing β-decays, the s-process path runs along the valley of stability in the nuclear chart. This allows the laboratory determination of the involved neutron capture cross sections and half-lives, making the s-process the probably best understood nucleosynthesis network from a nuclear physics point of view.

However, the main uncertainties in s-process predictions are still associated with the presently favored stellar sites. According to our current understanding, two s-process components are needed to reproduce the observed abundances. The ^{22}Ne(α,n)^{25}Mg reaction, which occurs during helium core burning of CNO material in massive stars (heavier than $10M_{\odot}$), is believed to supply the neutrons for the weak component that produces the nuclides with $A < 90$. Helium-flashes followed by hydrogen mixing into the ^{12}C-enriched region in low and intermediate mass ($< 10M_{\odot}$) AGB stars are believed to be the site of the main s-process component that builds up the heavy elements up to the Pb and Bi range. As suggested by recent AGB models, which include diffusive overshoot and rotational effects, protons are partially mixed from the H-rich envelope into the C-rich layers during the third dredge-up and are then captured on ^{12}C, which provides the fuel for producing ^{13}C via ^{12}C(p,γ)^{13}N(β,ν)^{13}C. The subsequent ^{13}C(α,n)^{16}O reaction is considered to be the principal neutron source for the main s-process component. These models predict that low-metallicity ($Z \leq 0.002$) AGB stars should exhibit large overabundances of Pb and Bi as compared to other s-elements. The discovery of such 'lead stars' (very low-metallicity stars enriched in s-elements and characterized by a large Pb overabundance compared to any of the other s-elements Ba, La or Ce) has been reported very recently. This discovery may

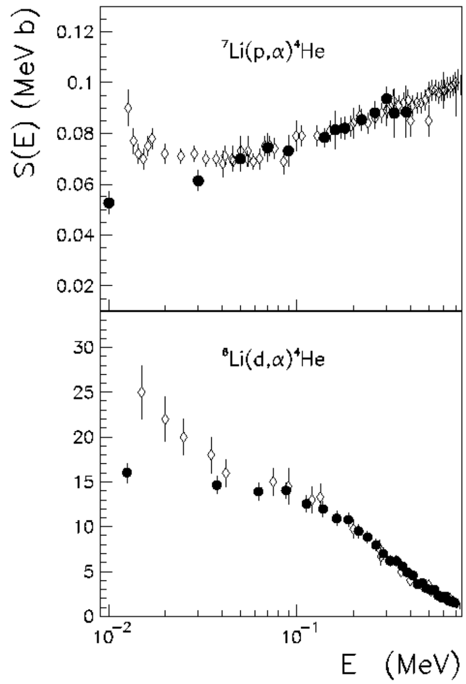

Figure 5: Comparison of directly measured astrophysical S-factors (open circles) for the ^{7}Li(p,α)^{4}He and ^{6}Li(d,α)^{4}He reactions with data obtained using the novel Trojan Horse method (full circles). While for direct measurements the cross sections are enhanced by electron screening effects at low energies, the Trojan Horse method is unaffected by such effects and promises to be also a useful tool to unravel the disturbing differences between observed and expected electron screening enhancements.

be the s-process "Rosetta stone" which validates the 'proton-mixing' scenario in AGB stars and also gives a clear indication that the s-process already took place early in the Galaxy.

Although the nature and extent of the convective processes as well as the low energy reaction cross section for ^{13}C(α,n) are largely unknown, our understanding of the nuclear mechanisms which are responsible for the production of the s-nuclei can be regarded as quite satisfactory, reflecting major experimental and theoretical efforts and progress in the last decade. As a highlight, a recent measurement has strongly reduced the uncertainties in the stellar ^{22}Ne$(\alpha\,,\mathrm{n})\,^{25}$Mg cross section. However, due to the importance of this reaction as a main neutron source, further effort via direct and indirect (e.g through (n,α) on ^{25}Mg) approaches is still highly desirable to reduce the remaining uncertainty.

S-process simulations require the knowledge of a large number of stellar neutron capture cross sections at typical energies of $10 \lesssim kT \lesssim 50$ keV on targets in the $12 \leq A \leq 210$ mass range. Much dedicated experimental work, in particular in university laboratories, has led to a substantial improvement in our knowledge of relevant (n,γ), (n,p) and (n,α) cross sections. In particular, the neutron capture cross section on the rarest stable nucleus in nature ^{180}Ta has recently been measured. Furthermore, it has experimentally been demonstrated that the short-lived ground and the long-lived isomeric state of ^{180}Ta can be equilibrated at stellar temperatures in excess of about 4 10^8 K, changing the effective half-life of ^{180}Ta by 15 orders of magnitude. These difficult experiments are of particular relevance to our undertanding of the possible s-process contribution to the galactic ^{180}Ta enrichment.

However, some neutron capture cross sections, in particular those for unstable nuclei on the s-process path, are not yet determined with the required accuracy, especially at the energies of $kT \simeq 10$ keV relevant for the s-process in AGB stars. The new unique neutron time-of-flight facility at CERN with its high neutron fluxes is expected to strongly improve the experimental determination of radiative neutron capture cross sections. One of the first astrophysically relevant experiments at this facility will determine the capture cross section on the Os isotopes, which is of particular interest in the Re-Os cosmochronometry. A close investigation of neutron capture reactions on long-lived beta-unstable neutron-rich isotopes is particularly important, as these nuclei represent potential branching points in the reaction path. Detailed analysis of the observed s-process abundance distribution in conjunction with neutron capture and beta decay data on these branching point nuclei provide important information about the temperature, density, and neutron-flux conditions at the s-process site. Neutron capture measurements on branching point nuclei like ^{79}Se, ^{85}Kr, ^{107}Pd, ^{135}Cs, ^{147}Pm, ^{151}Sm, ^{155}Eu, ^{170}Tm, ^{186}Re, ^{204}Tl, and ^{193}Pt therefore offer a unique tool for testing the stellar s-process models. The determination of the relevant beta-decay rates can, however, be much complicated by the fact that thermally excited nuclear states might change the stellar half-lives significantly. With the exception of isomeric states, the half-lives of excited states cannot easily 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. A special β-decay mechanism, referred to as bound-state β-decay, can play an important role for ionized atoms, and significantly affect the production of some specific s-nuclides. The remarkable experimental observation of the bound-state β^- decay of the fully ionized ^{187}Re atom achieved at the GSI in Darmstadt has been a important step in the reduction of the uncertainties associated with the galactic Re-Os chronometry.

4 Supernovae and dense objects

Simulating core-collapse supernovae has been at the forefront in astrophysics for several decades and the general picture is now well developed [7]. There is a consensus that neutrinos play an essential role in the supernova mechanism. Therefore the development and incorporation of multi-group (i.e. neutrinos of different flavors and energies) Boltzmann neutrino transport into the one-dimensional models has been a major recent achievement; a similar treatment in multi-dimensional collapse simulations, which currently consider neutrino transport rather crudely, is computationally extremely demanding and remains a major challenge for the next generations of supercomputers. Despite significant progress, one-dimensional collapse simulations currently fail to explode. Does this imply that some of the microphysics ingredients of the models are incorrect and need improvement or do supernova explosions rely on three-dimensional effects such as convection or rotation? This fundamental question is still open. Much of the relevant microphysics relates to weak-interaction processes in nuclei and nuclear matter under extreme conditions (density and temperature), but also uncertainties in the nuclear equation of state (EOS) might prove to be essential. The latter also plays a major role in the description of neutron stars, which are generally viewed as the laboratory for nuclear physics under extreme conditions. Progress in computer technology, the development of new and advanced many-body models and, probably most importantly, the new era of experimental facilities promise to reduce the nuclear-physics related uncertainties in supernova simulations and neutron star models.

4.1 Nuclear input for core-collapse simulations

After the formation of an iron core in its center, a massive star has run out of nuclear fuel to counteract gravity. The core starts to contract and becomes unstable against electron capture due to the associated increase in electron chemical potential. Electron captures cool the core, as neutrinos carry away energy, but also reduce the electron degeneracy pressure which counteracts the contraction. Both effects accelerate the collapse. Furthermore, the core composition is driven to more neutron-rich and heavier nuclei.

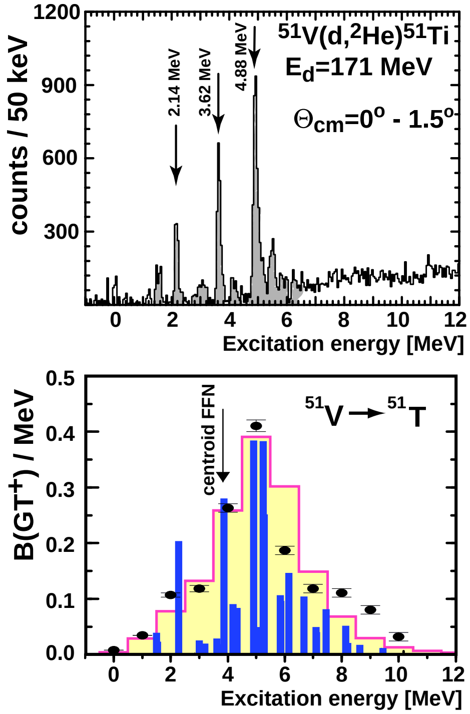

Figure 6: Spectrum of the reaction ^{51}V(d,^{2}He)^{51}Ti at 170 MeV incident energy measured at the AGOR cyclotron at the KVI in Groningen showing a number of strong GT transitions. The experimental resolution is 140 keV. The lower part shows the results from TRIUMF using the (n,p) probe where the resolution was typically of order 1 - 1.5 MeV (full data points). The bars (not to scale) indicate the results of the shell model calculation, which, after folding with such resolution, yields the full curve. The good experimental resolution in the (d,^{2}He) case (upper part) now allows a highly detailed comparison with theoretical calculations. The location of the GT centroid from the FFN parameterisation is also indicated.

Under collapse conditions, electron captures are dominated by Gamow-Teller (GT) transitions. With recent advances of nuclear many-body models, relevant capture rates have been evaluated on the basis of large-scale shell model diagonalization and experimental data, whereever available, for nuclei with $A \leq 65$ and of a hybrid model (Shell Model Monte Carlo plus Random Phase Approximation) for $A \sim 65-100$. The results are quite distinct from the phenomenological input, which has conventionally been used in collapse simulations and which is based on an intuitive parametrization of the GT resonance energies and strengths, and on the experimental data available at the time when Fuller, Fowler and Newman (FFN) performed their seminal work [13]. The consequences for the so-called presupernova models, which study the collapse until the core reaches a density of about 10^{10}g/cm^3 and neutrino transport becomes an important ingredient, are significant. Interestingly, β-decays can compete with electron captures for a short period during silicon burning, adding an important cooling source. Implications for the final collapse, where electron captures on nuclei have been treated very crudely, are currently being explored.

Given the importance of weak-interaction processes during the collapse, a strong and dedicated experimental program to test and give credibility to the new shell model calculations is therefore warranted. Experimentally, GT transitions can be studied using intermediate nucleon-nucleus scattering at low momentum transfers. In the GT$_-$ direction (important for β decays) this goal has been achieved through (p,n) and (^{3}He,t) charge-exchange reactions. On the other hand, the determination of the B(GT$_+$) strength, as required for electron captures, is considerably more difficult. The neutron beams, which were used in the pioneering (n,p) experiments at TRIUMF, were secondary beams produced through the ^{7}Li(p,n) reaction, and typical values for the resolution obtained in these experiments were on the order of 1 MeV. Further, the low intensities and low detection efficiencies require thick targets, which makes a study on rare isotopes (like e.g. the odd-N nuclei) prohibitively expensive. More recently, secondary triton beams at sufficiently high energies have become available, which allow the study of GT$_+$ transitions rather competitively through the (t,^{3}He) reactions. Another and potentially even more powerful tool to explore the spin-isospin-flip transitions in the GT$_+$ direction is the (d,^{2}He) reaction. Here ^{2}He denotes a two-proton unbound state in the $^1S_0$(pp), T=1 channel.

A major development step for (d,^{2}He) experiments was recently achieved by a group at the KVI Groningen who demonstrated that a resolution on the order of 150 keV can readily be obtained with their spectrometer equipment [14].

In the case of vanishing momentum transfer, the (d,^{2}He) reaction proceeds through the same $\boldsymbol{\sigma\tau}$ part of the effective interaction as in the (n,p) case and the measured cross section is directly proportional to the B(GT$_+$) strength. The equivalence of the (n,p) and the (d,^{2}He) reactions has recently been demonstrated by a detailed comparison with the (p,n) reaction on the self-conjugate nuclei ^{12}C and ^{24}Mg. The study of the (d,^{2}He) reaction for heavier nuclei, like those in the pf-shell, is now successfully underway. A recent spectrum for the reaction ^{51}V(d,^{2}He)^{51}Ti is shown in Fig. 6 and contrasted with what was previously possible using the (n,p) probe. The present energy resolution of about 150 keV (FWHM) allows a rather detailed comparison with theory up to individual levels. An extensive experimental program, using the promising GT$_+$ probe, will not only supply direct information about specific GT$_+$ transitions and energies, which can be used in the electron capture rate evaluations, it will also detect possible shortcomings in the shell model residual interaction and hence indirectly improve the rate compilations. Data which are of paramount importance include GT strength distributions for odd-odd nuclei and odd-A odd-N nuclei, for which the shell model predicts the GT$_+$ strength to reside systematically higher in excitation energy than parametrized in the FFN compilations. These systematic differences are often amplified to more than an order of magnitude differences in the capture rates. Clearly this situation warrants clarification.

In the later stage of the collapse, the matter composition involves many nuclei with proton numbers $Z < 40$ and neutron numbers $N > 40$, for which GT$_+$ transitions in the simple independent particle model are completely blocked. Here it is essential to know how strongly thermal excitations and correlations, which mix the (fp) and (gds) orbitals, provide an unblocking of the GT$_+$ strength. An experimental program must be therefore extended into this mass range.

Clearly some essential and much needed information can be obtained with charge-exchange experiments on stable nuclei. However, many unstable neutron-rich nuclei are quite abundant in the core, particular during the final collapse. To obtain these GT$_+$ data, requires the availability of radioactive ion-beams and charge-exchange experiments using inverse kinematics.

We mention that dedicated β decay measurements, also involving unstable nuclei, are important. For one, they can supply relevant information about low-lying transitions which are often decisive for the stellar weak-interaction rates at the onset of the collapse, and further, they deliver data against which charge-exchange measurements can be compared with or normalized to.

During the collapse, electron capture processes produce ν_e neutrinos in the energy range of MeV's to tens of MeV. The role neutrino-nucleus reactions play is not fully explored. While charged-current (ν_e, e^-) reactions are strongly Pauli-blocked due to the large electron chemical potential, inelastic neutrino-nucleus scattering may compete with inelastic neutrino-electron scattering as the energy-exchange mechanism to thermalize the neutrinos in the core. Reliable estimates of (ν, ν') cross sections, which can be enhanced significantly due to finite temperature, require the knowledge of the GT and first-forbidden isovector spin-dipole response, where the finite-temperature effects are mainly sensitive to the detailed distribution of the GT$_0$ strength. Due to the potential importance of inelastic

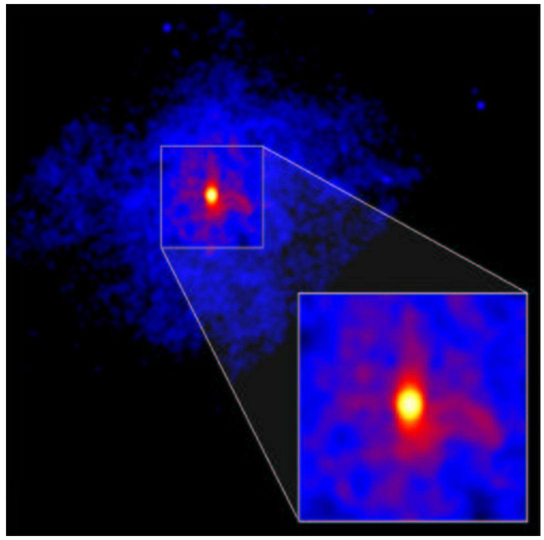

Figure 7: The photon radiation of the neutron star in the supernova remnant 3C58, born in AD 1181, and observed by AXAF-Chandra. The results were published in April 2002. This youngest observed neutron star is too cold to be explained by a standard cooling scenario. Courtesy of NASA.

neutrino-nucleus scattering, systematic theoretical estimates for these reactions should be made and an experimental program to test and improve the theoretical estimates is needed.

4.2 Weak-interaction processes in hot, dense matter

Neutron stars (NS) are formed in the center of massive stars during their supernova explosion. Here the matter temperature can exceed 10^{11} K, making the EOS of hot, dense matter and neutrino transport (opacities) crucial ingredients for NS births and supernova explosion models [15]. Calculations of the EOS and neutrino opacities under such conditions have to be improved by using more realistic strong interactions, which, in particular, include the effects of tensor correlations among nucleons. If one considers that about 99 % of the energy released in the explosion is carried away by neutrinos and that only a tiny $\sim 1\%$ fraction of this energy must be transferred by neutrino absorption on nucleons to matter behind the stalled shock wave to achieve a successful explosion, then it is quite obvious that neutrino transport in hot, dense matter is of paramount importance for reliable supernova models.

Weak interaction processes accompanied by neutrino emission are responsible for the cooling of neutron stars during the first 10^5 years of their life. An improved description of such processes, based on more realistic strong interactions and considering the in-medium renormalization of the weak interaction, is necessary. The effects of nucleon superfluidity on NS cooling should further be studied. Forthcoming observations of cooling neutron stars at known distance and age will be decisive for constraining the theoretical models. Also the discovery of young neutron stars of known age would be of great importance, as they can supply convincing arguments for the presence of non-standard neutrino-emission processes (direct Urca with nucleons, pion or kaon condensates, or maybe even quark matter) in neutron-star cores (see Fig. 7).

4.3 Neutron star models

Current models divide the interior of a neutron star into two regions - the crust and the core [16, 17]. The crust, forming the outer layer of ~ 1 km thickness, contains atomic nuclei immersed in a dense electron gas, and, above the neutron-drip point at densities $\rho \sim 5 \times 10^{11}$ g/cm^3, also in a neutron gas. At the bottom of the crust the density reaches $\rho \sim 10^{14}$ g/cm^3, and only a few percent of nucleons

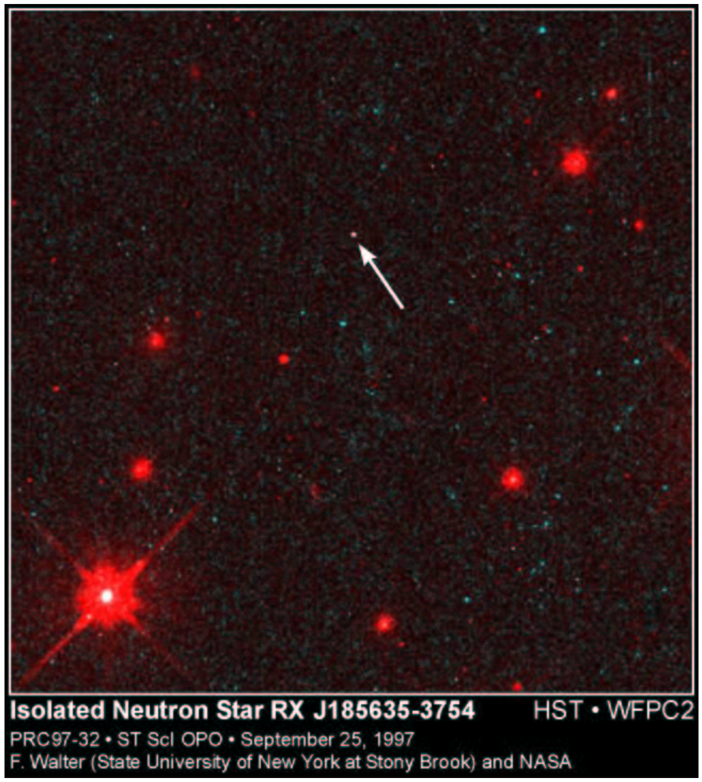

Figure 8: The arrow points to the solitary neutron star RX 185635-3754 at 120 pc from the Earth. The measurement of its photon spectrum by several space detectors (AXAF-Chandra, Hubble Space Telescope, IUE) enabled the determination of its radius. In spring 2002, a heated debate started on whether it is a quark star. See also Fig. 9. Courtesy of NASA.

are protons. Under the crust lies the liquid core. For nuclear densities around $\rho \sim 3 \times 10^{14}$ g/cm^3 it consists of a plasma of neutrons with a few percent admixture of protons and electrons. With increasing density, muons and hyperons are expected to appear in the matter. The central density of neutron stars can be as high as $(5-10)$ times nuclear densities. This makes theoretical models rather uncertain. Some of these models predict that the inner core of neutron stars consists of kaon or pion condensates, or even of quark matter. It will be one of the major challenges to test these predictions in the future.

The outermost layer of a neutron star is called the outer crust. It is composed of neutron-rich nuclei immersed in a dense electron gas. These nuclei, which are beta-unstable in the laboratory, are stable in dense matter due to the Pauli-blocking of the final electron states by the degenerate electron gas. For matter densities $\rho < 10^{11}$ g/cm^3 the outer crust is expected to contain nuclei which can be studied in the laboratory. Of particular interest is the doubly-magic nucleus ^{78}Ni which is expected to be quite abundant at densities $\rho \simeq 10^{11}$ g/cm^3, found in the outer crust some 300 m below the neutron-star surface. Therefore, experimental and theoretical studies of this and the neighboring nuclei are of great interest. Nuclei, present at higher densities (depth), have to be described by nuclear-mass formulae. More reliable mass formulae at $Z/A \simeq 0.3$ are essential for the correct modelling of the bottom layers of the outer crust. The structure of the outer crust, and in particular its matter composition, is essential for the correct interpretation of surface temperature data of cooling neutron stars, obtained form X-ray observations.

The structure of the inner crust, in which very neutron-rich nuclei are immersed in a neutron gas, can only theoretically be calculated. New and more reliable effective nuclear interactions as well as efficient and precise many-body simulations are needed to improve models of this part of the

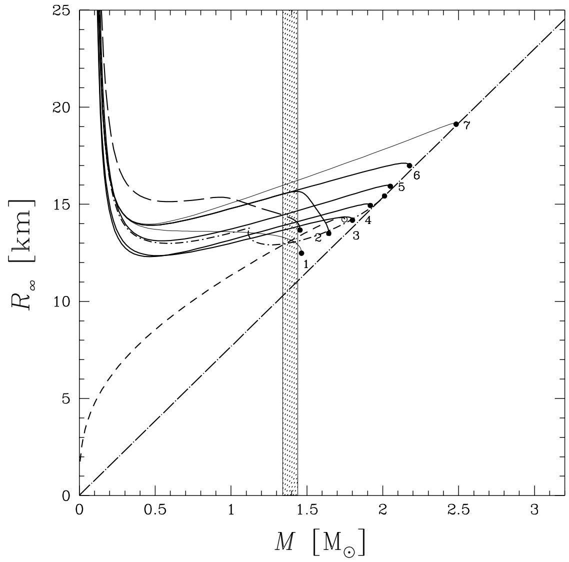

Figure 9: The so-called "radiation radius" (or "apparent radius") R_∞, as measured by a distant observer, versus the neutron star mass M, for several theoretical Equations of State of dense matter. The dashed strip corresponds to precisely measured masses of neutron stars. The long-dashed-dotted line is an absolute lower-bound on R_∞ at a given M which is a consequence of space-time curvature around the neutron star. The short-dashed line, which allows for very low values of R_∞, corresponds to strange (quark) stars. Notice that R_∞ cannot be smaller than 11 km for ordinary neutron stars. Sensational reports in April 2002 claimed that RX 185635-3754 has the apparent radius smaller than 8 km (and is therefore a low-mass quark star); however, this result was questioned later. Courtesy of P. Haensel.

crust, which is important for the understanding of phenomena like the glitches in radio-pulsar timing. Particularly important here is the determination of the structure of the crust-core interface and of the interaction of superfluid neutrons with nuclei forming a crustal lattice. These two aspects are currently treated rather crudely in neutron star models. While the knowledge of the EOS of the crust is relatively good, the uncertainties in the actual crust composition (pure or heterogeneous), which depends sensitively on the kinetics of its formation, are still large.

The core of the neutron star is expected to contain some $95-98\%$ of its mass. The core EOS is essential for the neutron-star structure, and in particular for the determination of the maximum mass for neutron stars, $M_{\rm max}$; compact objects with $M > M_{\rm max}$ then have to be black holes. The knowledge of the core composition and the EOS above twice nuclear densities becomes increasingly worse with increasing density and is clearly insufficient at 5-10 times nuclear densities. Up to now, the most reliable existing EOS of the core were derived assuming the simplest possible composition (neutrons, protons, electrons, muons) and using the best realistic nucleon-nucleon interactions supplemented with phenomenological three-body forces. These EOSs predict a maximum neutron star mass $M_{\rm max} = (1.9-2.2)\ M_\odot$. State-of-the-art many-body theories with the best existing N-N interactions should be implemented to narrow the ambiguities of the present EOSs, taking advantage of the impressive power of the forthcoming computing facilities. The role of the three-body and four-body forces as well as of relativistic effects in the many-body problem must be clarified. Studies of the impact of hyperons on the EOS should be continued, including the extension of the nucleon interactions to the hyperon sector. However, the progress is here to a large extent limited by poor experimental knowledge of the hyperon-nucleon and hyperon-hyperon interaction.

The development of a reliable core EOS can benefit significantly from heavy-ion collision experiments, which probe the EOS of dense hadronic matter, albeit under different physical conditions than those in neutron star cores.

On the observational side, new determinations of NS masses in binary systems, and in particular more precise measurements of masses in the range $(1.6 - 2.0)\ M_\odot$ (measured in some X-ray binaries) could shed light on the actual value of $M_{\rm max}$ for neutron stars and would put severe constrains on the hyperon-nucleon interactions in dense matter, which are decisive for the thresholds at which hyperons appear in dense matter. The NS radius is very sensitive to the EOS. Calculations show a correlation of neutron star radii with neutron radii of heavy nuclei; precision measurements of such radii for lead isotopes might be quite helpful. The observational determination of NS radii has just begun, but holds great future potential. The measurement of radii of neutron stars with $M = (1.0 - 1.6)\ M_\odot$ will allow the determination of the EOS at two-three times nuclear densities, and puts severe constrains on the theory of nuclear matter at supranuclear densities (Figs. 8, 9). We note that the neutron star structure is also important for the shape of gravitational waves emitted at the final stage of the coalescence of a neutron star - neutron star binary, which is considered as the most promising astrophysical source of gravitational radiation searched for by the gravitational-wave detectors which will become operational in this decade.

Different models predict the existence of quite exotic phases of dense matter in neutron stars (pion and kaon condensates, quark matter). Therefore experimental searches for the precursors of phase transitions in dense nuclear matter, as they might be produced in heavy-ion collisions, are of paramount importance. A possible candidate is the enhancement of the K^- yield observed in heavy-ion collisions at the GSI. Such experimental efforts have to be extended. Observational signatures for a phase transition in the NS core can be deduced from anomalies during spin-down or from abnormally small pulsation frequencies or radii. There is general concensus that the observation of a stellar "apparent radius" smaller than 11 km will be a reliable proof that strange quark stars built from deconfined self-bound quark matter exist (see Figs. 8-9). Further important constrains come from experiments at CERN and RHIC searching for the quark-gluon plasma and, in particular, for stable or metastable strange-matter.

5 Explosive burning

5.1 The p-process

It is now well accepted 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 to 3 billion degrees, which can be reached in those layers, the p-nuclei are synthesized by (γ,n) photodisintegrations of preexisting 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 as in the envelope of exploding sub-Chandrasekhar mass white dwarfs on which He-rich material has been accreted. These alternative sites require improved explosion modelling to guarantee a reliable p-process seed abundance distribution.

The p-process is essentially a sequence of (γ,n), (γ,p) or (γ,α) photodisintegrations reactions, possibly complemented by captures of neutrons, protons or α-particles at energies typically far below 1 MeV or the Coulomb barrier in the case of charged particles. So far, relevant rate measurements, mainly involving radiative neutron and proton captures, are only available for stable targets. This data base covers not more than a minute fraction of the needs for p-process simulations. As the measurements are for the target ground state only, possible contributions of excited states to the stellar rates will have to be modelled. The available experimental data play an important role in the validation of the various nuclear ingredients entering theoretical predictions (see Sect. 7) and can also be used in estimates of reverse photonuclear rates.

Recent experiments have provided direct measurements of some (γ,n) reactions at the low energies of interest for the p-process, i.e close to the photodisintegration threshold. One of the techniques is based on the construction of a quasi-thermal photon spectrum from a superposition of bremsstrahlung spectra with different endpoint energies. As an alternative, the 'Laser Inverse Compton (LIC)' γ-ray source uses a real photon beam in the MeV region produced by head-on collisions of laser photons on relativistic electrons and produces quasi-monochromatic γ-rays in the energy range 1 to 40 MeV. An important advantage of the LIC γ-rays over the bremsstrahlung approach is their more intense peaking in the energy window of astrophysical interest in addition to their better quasi-monochromaticity. The bremsstrahlung and LIC techniques have been used so far to measure the rates of a few (γ,n) reactions. In particular, the latter experimental approach has provided cross sections to the ground and isomeric state for the $^{181}\mathrm{Ta}\,(\gamma\,,\mathrm{n})\,^{180}\mathrm{Ta}$ reaction, which is of special interest in p-process models. These measurements have to be complimented by the determination of the $^{180}\mathrm{Ta}^{\mathrm{m}}\,(\gamma\,,\mathrm{n})\,^{179}\mathrm{Ta}$ reaction rate. Another prime interest in p-process studies is the synthesis of the rare odd-odd p-nuclide ^{138}La. This requires the measurements of the $^{139}\mathrm{La}\,(\gamma\,,\mathrm{n})\,^{138}\mathrm{La}$ and $^{138}\mathrm{La}\,(\gamma\,,\mathrm{n})\,^{137}\mathrm{La}$ reaction rates. More generally, systematic measurements of the photoneutron cross sections at energies close to the neutron threshold will certainly reduce the remaining uncertainties in the stellar rates for the numerous isotopes involved in the p-process.

Experimental data for charged-particle induced reactions of p-process interest used to be scarce. This situation is largely due to the smallness of the related reaction cross sections at the sub-Coulomb energies of astrophysical interest. However, an important effort has recently been devoted to the measurement of a series of (p,γ) reaction cross sections on medium mass nuclei with $34 \le Z \le 51$ at low enough energies to be of astrophysical relevance. These experiments conducted principally at small facilities (Demokritos, Stuttgart) make use of two techniques, the activation method and the in-beam measurements. So far, data are available only for stable targets up to about Sb. A compilation of the present data, as well as an extension of the experimental efforts towards heavier ($Z > 50$) targets would be most valuable in order to better constrain and improve global reaction models (Sect. 7).

The (γ,α) reaction rates are usually determined from data on the reversed reactions. However, relevant (α,γ) data are very rare. At this point, the only reactions which have been studied experimentally at sub-Coulomb energies are $^{70}\mathrm{Ge}\,(\alpha\,,\gamma)\,^{74}\mathrm{Se}$, $^{96}\mathrm{Ru}\,(\alpha\,,\gamma)\,^{100}\mathrm{Pd}$, $^{139}\mathrm{La}\,(\alpha\,,\gamma)\,^{143}\mathrm{Pr}$, and $^{144}\mathrm{Sm}\,(\alpha\,,\gamma)\,^{148}\mathrm{Gd}$. The recent $^{144}\mathrm{Sm}\,(\alpha\,,\gamma)\,^{148}\mathrm{Gd}$ experiment is not only of special astrophysics interest, but also a stringent test case for a reliable determination of the α-nucleus optical potentials at low energies. Indeed, all parametrizations failed to give a satisfactory description of the reaction cross section at the lowest energies (around 10 MeV) of interest for the p-process. This measurement illustrated quite drastically the difficulties to reliably predict low-energy (α,γ) cross sections. New experimental data, especially for low-energy radiative captures on nuclei in the $A \simeq 100$ and $A \simeq 200$ mass range, are strongly required in order to further constrain the determination of a reliable global α potential. In this respect, low-energy elastic α-scattering, as well as captures of the (α,n), (n,α) or (α,p) types will also bring valuable information about the α-particle-nucleus interaction.

5.2 Neutrino nucleosynthesis

When the flux of neutrinos generated by the cooling of the neutron star in a type II supernova passes through the overlying shells of heavy elements, substantial nuclear transmutations are induced, despite the extremely small neutrino-nucleus cross sections. Specific nuclei (e.g. ^{10,11}B, ^{15}N, ^{19}F) might be, by a large fraction, made by this neutrino nucleosynthesis. These are the product of reaction sequences induced by neutral current (ν,ν') reactions on very abundant nuclei such as ^{12}C, ^{16}O or ^{20}Ne. If the inelastic excitation of these nuclei proceeds to particle-unbound levels, they will decay by emission of protons or neutrons, in this way contributing to nucleosynthesis. As the nucleon thresholds are relatively high, effectively only ν_μ, ν_τ neutrinos and their antiparticles with their higher average energies contribute to the neutrino nucleosynthesis of these elements. It is generally assumed that the ν-process might also be responsible for the production of ^{138}La and to a fraction of the ^{180}Ta abundance. The ^{138}La nuclide is of special interest as it appears to be produced by the charged current (ν_e, e^-) reaction on the s-process element ^{138}Ba. Complimenting the constrains for supernova $\bar{\nu}_e$ neutrinos from their observation in the water Cerenkov detectors for SN1987A, its sensitivity to the flux and distribution of supernova ν_e and ν_μ, ν_τ neutrinos makes the ν process an important test for the predictions of supernova models. This test is particularly stringent, if neutrino oscillations involving ν_e neutrinos occur in the supernova environment.

Simulations of neutrino nucleosynthesis requires the knowledge of neutrino-induced particle emission cross sections. For the lighter elements this requires the determination of the Gamow-Teller (GT_0) and spin-dipole response on nuclei like ^{12}C, ^{16}O and ^{20}Ne, including the cascade of decays of the excited levels. The cross sections for ^{20}Ne, needed for the ^{19}F production, appear to be the most uncertain. The modelling of the ^{138}La (and ^{180}Ta) ν-process abundance needs, in particular, the knowledge about the allowed GT_- response on ^{138}Ba below the particle thresholds in ^{138}La. Furthermore, ν nucleosynthesis of ^{138}La and ^{180}Ta competes with the p-process production of these elements, making a reliable determination of the p-process abundances also important. We note that precision measurements at electron-beam facilities can provide important detailed information about several of the relevant reactions.

5.3 Nucleosynthesis in explosive Binary Systems

Thermonuclear explosions in accreting binary star systems have been an object of considerable attention. The basic concept of the explosion mechanism seems reasonably well understood, but there are still considerable discrepancies between the predicted observables and the actual observations. The proposed mechanism involves binary systems with one degenerate object, like white dwarfs or neutron stars, and is characterized by the revival of the dormant objects via mass overflow and accretion from the binary companion. The characteristic differences in the luminosity, time scale, and periodicity depend on the accretion rate and on the nature of the accreting object. Low accretion rates lead to a pile-up of unburned hydrogen, causing the ignition of hydrogen burning via pp-chains and CNO-cycles with pycnonuclear enhancements of the reactions after a critical mass layer is attained. On white dwarfs this triggers nova events, on neutron stars it results in X-ray bursts. High accretion rates above a critical limit cause high temperatures in the accreted envelope and less degenerate conditions, which result in stable hydrogen burning. Such high accretion conditions on white dwarfs cause supernova type Ia events. These events are the largest thermonuclear explosions in the Universe and the observed relation between lightcurve and intrinsic brightness for nearby type-Ia supernovae makes them astronomical standard candles. In the last years an extended program of observation of high-redshift supernovae led to the spectacular and surprising finding of an accelerated expansion of the Universe. Here, a better knowledge of the explosion mechanism is essential to confirm the brightness-lightcurve relation also for low metallicity SN. Type Ia supernovae are usually associated with a large amount of ^{56}Ni formation and, hence, are considered the main producers of iron elements in the Universe. Electron captures on the incinerated material, plus the neutron excess previously stored in the He-burning product ^{22}Ne, lead to the production of neutron-rich isotopes such as ^{48}Ca, ^{50}Ti, and ^{54}Cr. The final amount depends sensitively on the propagation speed of the burning front and the relevant electron capture rates, the latter being likely the most important nuclear physics input required in type Ia models.

Currently large uncertainties are associated with the modelling of accretion, explosion mechanism and burning front development and with the microscopic nuclear physics component of novae and

X-ray bursts. The nuclear energy generation provides the observed luminosity of the event, the combination of rapid mixing, convection and far-off-stability nucleosynthesis is responsible for the observed abundances in the ejecta. Simulations of novae and X-ray bursts will noticeably benefit from post-accelerator facilities for radioactive ion-beams. After the pioneering work at Louvain-la-Neuve, new facilities just started operation at CERN (Rex-Isolde), at Ganil (Spiral) and at TRIUMF (ISAC-1) which promise to remove the uncertainties of some of the key reactions involved in the respective nuclear networks.

Novae White dwarfs, which are extremely dense degenerate stars, constitute the final phase of the evolution of low and intermediate mass stars. Their composition is mainly C, O or O, Ne, depending on the progenitor mass. Accretion of hydrogen-rich material from the envelope of a companion star and its mixing into the white dwarf matter leads to the onset of hydrogen burning under degenerate conditions. After accretion of a critical amount of matter, the hydrogen is burned explosively via the hot CNO, NeNa and MgAl cycles at high temperature ($T \leq 2{\cdot}10^8$K) and density ($\rho \approx 10^4$ g/cm^3). The burning products are ejected into the interstellar medium, where they can be detected by astronomical observations, which put important constrains on the models.

The principal interest in novae modelling in the past five years focussed on the synthesis of the radioactive isotopes ^{7}Be, ^{18}F, ^{22}Na and ^{26}Al. The observation of the characteristic gamma-ray emission of these isotopes from a nearby nova is among the objectives of the European satellite INTEGRAL. Comparison of the observed *isotopic* yields with model results will give stringent constrains to some model parameters, and in particular on the still uncertain mixing process of the accreted hydrogen with the white dwarf material and the magnitude of the ejected mass. Nuclear astrophysics in Europe is especially well prepared to advance significantly in these questions with the availability of a state-of-the-art hydrodynamical nova code at Barcelona and the large amount of INTEGRAL data to be expected. However, some important nuclear input to these models is still needed to achieve this goal, especially reaction cross sections involving unstable isotopes.

The nuclear reaction network in nova explosions extends up to mass $A \approx 35$ and includes proton capture reactions on several short-lived isotopes on the neutron-deficient side of the stability valley. The determination of the relevant cross sections has begun in some pioneering experiments at radioactive ion-beam facilites like ORNL, Argonne and Louvain-la-Neuve for the ^{18}F(p,α) reaction, which determines the final amount of ^{18}F synthesized in novae. This isotope is detectable in the first few hours after the explosion in the expanding shell of the ejected material by the characteristic e^+e^- annihilation radiation following its β-decay. Other important reactions for the synthesis of ^{22}Na and ^{26}Al include e.g. the short-lived isotopes ^{21}Na and ^{25}Al. The flow out of the MgAl-cycle to higher masses passes by several neutron-deficient P and S isotopes. For all these isotopes, including also some stable ones, proton capture cross sections at thermonuclear energies must be determined.

Much progress will certainly come in the near future from the availability of beams of these unstable isotopes at radioactive ion-beam facilities. Reaction cross sections at nova temperatures are generally very small and indirect approaches, like transfer reactions, ANC or the recently developed Trojan horse method will play an important role besides direct measurements to determine proton and α-particle spectroscopic factors and branching ratios, needed for the determination of thermonuclear reaction yields. However, also some capture cross sections on stable isotopes have to be known with improved accuracy making facilities for stable isotopes an important complement to the radioactive ion-beams in the near future.

X-Ray Bursts For an X-ray burst, the thermonuclear runaway is triggered by the ignition of the triple-alpha reaction and the break-out reactions from the hot CNO cycle. Therefore the on-set of the

X-ray burst critically depends on the rates of the alpha capture reactions on ^{15}O and ^{18}Ne. Although recently progress in experimentally determining these rates has been achieved by using either indirect techniques or radioactive ion-beams in inverse kinematics, both rates are not known with the necessary accuracy. The thermonuclear runaway is driven by the αp-process and the rapid proton-process (short rp-process) which convert the initial material rapidly to ^{56}Ni causing the formation of Ni oceans at the neutron star surface. The αp-process is characterized by a sequence of (α,p) and (p,γ) reactions processing the ashes of the hot CNO cycles, ^{14}O and ^{18}Ne, up to the ^{34}Ar and ^{38}Ca range. The rp-process represents a sequence of rapid proton captures up to the proton drip-line and subsequent β-decays of drip-line nuclei processing the material from the argon, calcium range up to ^{56}Ni and beyond. The runaway freezes out in thermal equilibrium at peak temperatures of around 2.0 to 3.0 billion degrees Kelvin. Re-ignition takes place during the subsequent cooling phase of the explosion via the rp-process beyond ^{56}Ni. The nucleosynthesis in the cooling phase of the burst alters considerably the abundance distribution in atmosphere, ocean, and subsequently crust of the neutron star. This may have a significant impact on the thermal structure of the neutron star surface and on the evolution of oscillations in the oceans.

To verify the present models nuclear reaction and structure studies on the neutron deficient side of the line of stability are essential. Measurements of the break-out reactions will set stringent limits on the ignition conditions for the thermonuclear runaway, measurements of alpha and proton capture on neutron deficient radioactive nuclei below ^{56}Ni will set limits on the time-scale for the actual runaway, but will also affect other macroscopic observables. Recent simulations of the X-ray burst characteristics with self-consistent multi-zone models suggested a significant impact of proton capture reaction rates between A=20 and A=64 on expansion velocity, temperature and luminosity of the burst. Clearly, more experimental data are necessary to remove the present uncertainties.

Nuclear structure and nuclear reaction measurements near the doubly-closed-shell nucleus ^{56}Ni determine the conditions for the re-ignition of the burst in its cooling phase. Structure and reaction measurements beyond ^{56}Ni, in particular the experimental study of 2-proton capture reactions bridging the drip-line for even-even $N = Z$ nuclei like ^{68}Se and ^{72}Kr etc., are necessary to determine the final fate of the neutron star crust. These reaction measurements have to be complemented with decay studies. Of particular importance are beta-decay studies of isomeric and/or thermally populated excited states, which are not accessible by experiment with present equipment. In general there is a substantial need for nuclear structure information at the proton drip-line, especially in the Ge - Kr mass region and most likely up to the Sn-Te-I mass range where the endpoint of the rp-process is expected. The information needed to calculate the flow of nuclear reactions in X-ray bursts includes masses, lifetimes, level structures, and proton separation energies.

After an X-ray burst most of the breeded material is accumulated on the surface of the neutron star where it still is heated by the matter (hydrogen) which flows from the companion in the binary. This heating is highly non-symmetric and occurs mainly at the poles. It forces a pressure on the X-ray burst material underneath, and if the pressure exceeds certain thresholds, nuclei in this material can undergo electron captures. Due to nuclear pairing arguments, the capture will always be in a two-step process where mainly the latter generates some energy which will be released and can be absorbed in the vicinity. The matter will sink deeper into the neutron star, reaching higher densities and then undergoing further electron captures and ultimatively pycnonuclear reactions. The released energy in the captures and the pycnonuclear reactions can be locally stored in the neutron star's ocean and crust and will affect their thermal properties. To model such reaction sequences and their consequences, masses and electron capture rates on neutronrich nuclei are needed; an improved description of pycnonuclear reactions is desirable.

5.4 R-process

About half of the elements beyond Fe are produced via neutron-captures in very neutron-rich environments. The existence of abundance peaks, connected with the major neutron shell-closures, witnesses that neutron-captures have occured far from the valley of stability. Observations of r-process abundances in ultra-poor metal stars by the Hubble Space Telescope reveal what happened in the early age of the Galaxy, when primordial r-nuclides were formed. It is remarkable to see that the abundances of heavy-mass nuclei (beyond A=130) are solar-like and very similar in those stars, although they originate from very different regions of the galactical halo. Therefore, the robust r-abundance pattern above A=130 may be a signature of a unique early "main" r-process of primary nature. Below A=130, one observes "underabundances" in these stars compared to solar ones, with a strong odd-even-Z staggering, which is not present in solar r-material. The missing part to the solar pattern reflects the need for a second "weak" r-process of secondary nature, supported also by geochemical evidence from meteorites. These observations, added with the measured isotopic abundances of Eu and Ba, are a major breakthrough in our view of the r process and of the chemical evolution of the elements.

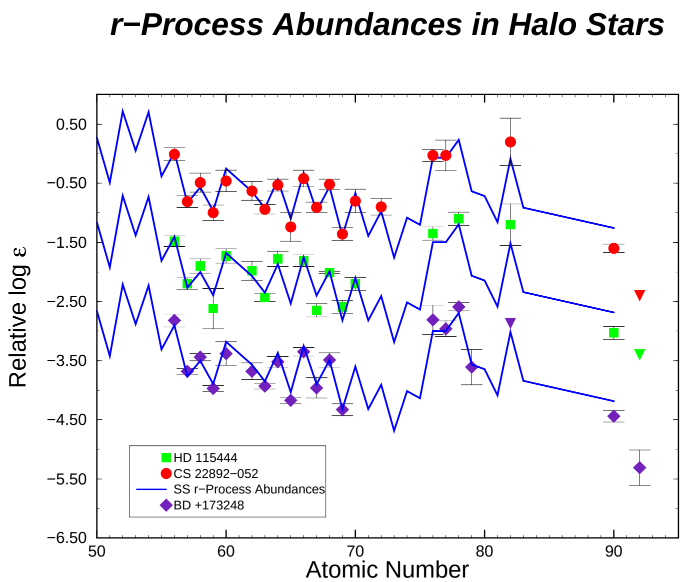

Figure 10: Elemental abundances in three metal-poor halo stars as compared to solar r-material, courtesy from J. Cowan

These findings are supported and supplemented by the abundance patterns of certain refractory inclusions of meteorites which reflect the stellar events in which they were formed. Large isotopic anomalies, with respect to solar, are found in some grains which point to a very neutron-rich production environment. The use of new ionic nanoprobes, which could reveal the composition of sub-micrometer size pre-solar grains, is expected to improve our understanding of the r-process.

Even if the high entropy bubble and neutron-star mergers are likely sites, the exact environment(s), where the r process(es) occurs, still remains a great mystery at present time. We know, however, that r-process nucleosynthesis is a dynamical process in which the r-process path in the nuclear chart depends on the changing conditions of the stellar environment. In hot and very neutron-dense environments, neutron-captures occur on very short timescales and quickly equilibrate with photodisintegrations for nuclei with low neutron separation energies. In such cases, the important parameters for modelling the r-process nucleosynthesis are the masses, which fix the location of the waiting points in each isotopic chain, the β-decay half-lives and the P_n values, which determine the amount of r-progenitors accumulated and to which extent their decay occurs via delayed-neutron(s) emission(s). When the r-process matter reaches lower neutron densities, at which β-decay times are shorter than neutron-capture times, branchings in each isotopic chain occur. It is of key importance to determine the three properties (β-decay half-lives, masses and neutron-capture cross-sections), especially at and around the major neutron closed-shells N=50, 82, and 126, associated with the r-abundance peaks. These magic nuclei (called waiting points) have also longer life-times than their non-magic neighbors and regulate the mass-flow and duration of the r-process.

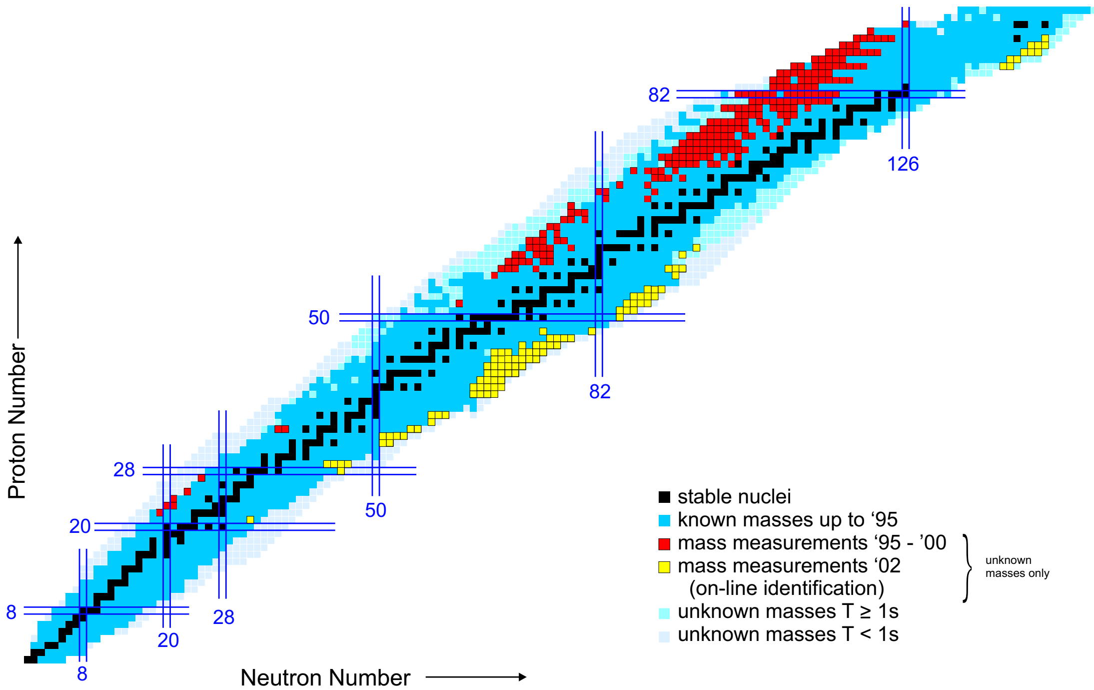

Figure 11: The current knowledge of nuclear masses. Preliminary results obtained on-line from the fragmentation or from the fission of a ^{238}U beam are shown in yellow color, courtesy of Y. Litivinov

As recent major experimental breakthroughs, the β-decays of about 30 neutron-rich nuclei on the r-process path(s) have been measured at the ISOLDE facility, including those of the $N = 82$ waiting points ^{130}Cd and ^{129}Ag. These new results, added to the previous studies at the N=50 closed shell, are important data needed to put constrains on the astrophysical conditions for the build-up and break-out of the A=80 and A=130 r-abundance peaks.

Atomic masses for nuclei far from stability might hold the key for the understanding of nuclear structure in the yet unexplored parts of the nuclear chart. Their knowledge is particularly essential for r-process simulations. In recent years the GSI at Darmstadt has developed a succesful program measuring masses of short-lived fission fragments of a high-energy Pb beam using time-of-flight and Schottky methods; as an illustrative example Fig. 11 shows more than 70 new masses in the $N = 50$ and 82 region obtained at the GSI with the isochronous time-of-flight method. The proposed GSI upgrade with a much higher primary beam intensity and an order of magnitude larger acceptance of the proposed cooler ring promises to measure several hundreds new masses on neutron-rich nuclei, including those of crucial r-process waiting points. Such data are essential to better constrain the location of the r-process for given stellar conditions and will also provide much needed information about potential shell-structure effects. Here, a strongly debated current issue is whether the shell gap in very neutron-rich nuclei (particularly for $N = 82$) is noticeably less pronounced than in stable nuclei. Such an effect would have significant impact on the r-process abundance pattern at the low-A wing of the peaks. Its firm verification, however, needs further experimental study of the r-process progenitor nuclei in the vicinity of the shell closure. In particular, major developments have to be started to produce and study the refractory elements (Mo to Pd) around N=82.

There are currently no data available for r-process nuclei in the region of the N=126 shell closure, which is associated with the third r-process peak at around $A \sim 195$. This is likely to change, when this region can be reached by the high-energy fragmentation of Pb or U beams at GSI. These key experiments will then open a new era in nuclear structure and r-process research, in particular delivering the first measurements of halflives for $N = 126$ waiting points. Beyond $N = 126$, the r-process path reaches regions where nuclei start to fission, demanding an improved knowledge of fission barriers in extremely neutron-rich nuclei to determine where fission terminates the neutron capture flow and prevents the synthesis of superheavy elements with Z>92. If the duration time of the r-process is sufficiently long (as it could be found in neutron star mergers), the fission products can capture again neutrons, ultimately initiating "fission cycling" which can exhaust the r-process matter below $A = 130$ and produce heavy nuclei in the fission region. Fission can in particular influence the r-process abundances of Th and U. This would change the Th/U r-process production ratio with strong consequences for the age determination of our galaxy, which has recently been derived from the observation of these r-nuclides in old halo stars.

The direct measurement of neutron-capture cross sections on unstable nuclei is technically not feasible. This goal can, however, be achieved indirectly by high resolution (d,p)-reaction, which are considered the key tool to study neutron capture cross sections of rare isotopes at radioactive nuclear beam facilities. For r-process nuclides, particular technical advancements need to be made to produce the required beams of a few MeV/nucleon. Studies of beta delayed-neutron decays can help to determine the existence of isolated resonances above the neutron-emission threshold in the daughter nucleus. Such experimental studies will be performed for selected nuclei, in particular at the neutron shell closures, to guide and to constrain global theoretical models. Of particular importance are detailed studies of the soft pygmy resonance which are energetically expected around the neutron threshold and can strongly influence neutron capture cross sections.

6 Non-thermal nucleosynthesis

Spallation reactions induced by highly energetic particles, in particular by Galactic Cosmic Rays (GCR), are a well-established production mechanism for several light elements (Li, Be, and B) and for some isotopic anomalies in meteorites [18].

The understanding of the isotopic composition of the GCR at energies around one GeV per nucleon for elements up to Fe, has progressed significantly by observations made with spacecrafts like ACE and ULYSSES and balloon flights. Data for heavier elements are expected for the near future. This data record will serve to elucidate the origin and the source composition of the GCR, as well as their propagation and the associated production of secondary GCR nuclei by fragmentation reactions with H and He nuclei in the interstellar medium (ISM) [19]. A reliable modelling of the involved nuclear network is crucial. Of particular importance are the various spallation cross sections in the several hundred MeV to several GeV per nucleon range. Proton induced fragmentation cross sections for most of the light elements were determined at BEVALAC, SATURNE and recently at the GSI fragment separator and an extensive set of accurate data is available to interpret the GCR composition up to Fe/Ni. This effort must be continued to heavier elements and accompanied by theoretical studies to obtain a complete set of cross section data to interpret the observations.

Recent observations of the abundances of the light elements Li, Be, and B in metal-poor stars force us to modify our understanding of the Galactic chemical evolution of these elements. In the standard spallation model it is assumed that these elements are solely made by fragmentation reaction on CNO nuclei in the ISM, induced by fast protons and α-particles in the GCR. However, the new data suggest that significant amounts of Li, Be and B may be produced in OB associations, i.e. groups of stars that

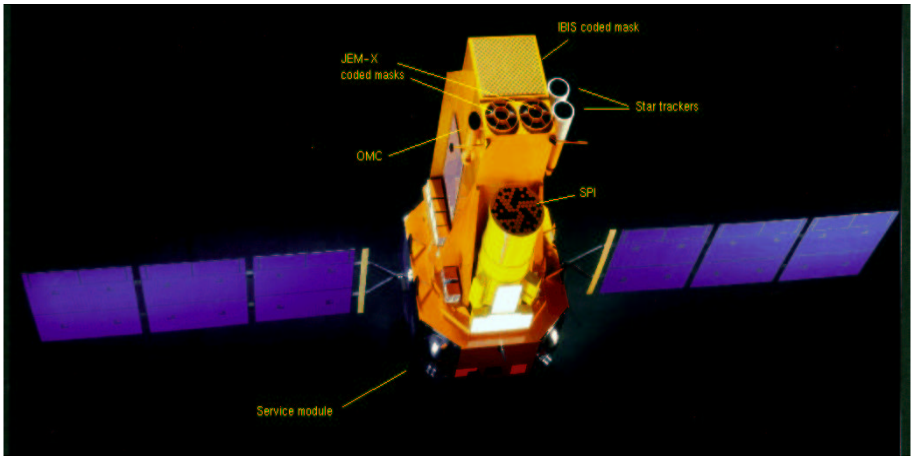

Figure 12: Artist impression of the INTEGRAL satellite. It combines unprecedented angular resolution (12 arcmin with the imager IBIS) and energy resolution (2.3 keV at 1.3 MeV with the spectrometer SPI) for gamma-ray astronomy. Among the scientific objectives are the galactic distribution of radioactive isotopes synthesized in stars, novae and supernova explosions and γ-rays from cosmic-ray interactions. Image: ESA/INTEGRAL

are dominated by main-sequence stars of O and B spectral types, via the spallation of accelerated C and O nuclei at energies below several hundred MeV per nucleon. This last process can be dominant in the early Galaxy. Detailed studies of the origin of the particles and their acceleration mechanism in OB associations and in the ISM are clearly needed.

Decisive progress in the solution of these questions is expected from γ-ray astronomy. Many of the nuclear reactions induced by cosmic-ray nuclei are accompanied by prompt de-excitation of excited nuclear levels populated by inelastic scattering, transfer or spallation reactions, or they are followed by delayed γ-ray emission from radioactive species or π^0-particles which are produced in these collisions. The associated nuclear γ rays will be observed by future space missions like INTEGRAL, AGILE and GLAST. For example, these missions will detect strong γ-lines produced in inelastic scattering of cosmic-ray protons and α-particles on nuclei like ^{12}C, ^{16}O and ^{56}Fe, which are abundant in the ISM, and from α-α reactions. As this γ-ray production is most effective for cosmic rays below a few hundred MeV per nucleon, the observed lines and their intensities can be converted into the determination of the cosmic-ray spectrum in this energy range. Similar γ-ray production occurs in strong solar flares. This field will benefit tremendously from the dedicated observations expected from the RHESSI spacecraft.

To make optimal use of the detailed high-resolution spectroscopic informations from INTEGRAL and RHESSI, progress in our knowledge of the various γ-ray emission processes and the completion of the required cross section data base are needed. In particular, differential particle and γ-ray cross sections and particle-γ correlations from threshold to typically one hundred MeV per nucleon must be known to interpret the observed line shapes. To complete the data base, cross sections above the γ-production threshold for proton- and α-induced reactions on the abundant nuclear species in the ISM between ^{12}C and ^{56}Fe are required. This is a task which is well suited for tandem accelerators at university or smaller research laboratories. The experimental efforts have to be accompanied by systematic optical model calculations.

Recent studies of extinct radioactivities in meteorites indicate that the gas and dust disk of the solar system might have been irradiated by energetic particles during a relatively short period of the solar system formation. By analogy with solar flares, where the energetic particle composition is greatly enhanced in ^{3}He, it is assumed that ^{3}He-induced reactions on relatively abundant nuclei like ^{24}Mg and ^{40}Ca could have produced an important amount of the exctinct ^{26}Al and ^{41}Ca nuclides. To test this hypothesis, which could have far-reaching consequences for our understanding of the solar system formation, measurements of several specific cross sections, especially for ^{3}He-induced reactions below hundred MeV per nucleon are required.

7 Nuclear modelling

The specific astrophysical conditions make a direct experimental determination of required nuclear input often impossible. Thus, despite important effort in the last decades to measure astrophysically relevant data, theoretical models are often needed to translate these data from laboratory to stellar conditions. For example, most charged-particle induced reactions at stellar energies, i.e. at energies far below the Coulomb barrier, have cross-sections that are far too low to be measured at the present time (Sect. 3). Stellar reactions often concern unstable or even exotic (neutron-rich, neutron-deficient, superheavy) species for which no experimental data exist. Certain astrophysical applications like the r- or p-processes (see Sect. 5) involve thousands of unstable nuclei for which many different properties have to be determined (including ground and excited state properties, strong, weak and electromagnetic interaction properties). In high-temperature environments, thermal population of excited states by electron or photon interactions, as well as ionization effects significantly modifies the nuclear properties in a way which is impossible to measure in the laboratory. For all these extreme conditions found in astrophysical environments, theorists are requested to supply the required nuclear input if it is experimentally not available.

The description of the many nuclear processes in stars requires a careful and accurate account of all physically relevant input data so that nuclear models have to be "physically accurate" and "globally applicable" at the same time. A global description of all required nuclear input within one unique model ensures a coherent prediction of all unknown data. The need of extrapolating data from experimentally known regions favors microscopic models with a sound first-principle foundation.

Many global microscopic approaches have been developed for the last decades and are now more or less well understood [20]. However, they were almost never used for practical applications, because of their lack of accuracy in reproducing experimental data on a global scale. The low global accuracy mainly originated from computational complications making the determination of free parameters in the models by fits to experminental data time-consuming. This shortcoming has been overcome in recent years and todays microscopic models can be tuned to the same level of global accuracy as the phenomenological multi-parameter models, which have conventionally been used to describe experimentally unknown input in astrophysical scenarios. The following subsections describe some of the advances and future needs in nuclear modelling.

7.1 Reaction models

As the degrees of freedom increase drastically with the number of nucleons, models of different sophistication have to be chosen for the various regions in the nuclear chart. Exact calculations using realistic nucleon-nucleon interactions, e.g. by Green's Function Monte Carlo techniques, are restricted to light nuclei. As an alternative, methods based on effective field theory have recently been developed for few-nucleons systems. Both approaches have demonstrated their ability to reliably describe reactions with light nuclei.

Another useful tool for the extrapolation of data for reactions of light and certain medium-heavy nuclei is the microscopic cluster model which groups the nucleons into clusters and determines the totally antisymmetrized relative wave functions between the various clusters by solving the Schrödinger equation for a many-body Hamiltonian with an effective nucleon-nucleon interaction. This approach has the major advantage of providing a consistent description of bound, resonant, and scattering states of a nuclear system and has successfully been applied to determine the low-energy cross sections for many astrophysically important reactions. Despite these successes, more effort in that direction is obviously needed.

For reactions involving heavy nuclei, most of the cross section calculations needed for nucleosynthesis applications are based on the statistical Hauser-Feshbach model. This model makes the fundamental assumption that the process proceeds via the intermediate formation of a compound nucleus in thermodynamic equilibrium. This assumption is justified if the level density in the compound nucleus at the projectile incident energy is large enough to ensure an average statistical superposition of states. However, when the number of available states in the compound system is relatively small, as this is the case for many proton capture reactions in the rp-process, the capture process is mainly dominated by direct electromagnetic transitions to a bound final state. In general, direct reactions play an important role for light, closed-shell or exotic neutron-rich systems for which no resonant states are available.

Both the direct and statistical models have proven their ability to predict cross sections accurately. However, these models suffer from uncertainties stemming essentially from the predicted nuclear ingredients describing the nuclear structure properties of the ground and excited states, and the strong, weak and electromagnetic interaction properties. The description of these fundamental nuclear properties will benefit significantly from recent progress and future advances in microscopic and semi-microscopic models which we will describe in the next subsections.

7.2 Ground state properties

Global mass models have recently been derived within the non-relativistic Hartree-Fock and relativistic Hartree methods. Making use of a Skyrme force which has been adjusted to essentially all known masses, it has been demonstrated that the microscopic Hartree-Fock approach can successfully compete in overall reproduction of the measured data with the most accurate empirical droplet-like formulas available nowadays. This quality is achieved not only when the pairing force is described in the BCS approximation, but also when the Bogoliubov method is adopted (HFB model), which treats the nuclear single-particle and pairing properties self-consistently. Although complete mass tables have now also been derived within the HFB approach, further developments which affect the mass extrapolations towards the neutron drip-line are still needed. Moreover, effective interactions for the present state-of-the art mean field models have to be developed which consistently describe the many observables needed (such as giant dipole or Gamow-Teller excitations, infinite nuclear matter properties). These various nuclear aspects are extremely complicated to reconcile within one unique framework and the quest towards universality will most certainly be a focus of nuclear physics research for the coming decade. This quest will tremendously benefit from future developments in nuclear models beyond the mean-field approach, like the shell model or the cluster expansion approaches.

7.3 Nuclear level densities

Until recently, only classical approaches were used to estimate nuclear level densities for practical applications. Several approximations used to obtain the nuclear level density expressions in an analytical form can be avoided by quantitatively taking into account the discrete structure of the single-particle spectra associated with realistic average potentials. In a recent global calculation, based on the HF-BCS model, it has been shown that all the experimentally available level density data can be described to an accuracy comparable with the widely used phenomenological formulas. Important effort still has to be made to improve the microscopic description of collective (rotational and vibrational) effects, as well as their dependence on the excitation energy. It looks promising that such calculations can soon be performed within the Shell Model Monte Carlo (SMMC) approach which allows the description of nuclear properties at finite temperature and has recently been successfully adopted to microscopically derive level densities for medium-mass nuclei. The SMMC model considers correlations among valence nucleons by a realistic interaction and, hence, treats pairing correlations in the ground and excited states consistently. Such a coherent description in level density models based on mean-field approaches is still needed. Future global combinatorial and shell model calculations of level densities will significantly improve the reliability of the predictions for exotic nuclei. These studies are eagerly awaited.

7.4 Optical potentials

Conventional global optical potentials are parametrized in nuclear astrophysical applications by a Woods-Saxon form. Recently a nucleon-nucleus optical potential has been derived from the Reid hard core nucleon–nucleon interaction within the framework of the Brückner–Hartree–Fock (BHF) approximation. This potential has been empirically renormalized to reproduce scattering and reaction observables for a large set of spherical and quasispherical nuclei in a wide energy range from the keV region up to 200 MeV. Although the resulting potential clearly represents a significant improvement, more future work is needed. In particular, the asymmetry component in the potential has to be improved to guarantee a reliable and accurate description of extremely neutron-rich nuclei. To achieve this goal BHF calculations of asymmetric nuclear matter would be most useful.

The derivation of reliable α-nucleus optical potentials is much more complicated and the latest developments are rather scarce. The very low energies which are of relevance in astrophysical environments (far below the Coulomb barrier) make the extrapolation of global potentials quite uncertain as has been demonstrated by the results of the recent ^{144}Sm$(\alpha,\gamma)^{148}$Gd experiment (see Sect. 5). For these reasons, new global potential parametrizations of Woods-Saxon or double folding types have been proposed in order to better take into account the strong energy and nuclear structure dependence which affects the absorptive part of the potential at low energies. However, experimental data at low energies (elastic and inelastic scattering, α-capture or (n,α) cross sections) are scarce making the predictive power of the new parametrizations still uncertain. Much theoretical and experimental work remains to be done in this area.

7.5 γ-ray strength functions

The radiative neutron capture rate at energies of relevance in astrophysics is sensitive to the low-energy tail of the giant dipole resonance, in particular if pygmy resonances exist close to the neutron threshold as recently been suggested by some experiments and model calculations. The E1 strength distribution is conventionally described by a generalized Lorentzian model. Due to its importance, however, improved global descriptions are warranted. A first systematic and microscopic attempt to derive global $E1$-strength functions is based on spherical QRPA calculations adopting a Skyrme force. Future calculations should be based on the HFB-QRPA model to guarantee a consistent description of pairing correlations and should consider nuclear deformation and higher-order QRPA effects. Such studies are expected to increase the reliability of the present predictions.

7.6 β-decay rates

The reliable calculation of β-decay rates is strongly complicated by the fact that the rates are highly sensitive to the low-energy wing of the spin-isospin response functions introducing a strong nuclear structure dependence. Recently first attempts to derive these rates based on a fully self-consistent HFB plus QRPA description of the ground state and β-decay properties have been made. Although promising, these calculations clearly need improvements. In particular, the global calculations should be based on a mass-independent finite-range effective nucleon-nucleon interaction that ensures a universal and accurate description of the spin-isospin excitations of arbitrary multipolarity in the whole nuclear chart. Furthermore, such fully self-consistent models for spherical and deformed nuclei need to be developed. Currently the reproduction of ground-state properties and the spin-isospin excitation with the same value of the Landau-Migdal interaction (as extracted from experimental data) is an open problem. In addition, the influence of forbidden transitions and higher-order QRPA effects on the β–decay rates need to be studied systematically.

Without doubt, the shell model, which takes all correlations among the valence nucleons into account, represents the method of choice to derive β-decay rates. Due to computational limitations, the model is currently restricted to light or intermediate-mass nuclei, and to nuclei with a single closed shell like the r-process waiting points. Extension of the model to heavier nuclei is certainly needed for future astrophysical applications.

8 Recommendations

One of the great attractions of nuclear astrophysics is its diversity, which is not only reflected by its strong interdisciplinary character, but also in the need for a wide span of experimental facilities, ranging from major international laboratories to small university-based research laboratories. We constitute therefore with satisfaction that many European research centers, including the GSI, Ganil, Louvain-La-Neuve, Gran Sasso, INFN, KVI Groningen and CERN, have endorsed a strong program towards nuclear astrophysics. At the same time, much of the important progress, which we witnessed in recent years, has been achieved by university groups. Both, the activities at the large research centers and at the university laboratories, have to be continued and extended. This is reflected in our recommendations:

1. At many frontiers in nuclear astrophysics, progress depends decisively on the knowledge of properties of short-lived, exotic nuclei far-off the valley of stability. Determining these properties and experimenting with such short-lived nuclei, as they naturally only occur at the extreme conditions of many astrophysical objects, requires the availability of intense radioactive ion-beams. With highest priority we recommend therefore the immediate construction of the radioactive ion-beam facility at the GSI in Darmstadt. This would make the GSI for many years a world-leader in experimental nuclear astrophysics, ideally supplementing the strong European efforts in astrophysics, cosmology and space research.

   Complimentary to fragmentation beams, top-level research in Europe in nuclear astrophysics also requires a second-generation ISOL facility. The construction of EURISOL is therefore highly recommended for the intermediate future.

2. The Underground Laboratory at the Gran Sasso has proven itself as a worldwide unique facility devoted to measure astrophysically important nuclear reactions to unprecedently low energies, sometimes even reaching the relevant stellar energies. To optimally exploit the unique opportunities, offered by this laboratory, we recommend with very high priority the installation of a compact, high-current 5-MeV accelerator for light ions equipped with a high-efficiency 4π-array of Ge-detectors.

3. Traditionally a strong component of the nuclear astrophysics research is carried out by smaller university groups and research laboratories. The expertise of these groups is vital for the field. We recommend, with very high priority, to continue and extend the dedicated nuclear astrophysics programs built around university accelerators. These accelerators also hold a potential for interdisciplinary research in other science areas (material research, life science etc.) providing additional training grounds for young researchers. We also point to the broad educational benefits of dedicated experiments at such university laboratories allowing young researchers to be responsibly involved from the design phase of the experiment to the data taking and analysis.

4. Many European large-scale facilities have endorsed strong research programs related to nuclear astrophysics. These programs should be continued and extended. In particular, an immediate upgrade of existing facilities like Spiral at Ganil and Rex-Isolde at CERN to accelerate also heavier nuclei is highly recommended, to bridge the gap until the second-generation radioactive ion-beam facilities are operational.

   The construction of the new facilities has to be supplemented and supported by the development and construction of appropriate instrumentation and detection devices.

5. There is a strong need to develop the necessary infrastructure to coordinate the specific nuclear astrophysics needs like up-to-date and exhaustive data bases. Furthermore, due to the interdisciplinary character of the field, progress in nuclear astrophysics requires an extensive contact and exchange of ideas between theoretical and experimental nuclear physicists and astrophysicists, cosmologists and observers. The European Center for Nuclear Theory and its Applications ECT* in Trento offers the ideal environment for such contacts and will continue to play a crucial role here.

6. Theoretical development should focus on nuclear structure far-off from stability, the development of nuclear reaction models which allow more accurate extrapolations of data to astrophysically relevant energies, the nuclear equation of state, neutrino opacities of hot, dense matter, and neutrino emissivities of dense matter in neutron star cores. These efforts require access to powerful computers.

Finally we stress that nuclear astrophysics has now developed into one of the major fields in subatomic physics and will further grow in its importance. Progress and new knowledge in this field attracts an enormous public interest and appeal. To fulfill these public expectations and to match the development of the field, it is absolutely essential and of highest priority that new positions at universities and research laboratories are being created.

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