Nuclear Astrophysics – WG4

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Introduction

The world around us, from the silicon integrated circuits in our computers to the sunlight that supports life, is intimately linked with the properties and reactions of atomic nuclei. From the lives and deaths of stars, to the evolution of the Galaxy, it is nuclear physics that has shaped the Universe, linking processes that operate at femtometer scales to structures that stretch across thousands of light years. Nuclear astrophysics is the field that brings together different scientific disciplines to answer some of the key questions about the Universe. This endeavour requires the collaborative effort of astronomers, astrophysicists and cosmologists, as well as experimental and theoretical nuclear physicists.

The challenge of understanding the origin and evolution of the chemical elements, and the role of nuclear physics in the lives and deaths of stars, requires state of the art experimental, theoretical and observational capabilities.

Terrestrial telescopes are now complemented by a fleet of space observatories, all of which are delivering a vast variety of large amounts of astronomical data from all parts of the electromagnetic spectrum. This is supplemented with neutrino, cosmic rays and gravitational waves observations. Embedded therein is information on the properties and evolution of individual stars, the signatures of stellar explosions, and the history to the beginnings of the Universe. These multi-messenger signals allow us to benchmark and test the predictions of astrophysical models, and the nuclear physics as one of their major ingredients.

Technological advances in computation now allow us to model stars and stellar explosions in three dimensions. These multi-dimensional simulations have emerged as a new approach over the past two decades. Their advantage is that they offer a consistent description of fluid dynamics and avoid artificial symmetry assumptions. This comes with the price of more complexity and higher demands on computational resources. Progress in this field is linked to the implementation of advanced numerical techniques and to the constant growth of supercomputational power. They allow more accurate modelling of the effects of rotation and mixing processes, changing the interior structure of our model stars, and the nuclear physics processes therein. Models of stellar explosions, such as core collapse supernovae, are now detailed and realistic enough to be compared with explosion and remnant observations.

At the other end of the length scale, nature has supplied the Earth with about 300 stable as well as long-lived radioactive isotopes that we can study in the laboratory. However, a much greater variety of (mostly unstable) isotopes are produced during stellar explosions. Radioactive beam accelerator facilities provide access to an increasing number of these exotic nuclei. With current, and future generations of facilities we can study the properties of, and reactions among, these rare isotopes to give us insight into the nuclear processes that synthesise elements.

The nuclear properties relevant for the description of astrophysical process depend on the environmental conditions. Nuclear theory is fundamental to connect experimental data with the finite temperature and high density conditions in the stellar plasma. Advances in the description of nuclear interaction based on the symmetries of quantum chromodynamics together with novel many-body techniques allow for parameter-free calculations of reactions relevant for stellar burning. Unified approaches from light toward heavy nuclei will allow for theoretical predictions with uncertainty estimates relevant for the description of explosive scenarios.

The recent detection of gravitational waves opens another window on the Universe. Gravitational waves probe extreme conditions of matter densities that electromagnetic signals cannot elucidate, but within which nuclear physics undoubtedly plays key roles. New demands will be placed on our field, requiring innovative techniques and interdisciplinary approaches.

Nuclear physics is crucial for our understanding of the evolution and explosion of stars, the chemical evolution of the Galaxy and its assembly history. It contributes to key science questions:

- What are the nuclear processes that drive the evolution of the stars, galaxies and the Universe?
- Where are the building blocks of life created?
- How do nucleosynthesis processes evolve with time?

- What is the nature of matter under extreme conditions? Can multi-messenger observations provide access to conditions not reached at present laboratories?

In this chapter, we will outline the current state of knowledge in nuclear astrophysics, highlight the future directions of the field and provide recommendations and priorities.

The Life Cycle of Matter

Cosmic gas is collected by gravitational attraction into higher density regions, to eventually form stars of different masses. These stars are stabilised against further gravitational concentration by the release of nuclear binding energy in their interiors. Depending on the total mass of the star different nuclear fusion reactions process isotopes on their way from light elements, such as hydrogen, to iron nuclei, where nucleons are bound most tightly in an atomic nucleus. Low-mass stars remain in such equilibrium between gravity and nuclear heating for a time comparable to the age of the Universe, while for massive stars it takes just millions of years until an iron core has been formed, and gravitational collapse to more compact forms of matter ensues. Such gravitational collapse mostly leads to a supernova explosion, ejecting large amounts of stellar gas into the environment again. This stellar gas and the supernova ejecta have now been enriched with products of nuclear fusion reactions, changing the composition of interstellar gas that will again form stars of a second generation, now proceeding in their evolution as above, but with modifications due to the change in initial composition. Such is the cycle of cosmic matter, which successively enriches cosmic gas from its initial composition left over after the big bang to a composition rich in the variety of elements we observe, and which is the prerequisite to life in the Universe and on our planet Earth. Additional contributions to such "chemical evolution" of cosmic gas arise from stellar winds, and from nuclear processes and explosions on the surfaces of compact stars such as white dwarfs, which also may disrupt the entire compact star and thus contribute a specific and different composition of ashes from nuclear reactions in such explosions.

We will discuss in the following what we know about the different stages and sites of nuclear processing of cosmic matter, starting from the Big Bang, then through stars and their explosions.

Big Bang nucleosynthesis

The standard model of cosmology and particle physics provides our current best physical description of the Universe. Two important predictions of this model have been experimentally confirmed. They include the production of the lightest elements during the first minutes after the Big Bang, known as Big Bang Nucleosynthesis (BBN), and the existence of a relic cosmic microwave background (CMB). Within the standard BBN (SBBN) the abundances of the four light nuclei ^{2}H(D), ^{3}He, ^{4}He, and ^{7}Li depend on the density of baryonic matter, Ω_b, and on the expansion rate of the Universe. The latter depends on the effective number of neutrino species where the standard model value corresponds to $N_{\text{eff}} = 3.046$. Deviations from this value could indicate new physics not presently captured by the standard model. The most precise measurements of these quantities are due to the careful analysis of the CMB anisotropies, recently measured with exquisite detail by the Planck collaboration. Their analysis gives $N_{\text{eff}}(\text{CMB}) = 3.04 \pm 0.36$, consistent with the standard model predictions. However, as CMB and BBN probe different epochs of the Universe, there could be new physics that operates at the BBN epoch and not necessarily during the phase of photon decoupling that shapes the CMB. It turns out that the primordial abundance of D is sensitive to the baryon density while the mass fraction of

^{4}He depends strongly on N_{eff}. Precise measurements of the primordial abundances of these elements can provide important constraints on those parameters within the context of SBBN. Indeed, SBBN calculations based on the CMB parameter values reproduce with unparalleled precision the measurement of the D/H ratio. However, the latest measurements of the mass fraction of ^{4}He tentatively suggest $N_{\text{eff}}(\text{BBN}) > N_{\text{eff}}(\text{CMB})$. This conclusion may depend on systematic differences in the analysis strategies of ^{4}He observations. It is expected that in the near future high-resolution data on ^{4}He emission lines will further reduce the uncertainties in primordial helium determination. Alternative probes such as the ^{3}He/^{4}He ratio are being pursued to address possible systematic uncertainties in the ^{4}He ratio. ^{3}He abundances can be determined from the ^{3}He I flux from nearby low metallicity H II regions.

Nevertheless, to obtain bounds on the relevant parameters from SBBN that are competitive with those of CMB analysis, a further reduction of the uncertainties in the nuclear reactions responsible for the production of D and ^{4}He is necessary. The rates that determine the D/H ratio are $d(p,\gamma)^3\text{He}$, $d(d,n)^3\text{He}$ and $d(d,p)^3\text{H}$. For the He isotope ratio the most important reactions are $d(p,\gamma)^3\text{He}$, and $^3\text{He}(d,p)^4\text{He}$. Figure 1 illustrates the impact that knowledge of the relevant reaction rates with 1% uncertainty will have on the SBBN predictions. Interestingly, the BBN contours are comparable in size to the latest CMB results. The crucial $d(p,\gamma)^3\text{He}$ reaction has been recently calculated based on an *ab initio* approach that includes two- and three-nucleon interactions and two-body contributions to the electromagnetic current. The calculations predict an increase of 10% in the S-factor at BBN energies with a quoted uncertainty below 1%. Experimental data for the remaining reaction rates are needed.
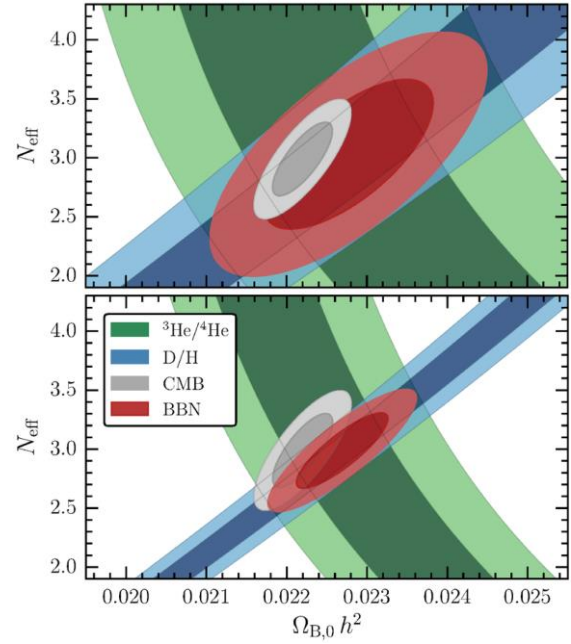

Figure 1 Confidence contours of the baryon density and effective number of neutrino species that reproduce the observed D/H and ^{3}He/^{4}He. The lower panel illustrates the impact of a 1% uncertainty on the nuclear reaction rates. [Adapted from R. J. Cooke, Astrophys. J. **812**, L12 (2015)]

^{7}Li has the smallest observable abundance predicted by SBBN, but serves as a consistency check on the theory and could potentially be sensitive to physics not captured by the production of the other elements. The main observational signature of primordial Li is the existence of the Spite plateau with very small scatter for halo stars with metallicities down to $[\text{Fe/H}] \sim -3$. However, observations at lower metallicities indicate a much larger scatter with stars having Li/H ratios below the Spite plateau ratio. It seems that some halo stars destroyed their lithium. Addressing the mechanism responsible becomes fundamental to solve the "lithium problem" according to which the observed primordial Li abundance based on stellar observations of the Spite plateau is a factor 3 lower (4σ away) than the predictions of SBBN. Observations of interstellar lithium in galaxies at low metallicity will help to test the mechanism potentially responsible for its depletion in stars. Additionally, one needs to understand the processes responsible for the production of lithium after the Big Bang.

Nuclear reactions responsible for the production of ^{7}Li are known to ~10% or better. Further improvements are necessary. However, it is a possibility that the lithium problem points to new physical processes at play during, or after, primordial

nucleosynthesis. The challenge is to find a mechanism that would reduce ^{7}Li without affecting the other abundances. *The recent precise measurement of D/H now tightly constrains the allowed range of values, and challenges if not excludes most of the sometimes exotic solutions to the lithium problem which have been proposed so far.*

Lives of stars

Stars consist mainly of the elements hydrogen and helium. Nuclear reactions in their interiors are responsible for the synthesis of heavier isotopes and elements, initially burning hydrogen to helium, then helium to carbon, carbon to oxygen and neon, and so forth to iron and silicon, thus releasing the energy necessary to maintain their stability against gravitational collapse. Except for the relatively short periods when there is a transition from one major such burning stage to the next, and for the very dynamical final phases, during most of their lifetimes stars are in hydrostatic equilibrium. Nuclear reactions thus are important, not only for producing such energy, but also for synthesising the elements that surround us, and so a detailed understanding of these nuclear reactions is vital.

There are many successes of a spherically symmetric approach to modelling stars, which has culminated in sophisticated codes with detailed microphysics. Some of this codes are open source opening new opportunities in education. Large grids of stellar models are available which probe the parameter space of initial stellar mass, composition and rotation rates including rather large nuclear reaction networks for the nucleosynthesis. The existence of these modelling capabilities also facilitates studies of the sensitivity of astrophysical predictions to nuclear physics uncertainties (e.g., heavy element production dependence on n-capture reaction rates). Models of asymptotic giant branch (AGB) stars are able to explain the abundances of s-process nuclei observed in the Sun, pre-solar grains and galaxies. Models of massive stars that include the physics of rotation with spherically symmetric prescriptions can explain the enhancement of ^{14}N in the early Universe and, thus, the enhanced efficiency of the weak s-process in that epoch. Significant progress has also been made in the theoretical description of stars close to the transition mass between AGB and massive stars and the limit for forming a white dwarf or a neutron star.

However, there remain many challenges: even models that have been validated by observations contain assumptions and approximate physics with numerous free parameters that severely limit their predictive power. Present and future efforts are now focussing on developing simplified physics models with multi-dimensional simulations and experiments (forward modelling) rather than by calibrating free parameters to the observables they are trying to explain (inverse modelling), as has been done in the past. The common use of multi-dimensional hydrodynamic simulations has taken longer to emerge in the field of stellar evolution (compared to supernova theory) largely owing to the additional challenges of longer time scales, the importance of reaching steady states and the encroachment on the low Mach-number regime, which requires specialised numerical methods.

In the last decade alone, 2D and 3D hydrodynamic simulations of stars have already yielded several important results including predictions of:

- Entrainment rates across convective boundaries,
- Pre-supernova velocity fields that are seeds for the neutrino-driven convection in multidimensional core-collapse supernova simulations
- Nucleosynthesis in convective-reactive events, that are able to explain the neutron capture abundance pattern of the post-AGB star known as Sakurai's object

Stellar models should, where possible and appropriate, be validated with observational data. Recent years have seen a plethora of illuminating data with which stellar models can be validated and challenged:

- Asteroseismic observations show that convective cores are larger than predicted by classical convection theory.
- Large binary fractions are found amongst massive stars. Binary interactions influence their evolution and fate.
- The discovery of very massive stars in the local Universe with initial masses up to 320 solar masses (well above the previously accepted upper mass limit of stars around 150 solar masses) challenges star formation scenarios

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and opens the possibility of exotic pair-instability supernovae.

- With current large surveys, many faint and fast transients are observed. These so-called supernova impostors provide more constraints and questions about the evolution of stars.
- The Gaia satellite, as well as large ground-based surveys, is now producing extremely large datasets that will place dramatically stronger constraints on stellar populations in the nearby Universe.
- Surveys of metal-poor stars provide key information about the first stellar generations and will continue to challenge the modelling of the first stars, their formation scenarios and the early evolution of the Universe.

In all of these scenarios, nuclear physics has a significant role.

Hydrogen burning

Hydrogen burning is the best understood phase of stellar evolution, particularly in low mass stars. This is due to the high quality of multi-messenger data for our Sun, including elemental abundance observations in the solar atmosphere, helioseismic waves that probe the solar interior and neutrino observations that provide a direct snapshot of the nuclear reactions in the Sun's core. The observation of neutrinos from the Sun was one of the scientific milestones from last century and has been the recipient of two Nobel prizes (2002, 2015), the latter being awarded to the SNO collaboration for the direct confirmation that neutrinos produced in the Sun change their flavour as they travel to Earth. This was the final resolution to the "Solar Neutrino Problem" that started with the pioneering experiment of Ray Davis in 1968. Nuclear astrophysics played a fundamental role in solving the problem by providing ever more accurate predictions of the solar fusion cross sections. These improved predictions came as a result of combined high precision experiments and theoretical advances. Thanks to these advances, and based on the measurement of the ^{8}B solar neutrino flux, we have been able to determine the temperature in the Sun's core with a precision of 1%. Similarly to the situation in BBN, solar modelling is entering a precision era. At present, all neutrino fluxes from the pp-chain reactions have been measured. This has confirmed our basic understanding of neutrino flavour oscillations in the presence of matter.
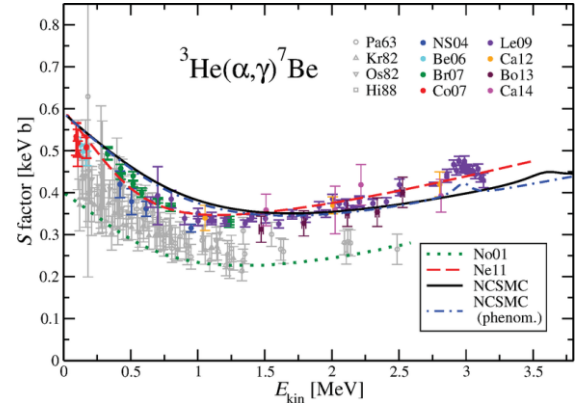

Figure 2 Parameter free ab-initio calculations are now possible for key astrophysical reactions involving light nuclei [From J. Dohet-Early, et al., Phys. Lett. B 757, 430 (2016)]

The development of sophisticated three-dimensional non-local thermodynamic equilibrium models for the Sun's atmosphere has led to a substantial reduction in the expected abundances of metals (elements heavier than helium), in particular C, N and O, when compared with previous predictions based on one dimensional models. This has created the "Solar abundance problem", in which solar models that incorporate the new abundances have problems reproducing the sound speed profile measured by helioseismic observations. A possible solution comes from the assumption that the solar abundance of metals is not homogeneous and that the surface may be depleted in comparison to the interior. This behaviour is expected due to the diffusion of heavy elements to the solar interior over the Sun's lifetime. It becomes particularly important to address the "solar abundance problem" from the point of view of neutrino observations. Predictions of neutrino fluxes based on the 2011 compilation of solar fusion cross sections do not favour a metal rich versus depleted interior. However, recent theoretical and experimental improvements in the key reactions: $p(p,e^+\nu_e)d$, $^3\text{He}(\alpha,\gamma)^7\text{Be}$ and $^7\text{Be}(p,\gamma)^8\text{B}$ have resulted in changes in the ^{7}Be and ^{8}B solar neutrino fluxes that favour the model with higher metallicity. To further advance in this issue, and to address degeneracies in composition and opacity changes, it becomes fundamental to measure the neutrino fluxes for CNO reactions. This is in fact the goal of the Borexino collaboration. The experimental challenge ahead is a comparison of the Sun's electromagnetic and neutrino luminosities with a precision of 1%. The current limit is 7%. This will allow a direct comparison between the energy production rate and energy delivery rate and improve our

understanding of energy transport in stars. It will also put strong constraints on neutrino flavour oscillations to sterile flavours.

Helium burning

Stellar fusion of helium is a key bottleneck in producing elements other than hydrogen and helium. The reaction is hindered because it proceeds through the (almost) simultaneous fusion of three helium nuclei. The three-particle nature of this process, the triple-alpha process, makes experimental investigation of the reaction extremely difficult. At the temperatures of most helium-fusing stars, the reaction proceeds in two steps through the very short-lived ^{8}Be nucleus and a similar quantum state in ^{12}C known as the Hoyle state, named after Fred Hoyle who proposed the necessity of the resonance and was instrumental in its experimental discovery.

The reaction and the detailed properties of the Hoyle state remains the focus of both theoretical and experimental investigation. Key advances have, over the past decade particularly, included detailed theoretical studies of the three-body dynamics of the reaction at very low temperatures, where the stellar scenarios do not have sufficiently high temperature to populate the Hoyle state. Contrasting this, experimental searches for a key rotating mode of the Hoyle state have been carried out using a variety of nuclear probes: reactions, decays and absorption. At the highest stellar temperatures, the resulting resonance could dominate the helium-fusion process.

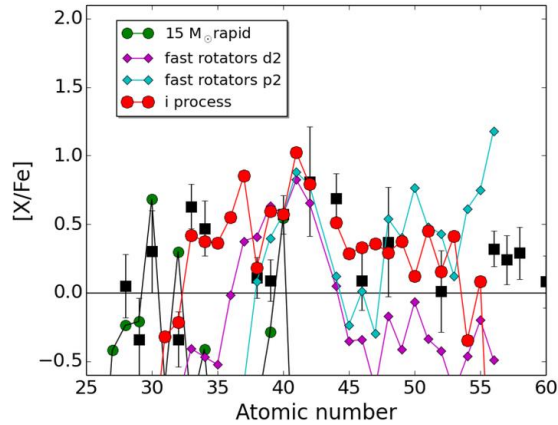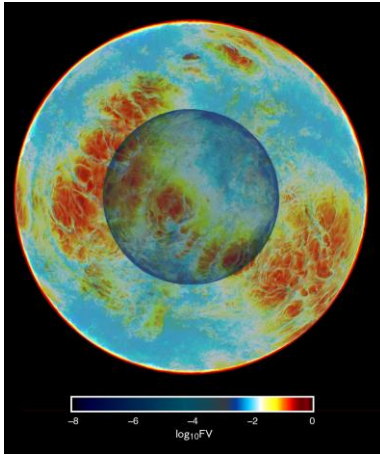The creation of carbon and oxygen in our Universe is fundamental to understand the origin of life on Earth and the life cycle of stars. A key ingredient is the precise termination of the reaction rate of $^{12}C(\alpha,\gamma)^{16}O$, whose precise determination has eluded both theory and experiment. Theoretically is very challenging due to contribution of different underlying mechanisms. Experimentally there have been more success but the small cross section requires direct measurements at the limit of current state of the art techniques. Indirect techniques, mainly via the β delayed α emission spectra of ^{16}N, have contributed to reduce the uncertainties to the 15% level. High precision measurements of the total capture rate are planned with precision on par with indirect methods. Particularly important is the determination of the ground state cross section.

Advanced burning phases.

Once helium burning has halted, the core is made mostly of carbon and oxygen with small amounts of heavier elements. The next burning regime proceeds through the fusion of two carbon nuclei to neon and sodium. The rates of these carbon fusion reactions are crucial for determining whether stars proceed on to carbon burning or become CO white dwarfs. These reactions are also important for understanding the triggering of thermonuclear supernovae (type Ia). Due to their extremely low cross sections, direct measurements of these reactions are very challenging and to date no data are available across the relevant energy range. Recent progress has been made in developing the experimental techniques for studying these reactions, and these reactions are now key goals of the new upgrade to LUNA.

After carbon burning, massive stars go through three more burning stages: neon, oxygen and silicon burning. The case of oxygen burning is very similar to carbon burning since it proceeds by the fusion of oxygen into silicon, phosphorus and sulphur. Neon and silicon burning proceed via a combination of photo-disintegrations and alpha-particle captures. Furthermore, weak interactions play an increasing role. Deleptonisation is the key process that facilitates the onset of collapse. While these phases have been studied extensively in spherically symmetric models, in the last decades, several efforts have started to study these in multi-dimensional hydrodynamics simulations. These simulations show enhanced mixing. They also show that collapsing stars are not necessarily perfectly symmetric. These asymmetries might aid successful explosions. Future simulations need to investigate in more detail the interplay between convective mixing and nuclear reactions since extra mixing changes energy generation and small variations of endothermic reactions (for example photo-disintegrations) affect turbulent flows.

Neutron capture nucleosynthesis

The elements from carbon to iron are produced by charged particle reactions during the stellar evolutionary phases from helium to silicon burning. On the other hand, most elements heavier than iron are essentially built up by neutron capture processes. We distinguish environments with low neutron fluxes, the "s process", from environments with such high neutron fluxes that neutron captures proceed until neutron drip line (the "r process").

The s-process

The slow neutron capture (s) process, which takes place during helium and carbon burning, is characterised by comparably low neutron densities, typically $10^8 - 10^{10}$ cm^{-3}, so that neutron capture times are much longer than most β-decay times. The reaction path of the s-process therefore follows the valley of stability with the important consequence that the neutron capture cross sections averaged over the stellar neutron energy spectrum are of pivotal importance for the determination of the s-process abundances. Additionally, the r-process abundances are defined by subtracting the computed s-process abundances from the solar system abundances.

The main s-process operates in the late phases of low-mass stars (AGB stars) and is responsible for the production of half of the elements heavier than iron. The main neutron sources are $^{13}C(\alpha,n)$, with a smaller contribution from $^{22}Ne(\alpha,n)$ for more massive

AGB stars. $^{13}C(\alpha, n)$ is active in the so-called ^{13}C-pocket, the formation and evolution of which is still uncertain and thus an active area of research, particularly regarding the impact of rotation and magnetic fields.

The weak s-process takes place in massive stars during core helium and shell carbon burning phases. The main neutron source is $^{22}Ne(\alpha, n)$. Recent models including the effects of rotation produce large amounts of primary nitrogen and ^{22}Ne, which enables a significant production of elements up to barium at low metallicities (where none was expected from non-rotating models). These effects can explain the large observed scatter in the strontium versus barium ratio in carbon enhanced metal poor (CEMP) stars.

Present experimental s-process studies focus on the measurement of several branching point nuclei, where competition between neutron capture and β-decay yields a local isotopic abundance pattern, which is also strongly influenced by the physical conditions of the s-process environment. In general, both reaction branches need to be known with sufficient precision, but usually the neutron capture branch urgently needs experimental improvements. A few of these difficult measurements have been successfully carried out over the stellar energy range of interest using the corresponding samples of radioactive material, both by means of activation (^{60}Fe, ^{147}Pm, etc.) and TOF-measurements (^{63}Ni, ^{93}Zr, ^{99}Tc, ^{107}Pd, ^{151}Sm, ^{171}Tm or ^{204}Tl). Thus valuable information has been obtained on the thermal and density conditions of the environment, as well as the timescales of the different evolutionary stages. Nevertheless still 10-to-20 relevant branching nuclei remain to be measured due to the difficulties inherent in the production of a suitable capture sample, and to the limitations of the radiation detectors used for this kind of measurement. As significant improvements in neutron capture rates are being made, the stellar β-decay rates also become important subjects of experimental s-process research. Moreover, stellar decay rates can differ from terrestrial rates by orders of magnitudes. These effects can and should be investigated in ion storage rings (bound-state beta-decays) or in inverse kinematics applying charge-exchange reactions.

The r process

The rapid neutron capture (r) process is perhaps the least understood nucleosynthesis process. It occurs over a vast range of rapidly changing physical conditions, and involves more than 5000 nuclear species. The main reactions include neutron capture and β-decay of unstable neutron rich isotopes, most of them currently experimentally inaccessible. Fission is expected to contribute in environments involving large neutron densities like neutron star mergers. For this reason, state-of-the-art r-process network calculations have to rely, to a very large extent on nuclear and decay properties derived from theoretical models. Thus, the calculated abundance patterns exhibit uncertainties that are much larger than those obtained from spectroscopic observations. This significantly hinders efforts to determine the properties of the, so far, unidentified astrophysical site(s) of the r-process based on nuclear physics constraints.

UV spectroscopy surveys made with HST/STIS and ground-based telescopes have provided abundances for nearly every element from hydrogen through to bismuth in most metal-poor stars. These studies provide new insights into the stellar nucleosynthesis in the earliest generations of stars, yield accurate constraints on the r-process, and offer a unique opportunity to understand the chemical evolution of our Galaxy. Combined with observations of dwarf galaxies and the sea floor abundance of ^{244}Pu, there is growing evidence that the r process is associated with rare high yield astrophysical events. From the experimental side, recent surveys at RIKEN (Japan) exploiting high-current cyclotrons have provided beta-decay half-lives for many r-process nuclei around N=82, which show a direct impact in r-process abundance calculations. Important advances have also been achieved at GSI, JYFL and ISOLDE by mass and spectroscopic measurements around N=82 including the two key r-process nuclei ^{130}Cd and ^{128}Pd. These data have contributed to the solving of the long standing issue of shell-quenching around N=82 and has led to dramatically improved shell-model calculations around this region.
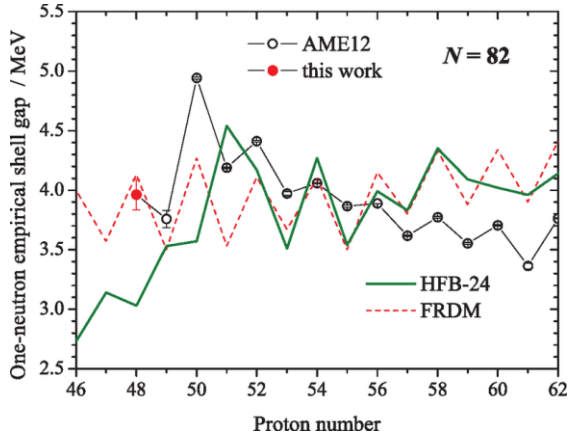
Figure 3 Masses adjacent to the r-process waiting point nucleus ^{130}Cd have been measured at the Penning-trap spectrometer ISOLTRAP at ISOLDE/CERN. They provide important constraints on the evolution of the N=82 shell gap and the production of A = 127-132 nuclei by the r process [From Atanasov, et al., Phys. Rev. Lett. 129, 232501 (2015)]

Most of the r-process nuclei have not been experimentally produced. Particularly in the region around N=126 and above there is no single r-process nucleus that has been experimentally produced or measured yet. In this respect, the first experimental challenge in the near future is to develop new and more powerful techniques and facilities that allow us to expand the border of knowledge of the nuclear chart towards the heavy mass region. It is worth emphasising that almost all nuclei which have to be discovered yet, around 3000 species, are neutron-rich nuclei. Owing to limitations in existing RIB-facilities, to the very small production cross sections, and to the difficult background conditions, the heavier the element is, the more extended becomes the region of the so-called terra-incognita.

Advances in astrophysical modelling have clarified the likely candidates for the r-process astrophysical site. Neutrino-driven outflows from the hot neutron star formed after a core-collapse supernova explosion were considered for a long time as the astrophysical site for r process. However, advances in the description of neutrino-matter interactions and its implementation in Boltzmann radiation transport codes have shown that most of the ejected material is proton-rich or slightly neutron-rich and do not allow for a strong r process. Nevertheless, neutrino driven winds remain a likely candidate to produce elements around A~100 by a combination of weak r process and/or νp-process.

The merger of double neutron stars (NS-NS) and neutron star-black hole (NS-BH) binaries constitutes at present the most likely source to account for most of the r-process material in the Galaxy. Several binary pulsar systems have been observed. The secular variation of their orbital period agrees perfectly with general relativistic predictions for the emission of gravitational waves. This in fact provided the first indirect evidence for gravitational waves, years before their direct detection by the LIGO/VIRGO collaboration. While this first direct detection was from a system of two black holes, a detection originating from a neutron star- neutron star merger or a neutron star - black hole coalescence is expected soon.

Neutron-star mergers and merging neutron star-black hole systems touch two nuclear physics aspects. First, the partly unknown properties of the high-density equation of state strongly affect merger dynamics and thus the gravitational-wave signal of such events. In turn, this offers the possibility of inferring equation-of-state (EoS) properties from a future gravitational-wave measurement. The second aspect concerns the nucleosynthesis of heavy r-process elements in the ejecta of mergers.

Progress has been made in understanding the EoS dependence of the GW signal of double neutron star and neutron star-black hole mergers. For instance, the late inspiral phase, where finite-size effects influence the phase evolution, carries an imprint of the equation of state. Also, the frequencies of the oscillations of the post-merger remnant are characteristic of the equation of state. These effects highlight future possibilities of constraining the high-density matter EoS. For instance, a measurement of the dominant post-merger oscillation frequency may allow the determination of neutron star radii with a precision of the order of about 200 meters, from a near-by merger event. If and, with what precision such measurements will succeed with the current detectors, depends on the not well known merger rate. Additional observational constraints will come from the study of X-ray binaries by the e-Rosita mission.

Merger contributions to r-process nucleosynthesis consists both of material ejected dynamically during the merger and outflows from the accretion disc around the central remnant. The properties of the dynamical ejecta depend on the nature of the

merger (NS-NS vs NS-BH) and its mass asymmetry. NS-BH and asymmetric NS-NS systems are expected to eject cold very neutron-rich material originating from the crust of the neutron stars. This material constitutes an ideal site for r process nucleosynthesis where fission rates and yields of superheavy nuclei determine the final abundances. In the case of almost equal mass NS-NS mergers the ejected material originates from the contact interface between neutron stars. This material is shock heated to high temperatures and weak interaction processes can potentially drive the originally very neutron rich material to moderate neutron rich conditions. The final impact on r process nucleosynthesis is not yet fully understood and depends on the finite temperature behaviour of the equation of state.
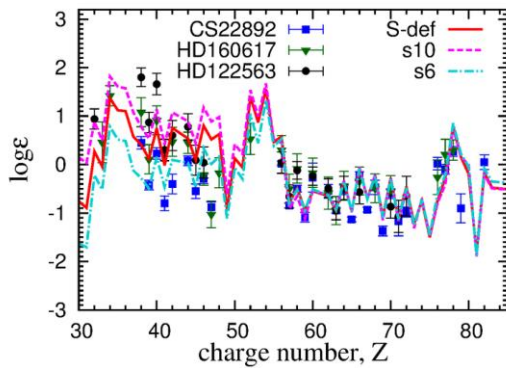

Figure 4 Compact binary mergers have the potential of accounting for the observations of r-process elements in metal-poor stars [From M.-R. Wu et al., Mon. Not. Roy. Astron. Soc. 463, 2323 (2016)]

The accretion disk properties and nature of the ejecta depend on the central compact object: promptly formed BH or a long lived hyper massive NS. In both cases, the disc can generate outflows on timescales much longer than the orbital time with a contribution to the total mass ejection that can be comparable or even larger than the dynamical ejecta. Neutrino heating is sub-dominant when a BH sits at the centre and the outflow is powered by angular momentum transport and nuclear recombination. The ejecta is moderately more neutron-rich than the dynamical ejecta. Neutrino heating is much more important if the merger produces a long-lived hyper massive neutron star, resulting in a larger ejected mass with higher proton fraction.

Mergers constitute also the most likely scenario where we can observe r-process nucleosynthesis operating in situ. The amount of ejected material in a single event is relatively large since the energy liberated by radioactive decay can drive an electromagnetic transient known as a kilonova. Kilonova light curves are expected to reach maximum luminosity on timescales of a week. A kilonova event has likely been recently observed associated to the short gamma ray burst GRB 130603B. In addition to providing a direct probe of the formation of r-process nuclei, kilonova observations provide a unique diagnostic of physical processes at work during the merger. This will be particularly important – and exciting - if a future observation is seen to be associated with a gravitational wave detection.

Addressing the impact of mergers in r process nucleosynthesis requires the contribution of both dynamical and disk ejecta to be considered. Individually or in combination, they may contribute to the production of the whole range of r process nuclides. The frequency and delay time from formation to merger remains an open issue. Gravitational wave detection from neutron star mergers will provide direct constraints to the merger rate of the present-day universe. However, the merger rate and/or delay time may not be enough to account for the early r process enrichment as seen in metal poor star observations. This points to the need of an additional site to account for the production of r process elements in the early Galaxy. A likely candidate is jet driven explosions of massive stars due to a combination of magnetic fields and rotation.

Evidence for additional nucleosynthesis processes

In the section "Lives of Stars", convective-reactive events in stars were briefly touched upon, with an example of the post-AGB star Sakurai's Object. Sakurai's Object is the dying remnant of an AGB star in which there is still some nuclear activity in a thin He-burning shell that lies beneath a layer of hydrogen. A thermonuclear runaway explosion in the helium layer drives the development of a deep convective layer, which engulfs a small portion of the hydrogen layer above. The result is that hydrogen and carbon are brought together under helium-burning temperatures and this releases significant energy in a small period of time. Indeed, this appears to be a timescale that is comparable to the convective time scale, which is the time scale on which the energy can be transported away. Therefore, the convection and the nuclear energy releases interact and this is why such events are called convective-reactive.

An interesting consequence of the combustion of carbon and hydrogen at helium-burning temperatures (usually hydrogen has been depleted before helium burning is ignited) is the production of neutrons via the $^{12}C(p,\gamma)^{13}N(\beta^+\nu)^{13}C(\alpha,n)^{16}O$ reaction sequence. Spherically symmetric nucleosynthesis models, guided by insight gained from 3D hydrodynamic simulations, suggest that characteristic neutron densities achieved in this scenario lie between those of the s- and r- processes (about 10^{15} cm^{-3}). The existence of this intermediate-process was suggested long ago but has recently received new attention thanks to improved hydrodynamical simulations and observational evidence. It has been named "i-process" for that reason.

Nucleosynthesis simulations of i-process conditions have recently been shown to match the puzzling abundance patterns of a sizeable subset of so-called carbon-enhanced metal-poor (CEMP) stars incredibly well. This agreement is much better than a calibrated blend of s- and r-process-enriched material fitted to the observations, which is the alternative scenario to explain the formation of CEMP-r/s stars. The i-process path of nuclei involves reactions between rather short-lived isotopes for which there are limited experimental data. However, as the i-process path lies closer to stability than the r-process, experimental information on nuclei in the i-process path are expected to be obtainable in the near future.

A tiny fraction of the heavy elements observed in the solar system is located on the neutron-deficient side of the valley of stability, which cannot be synthesised by the neutron capture s and r processes. The astrophysical "p process" responsible for the production of these isotopes is still not well understood, and requires further extensive experimental and theoretical effort in the forthcoming years. It is generally accepted that the major role in creating p isotopes is played by gamma-induced reactions in hot stellar environments (hence the name γ-process).

The astrophysical site where such a process can take place is still under debate. Encouraging calculations became available recently both for core collapse and type Ia supernovae, but the consistent reproduction of all p isotope abundances is still not possible. The further improvement of p-process models is therefore needed. In addition, there is

mounting evidence that deficiencies of the γ process models to account for the large abundances of neutron deficient isotopes of molybdenum and ruthenium do not have a nuclear physics origin. Alternative scenarios for the production of these isotopes have been suggested including the νp and ν process.

From the nuclear physics side, the study of the nuclear reactions of p-process relevance is also crucial, as the reliable reaction rates provide the necessary basis for p-process models. As is the case for the r-process networks, owing to the huge number of reactions involved in a p-process network, and the extremely small cross sections, the reaction rates are taken from nuclear theory. Comparison with the available but highly limited experimental database indicates the often poor performance of calculations. The nuclear reaction models must thus be improved, and will be enabled by the extension of the experimental database Therefore, further experimental investigations of p-process related nuclear reactions are recommended.

Results from recent years have shown that, in the case of reactions involving charged particles, the predictive power of nuclear reaction models is especially poor. Cross section measurements of proton- and alpha-induced reactions at low energies is thus of high priority. Measurements can on the one hand provide direct data for the astrophysical models and on the other hand can provide crucial nuclear parameters. For example, the low energy alpha-nucleus optical potential was found to be in need of substantial improvement. This can be studied by high precision elastic scattering experiments as well as by the measurement of alpha-induced cross sections. Other nuclear parameters, like nucleon-nucleus optical potentials, level densities and gamma-ray strength functions, must also be studied and made more precise. Although their direct relevance to the astrophysical p-process is limited, the usage of high intensity gamma-beams, such as the ones provided by the coming ELI-NP facility, will be useful for the precision study of the gamma-ray strength functions.

Stellar explosions

Supernovae play a crucial role in the synthesis of elements and in the dissemination of the nuclear burning products of stars. The past decade has witnessed the rapid development of multi-dimensional simulations

of both core collapse and thermonuclear supernova explosions. With the increasing power of supercomputers, an ever-more detailed treatment of the physical explosion processes has become possible. Simulations, initially carried out in spherical symmetry or two spatial dimensions, covering all or only parts of the exploding stars, and including predefined initial conditions for some key physics, all have now been developed into three-dimensional full-star models. Advanced multi-D hydrodynamical simulations are very sensitive to the microphysics ingredients. For example, small variations in neutrino interactions may turn an unsuccessful core collapse explosion into a successful one. Consequently, it is important to address and reduce the nuclear physics uncertainties in such simulations.

Thermonuclear supernova explosions have been modelled starting from their observed homogeneity as the evolutionary end of an accreting white dwarf that reaches the Chandrasekhar mass limit. The ignition in central regions of the white dwarf is rapid enough to disrupt the star, while nuclear burning reaches nuclear statistical equilibrium and thus leads to production of large amounts of iron group nuclei. Initially, one-dimensional models with empirical transition from deflagration to detonation were found to describe both explosions and outcome well. By trying to capture the physical processes in more detail, two, and recently three-dimensional models have been implemented. The main goals here were to capture the flame propagation under these degenerate high-pressure conditions, and how it leads to instabilities and turbulence and hydrodynamical consequences that change the local burning conditions and kinematics. The aim was to retain the observed homogeneity overall, but also to represent the variety of thermonuclear explosions that became clear in the much larger observational samples of recent years. By introducing a transition from deflagration to a detonation that can be motivated from a density gradient mechanism, such models were found to reproduce the observed variations between light curve rise and fall times and the absolute brightness. Thus, these delayed-detonation models seemed a good candidate to explain normal thermonuclear supernovae. Surprisingly, it was then found that observations seemed equally well reproduced in an entirely different class of models that exploded a white dwarf at masses well below the Chandrasekhar limit from a collision with

another white dwarf companion, the 'double degenerate' model variety. The non-violent variant of this starts from helium burning and thus may explain the variety of normal thermonuclear explosions, while the violent merger of two white dwarfs may explain variant subtypes. The main achievements of recent years are: i) the exploration of different explosion scenarios with three-dimensional full-star simulations that avoid tuneable parameters in their description of the explosion physics; ii) the determination of the nucleosynthetic yields from such models with postprocessing techniques based on tracer particles; iii) the derivation of synthetic observables from such three-dimensional simulations with three-dimensional (Monte-Carlo based) radiation transfer calculations, including optical spectra and light curves, but also predictions for gamma-ray observables, UV signatures, and polarimetric observables; the direct comparison of the derived observables with astronomical data.
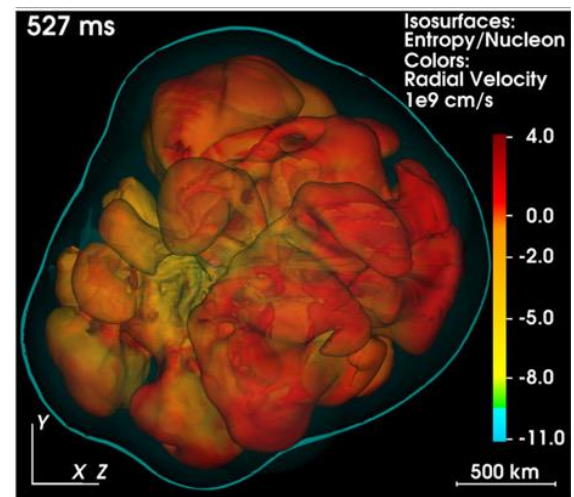

Figure 5 Explosive models of core-collapse supernova in three-dimensions have been developed. They show the important impact of hydrodynamic instabilities and neutrino reactions. [From Melson et al., Astrophys. J. 808, L42 (2015)]

The main goal of **core collapse supernova** modelling is to understand the explosion mechanism. While two-dimensional simulations taking into account a sufficient part of the star robustly reached explosion, this seems to be harder to achieve in three dimensions. Such results underline the importance of multidimensional hydrodynamical instabilities together with a detailed treatment of neutrino matter interactions in order to obtain successful explosions. It has been shown that small changes in neutrino opacities can turn a non-

exploding model into a successful explosion. Furthermore, the instabilities appearing during the explosive phase can imprint their signature into both the neutrino and gravitational signals whose observation could provide a direct view to the explosion dynamics.

The evolution during the collapse is determined mainly by electron capture in nuclei. The early collapse phase is dominated by iron group nuclei. In recent years, charge-exchange experiments have helped to validate theoretical calculations of this process. The challenge is to extend these experiments to unstable targets. Sensitivity studies have been carried identifying the 500 electron capturing nuclei responsible for the largest absolute change to the electron fraction (and therefore, to the whole CCSN dynamics) up to neutrino trapping. Nuclei located around N=50 and N=82 become most important during the last phases of the collapse. They are predicted to be very abundant because of their magicity. But magicity could be quenched away from stability. The nuclear mass of these nuclei is therefore the other key observable to be measured and connects with r-process nucleosynthesis discussed earlier. An improved understanding of electron capture and beta-decays is also becoming fundamental in efforts to understand the dynamics of ONeMg cores both in electron capture supernova and accretion induced collapse.
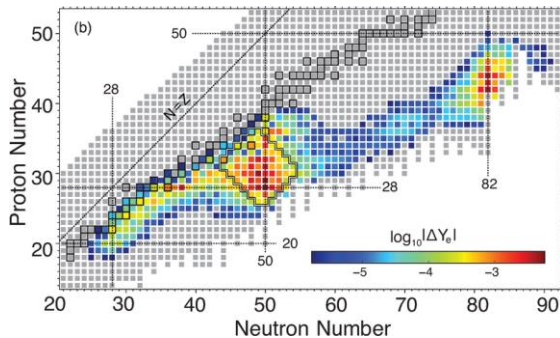

Figure 6 Regions of the nuclear chart with the largest impact on the collapse of massive stars. Many of these regions will become accessible at new radioactive beam facilities [From C. Sullivan et al., Astrophys. J. 816, 44 (2016)]

During the explosive phases of supernovae, neutrino matter interactions become fundamental. Neutrino energy transfer, together with the development of hydrodynamical instabilities, is fundamental to understand the multidimensional nature of supernova explosions. Recent years have seen important advances in the description of these processes consistently with the

underlying equation of state. Calculations now consider the full structure of the weak current including weak magnetism corrections. They provide accurate predictions whenever the system can be approximated as uniform nuclear matter. It remains to address the role of nuclear clusters and the role of correlations at high densities.

The main achievements in recent years of modelling **core collapse supernovae** are: i) and improved description of microphysics (e.g weak interaction processes, nuclear equation of state) together with their treatment in neutrino transport codes; ii) the emergence of two- and three-dimensional simulations, first covering parts of the exploding star and recently comprising the entire object; iii) the systematic study of the impact of different stellar progenitor structures on the explosion phase; iv) detailed calculations of expected nucleosynthesis yields; v) the prediction of neutrino and gravitational wave signals from the explosion models.

Nucleosynthesis in supernovae

Type Ia Supernovae are the main sources of iron group elements in the Universe. Per event, about half a solar mass of radioactive ^{56}Ni is produced that decays through ^{56}Co to ^{56}Fe. The exact composition of iron group yields depends sensitively on the conditions under which the thermonuclear burning proceeds. These differ in the assumed progenitor and explosion scenarios. In particular, the production of stable Ni is largely determined by the neutronization of the material that results from the metallicity of the progenitor and from electron captures in the ashes of thermonuclear burning to nuclear statistical equilibrium. A particularly informative tracer of the thermodynamic conditions under which nucleosynthesis proceeds in Type Ia supernovae is manganese. Its production is sensitive to the explosion scenario with observable consequences for galactic chemical evolution. Manganese abundances in stars and in solar system material can thus constrain the explosion scenario of normal Type Ia supernova. This demonstrates the importance of a detailed nucleosynthesis modelling for constraining the unknown progenitor systems of these events and opens a promising path to future research.

Most nucleosynthesis calculations are currently carried out based on tracer particles that are passively advected in the

multidimensional explosion simulations. These also reveal the detailed chemical structure of the explosion ejecta which form the basis of radiative transfer simulations that predict observables from hydrodynamic explosion models. While possible in principle, a detailed nucleosynthesis modelling directly in these simulations seems unnecessarily expensive in terms of the required computational resources. Nonetheless, a few such calculations may serve as a reference for judging the accuracy of the tracer-based method.

In addition to their contribution to iron-group nucleosynthesis, Type Ia supernovae have been considered as sites of the astrophysical p-process. Some of the explosion scenarios provide favourable conditions to produce p-nuclei in the observed ratios. The success and the contribution of Type Ia supernovae to the overall production of p-nuclei, however, depends on the amount of seed-nuclei in the progenitor material, that, in turn, is determined by the (theoretically rather unknown) evolution of the binary system out of which the supernova explosion emerges.

Core collapse supernovae are the major sources of carbon and oxygen in the Universe. In addition, they also determine the early enrichment of the Galaxy in iron, since the massive star progenitors evolve to explosion much faster than the white dwarf progenitors of thermonuclear supernovae. Consequently, they are fundamental to understanding the metallicity-age relationship. Supernova light curve observations indicate a broad range of explosion energies that are associated with the ejection of different amounts of ^{56}Ni. In addition to the canonical supernova explosions that liberate 1 Bethe (10^{44} J) in energy, we also observe superluminous explosions (hypernovae) and faint supernova explosions. This diversity points to the occurrence of several explosion mechanisms. The canonical explosion energies of 1 Bethe are probably associated to neutrino-driven explosions that produce neutron stars. Other categories may be driven by a different mechanism, likely involving rotation, magnetic fields and the formation of jets. Neutrino-driven supernova explosion simulations are currently at the forefront in astrophysical modelling. The situation is different for magnetorotational supernova requiring improvements in the modelling and a better understanding of the underlying microphysics.

The main challenge in core-collapse supernova simulations remains the development of fully self-consistent explosion models. This requires determination of which progenitors explode, and by which mechanism, and the ability to follow the explosion for the times relevant for nucleosynthesis and mixing in the stellar mantel. Giving the very different timescales involved, there is not a unified description of explosion and nucleosynthesis. Furthermore, despite the tremendous progress achieved, we have not yet fully understood the explosion mechanism and its dependence on progenitor structure. Hence, nucleosynthesis studies are based on parametric explosion models calibrated to observations. Recently, it has been possible to develop neutrino driven explosion models for a broad range of progenitor masses that have been used to determine the nucleosynthesis yields from core-collapse supernovae and associated light curves. In some particular cases multidimensional explosion models have been developed addressing the role of mixing during the explosion. This aspect is fundamental to connect with supernova remnant observations.

Neutrino interactions are not only fundamental for the explosion but they also determine the nucleosynthesis. Neutrino-matter interactions in the surface layers of the neutron star determine the spectra of the emitted neutrinos and the nucleosynthesis in neutrino driven winds. The neutron richness of the ejecta is directly related to the spectral differences between electron neutrinos and antineutrinos. This in turn is determined by the nuclear symmetry energy at substantiation energies. The nuclear symmetry energy has recently been determined for a broad range of densities by a combination of theory, observation and experiment. Simulations based on these constraints have provided improved nucleosynthesis predictions. As discussed above, they rule out the possibility of a strong r process in neutrino winds, but do allow for the possibility of producing elements around A~100.

Neutrino-nucleus reactions, including those that result in the emission of neutrons, protons and alpha particles, are fundamental to determine the nucleosynthesis in the stellar mantle. Neutrinos interact with the stellar material before, during and after the supernova shock passage. They contribute to the production of some key nuclear species such as ^7Li, ^{11}B, ^{19}F, ^{138}La and ^{180}Ta, and affect the production of long lived radioactive species like ^{26}Al. Neutrino-nucleosynthesis studies have benefited from novel predictions of the emitted neutrino spectra and from improved

predictions of neutrino-nucleus cross sections for several key nuclei including ^{4}He, ^{12}C, ^{20}Ne, ^{138}Ba and ^{180}Hf. In several cases the cross sections have been constrained by charge-exchange data.

The detection of neutrinos from our Sun contributed to the discovery of the phenomena of neutrino flavour oscillations. Neutrinos in the Sun are subject to the Mikheyev-Smirnov-Wolfenstein mechanism in which oscillations occur by a combination of vacuum and matter effects. The latter are due to neutrino-electrons interactions in the stellar plasma. In the context of core collapse supernovae, and in the vicinity of the proto-neutron star, the large neutrino fluxes allow for a non-linear coupling between neutrino flavour states. As a result, collective neutrino oscillations may occur in the region of neutrino decoupling and at greater radii. Our understanding of collective neutrino oscillations has improved dramatically in recent years. However, the impact on supernova dynamics, nucleosynthesis and neutrino detection on Earth is not yet fully understood. Collective neutrino oscillations are expected to be a general feature of astrophysical environments involving high neutrino densities. This includes the early universe, core-collapse supernovae and accretion discs.

Stars reborn
Classical novae and X-ray bursts

Many stars end their lives as a white dwarf or a neutron star. These stars have exhausted their fuel, no longer support nuclear fusion and so slowly cool down. However, if the star is part of a binary system, new fuel can be accreted from the companion star, reigniting nuclear fusion and giving the star a new burst of life. Due to the strongly degenerate conditions a thermonuclear runaway develops in the accreted material, driven by explosive hydrogen burning. If the dead star is a white dwarf a classical nova occurs, and if it is a neutron star then an X-ray burst is produced.

Novae:
Explosive hydrogen burning proceeds mainly through the hot CNO cycles, on the surface of the white dwarf. If seed material is present, nucleosynthesis up to calcium may occur, in particular with the NeNa cycle and the MgAl cycle. Processed material is ejected into the interstellar medium. Multi-wavelength observations of classical novae are performed in order to understand these objects and their

associated nucleosynthesis. Among these observations, gamma-ray astronomy and the study of presolar grains are of specific interest since they are sensitive to isotopic abundances instead of simply the elemental abundances that can be derived from optical or UV observations. However, to interpret these observations and therefore to constrain the astrophysical modelling of classical novae, it is crucial to reduce the nuclear uncertainties involved in the production of the isotopes of interest. Radioisotopes, such as ^{18}F, ^{22}Na and ^{26}Al, are of particular interest due to their predicted abundance and lifetime, Future instruments with better suppression of instrumental backgrounds (e.g. eAstrogam) are promising for detecting such a unique nova nucleosynthesis signal.

The contribution of novae to the lithium content of the Milky Way has been highlighted, based on the recent observation of radioactive beryllium, which decays into lithium. Among the implications of these results, the measurements of ^{7}Be lines in the near-ultraviolet range and within the lifetime of the element may well provide a way of estimating the contribution of novae to the lithium abundance in the Milky Way and in the Universe in its entirety.

Uniquely, of all stellar explosions, almost all the nuclear physics input to nova models is based on experimental data, and this makes them important tests for explosion mechanism models. As explosive hydrogen burning in classical novae involves stable and radioactive nuclei relatively close to the proton-rich side of the valley of stability, experimental studies of these nuclear processes are possible at small-scale stable beam accelerators and at the existing generation of radioactive ion beam facilities. However a few key reactions (e.g. ^{18}F$(p,\alpha)^{15}$O , ^{25}Al$(p,\gamma)^{26}$Si , ^{30}P$(p,\gamma)^{31}$S) are still not sufficiently well constrained and remain the target of further experimental attention.

The state-of-the-art in nova modelling relies on 1D, spherically-symmetric hydrodynamic simulations. Spherical symmetry demands that the explosion must occur simultaneously along a spherical shell. Despite many observational features that characterize novae have been successfully reproduced by such 1D hydrodynamic simulations, certain aspects like the way in which a thermonuclear runaway sets in and propagates, or the treatment of convective transport, clearly require a multidimensional approach.

To date, multidimensional (i.e., 2D and 3D) simulations of novae for realistic physical conditions have been restricted to "convection-in-a-box" studies, aimed at characterizing convective transport during the stages prior to mass ejection. The simulations performed rely on the evolution of an accreting white dwarf, initially followed in 1D and subsequently mapped into a 2D or 3D domain as soon as the temperature at the envelope base reached 100 MK. To reduce the overwhelming computational load, such simulations frequently include a very simplified nuclear reaction network to account exclusively for the energetics of the explosion. With the same aim, only a slice of the star is adopted. Simulations reveal a good agreement with the gross picture outlined by 1D models (e.g., the critical role played by the β+-unstable nuclei ^{13}N, ^{14,15}O, and ^{17}F in the ejection stage, and consequently, the presence of large amounts of ^{13}C, ^{15}N, and ^{17}O in the ejecta). However, some remarkable differences have also been found: first, the thermonuclear runaway is initiated as a myriad of irregular, localized eruptions at the envelope base caused by convection-driven temperature fluctuations. This suggests that combustion proceeds as a chain of many localized flames –not as a thin front-, each surviving only a few seconds. However, since turbulent diffusion efficiently dissipates any local burning around the core, the runaway ultimately spreads along the stellar surface, such that the expansion and progress of the runaway towards the outer envelope becomes almost spherically symmetric (although the initial burning process was not). Moreover, the core-envelope interface is now convectively unstable, providing a source for the metallicity enhancement (one of the long-lasting problems in nova modelling) through Kelvin-Helmholtz instabilities, which can naturally lead to self-enrichment of the accreted envelope with core material, at levels that agree with observations. Pioneering 3D simulations of mixing at the core-envelope interface during nova explosions provide as well with an explanation of the origin of the highly-fragmented, chemically-enriched, inhomogeneous nova shells, observed in high-resolution spectra, interpreted as a relic of the hydrodynamic instabilities that develop during the initial ejection stage.

X-ray bursts:
Type I X-ray bursts are bright and frequent events showing a rapid increase in luminosity due to a thermonuclear runaway on the surface of a neutron star. In order to understand type I x-ray burst light curves, and also the properties of the underlying neutron star, detailed information on nuclei and the nuclear reactions involved in the thermonuclear runaway is needed. Due to the higher temperatures and densities of neutron stars, as compared to classical novae, the nuclear flux can break-out from the hot CNO cycle through the ^{15}O$(\alpha,\gamma)^{19}$Ne, ^{14}O$(\alpha,p)^{17}$F, and ^{18}Ne$(\alpha,p)^{21}$Na reactions. Material is processed to heavier masses by the αp-process and then the rapid proton capture (rp)-process, which lies close to the proton dripline. The pathway may reach masses around $A = 100$, where the flow may terminate with the SnSbTe cycle.

Unlike classical novae that eject material into the interstellar medium, X-ray bursts are not thought to produce significant ejecta, due to the strong gravitational potential of the neutron star. There is therefore no observational information on the products of nucleosynthesis with which to compare the models. However, the light-curves are closely related to the energy released by (α,p) reactions and, to a lesser extent, (p,γ) reactions, and a comparison with observational data is possible.

In contrast to classical novae, most of the nuclear physics input to X-ray burst models is not experimentally determined. Despite significant effort over more than two decades the rates of the breakout reactions are still not sufficiently well known. Masses and lifetimes close to the proton-drip line are needed, and the reaction rates along the ap- and rp-process path are the focus of experiments.

Traditionally, hydrodynamic studies of type I X-ray burst nucleosynthesis have been performed in 1D with truncated nuclear reaction networks. However in the last decade, following fast developments in computational capabilities, several groups have carried out very detailed nucleosynthesis calculations coupling hydrodynamic models and extensive nuclear reaction networks containing $\sim 300 - 400$ isotopes (or up to 1300 isotopes in the framework of adaptive networks). All in all, 1D simulations have proved successful in reproducing the main observational features of type I X-ray bursts (i.e., light curve shapes, recurrence periods). The burning front likely propagates subsonically (i.e., a deflagration). The outburst is likely quenched by fuel consumption (rather than by envelope expansion as in novae), and is driven by a

suite of different nuclear processes. The most complex nuclear path is achieved for mixed H/He bursts, which are driven by the 3α-reaction, the αp-process (a sequence of (α, p) and (p, γ) reactions), and the rp-process (a series of rapid proton-captures and β-decays, which power the late light curve during decline).

Some important issues remain to be clarified, however. One is the potential contribution of type I X-ray bursts to the Galactic abundances, since ejection from the neutron star surface is challenged by the extremely large escape velocities. The second is the link between type I X-ray bursts and the production of very energetic superbursts. Indeed, the duration and energetics of superbursts suggest that fuel ignites at deeper layers than in normal type I bursts, at densities typically exceeding 10^9 g cm^{-3}, close to the neutron star crust. Since neither hydrogen nor helium likely survive at those depths, it has been suggested that superbursts may be powered by ignition of carbon-rich fuel. But controversy remains as to how much carbon is actually consumed during a type I burst, and whether enough carbon is leftover to power a superburst, a possibility not favored by current models. Alternative models rely on combined stable and unstable burning regimes of the accreted H/He mixture, but the scenario requires further analysis.

To date, no self-consistent multidimensional full simulation of an X-ray burst, for realistic conditions, has been performed. So far, a number of efforts have focused on the analysis of flame propagation on the envelopes accreted onto neutron stars or on "convection-in-a-box" studies aimed at characterizing convective transport during the stages prior to ignition. A number of multidimensional studies of detonation flames on neutron stars have been performed but imposing physical conditions that bear little resemblance with those expected during X-ray bursts.

Matter at extreme conditions: neutron stars

To understand the physics of neutron stars and binary mergers, it is important to constrain the equation of state (EoS) of neutron-rich strongly interacting matter. Although the EoS of symmetric nuclear matter has been constrained over a range of densities around the saturation density, the spread of values for the EoS at high densities still remains large. The knowledge of asymmetric nuclear matter is very limited, mainly because of difficulties in determining accurately the symmetry energy. It

describes the energy change of the nuclear system as a function of the excess of neutrons or protons. It favours nuclei with N~Z and is critical for understanding the properties of nuclei and the limits of stability.

Nuclear experiments provide important information to constrain the symmetry energy at nuclear densities. The symmetry energy and slope of the symmetry energy, both at the saturation density, represent the two quantities that have recently been extensively studied by a variety of experimental methods. The slope parameter provides the dominant baryonic contribution to the pressure in neutron stars and affects the neutron skin thickness. The latter can be extracted from experiments studying the parity violation in electron scattering or coherent pion photoproduction. Further relevant nuclear phenomena, that have recently been extensively studied, include various collective excitations, e.g., isovector giant dipole and quadrupole resonances, pygmy dipole transitions, Gamow-Teller resonances, anti-analog giant dipole resonances, etc.

Many-body calculations based on ab initio or nuclear energy density functional methods, that describe the properties of finite nuclei, represent the key approaches for the description of the EoS. In the framework of nuclear density functional theory, successful techniques have recently been developed and exploited in connecting the experimental data with the density dependence of the symmetry energy. Ab initio approaches based on chiral effective field theory have been used to determine the EoS of uniform neutron matter up to saturation density, including contributions of two and three body forces. Those calculations also provide important constraints and an important self-consistency check of how well realistic interactions that have been adjusted to scattering and few body data can be applied to describe homogeneous systems like neutron matter. Techniques to connect ab initio approaches for the low density regime with density functional approaches at the high density regime are also being developed.

Another promising approach is based on statistical methods associated to the covariance analysis of observables. It allows to identify relevant correlations between the properties that govern the EoS and those characterizing static and dynamic phenomena in finite nuclei. In particular, the isovector excitations in nuclei provide additional constraints for the neutron star core-to-crust

transition density and pressure. The dipole polarizability, associated to the isovector dipole excitations in nuclei, has been established as a novel promising constraint for the neutron skin thickness and the symmetry energy.

The incompressibility of symmetric nuclear matter, a measure of the curvature of the equation of state at saturation density, represents another relevant quantity. It can be determined from the compression modes of collective nuclear vibrations. There remain large uncertainties in the extracted value originating in the model dependent connection between experimental data and the nuclear matter incompressibility.
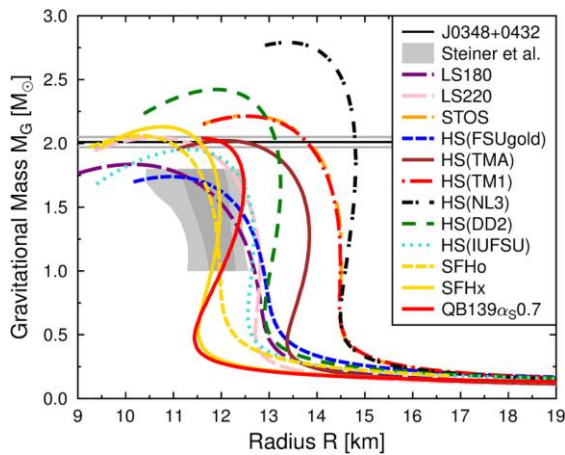
Figure 7 Current constrains on the mass and radius of neutron stars compared with predictions of different equations of state [From T. Fischer, et al., Eur. Phys. J. A 50, 46 (2014)]

Presently, the main astrophysical constraint for the EoS stems from the observation of two binary systems. In both, a very massive neutron star is partnered by a white dwarf. The masses of these two neutron stars have been measured precisely to be around two solar masses. This result severely constrains the stiffness of the EoS at high densities and excludes already many models. The ultimate constraint on the EoS would be a determination of radius and mass of the same object. For low-mass neutron stars this could be translated into a constraint for a particular combination of the incompressibility and slope of the symmetry energy.

The composition of matter at the suprasaturation densities reached in neutron star cores is very uncertain. Particles other than nucleons and electrons are expected to appear. Muons, pions, kaons and their condensates, hyperons, nuclear resonances and quarks have been considered. There is even the possibility of absolutely stable

strange quark matter and pure strange stars. The two solar mass neutron star constraint has triggered intensive discussions about the neutron star interior composition. The appearance of additional degrees of freedom tends to soften the EoS and lower the maximum mass but large uncertainties remain due to the poorly understood interaction in the medium. Phenomenological hadronic and quark models can easily be supplemented with the necessary repulsion at high densities so that maximum masses above two solar masses can be obtained. Hyperonic degrees of freedom, which are expected to appear at about twice the saturation density, are difficult to reconcile with a two solar mass neutron star. Addressing this "hyperon puzzle" requires additional repulsion to stiffen the high-density EoS. Hyperonic and three-body interactions have been extensively studied in this respect. However, experimental data are scarce and furnish only weak constraints on the interactions.

Several phenomenological EoS models exist that contain hyperons and predict maximum neutron star masses in agreement with observations. Microscopic models have difficulties accounting for the missing repulsion for hyperons. Nevertheless, recent calculations based on auxiliary field diffusion Monte Carlo techniques found a sufficiently strong repulsive three-body force, which is still compatible with the experimentally measured binding energies of hypernuclei. There are still many open questions regarding the role of hyperons and other non-nucleonic degrees of freedom in neutron stars.

There exist plenty of EoSs for cold neutron star matter. To a lesser extent, this still holds for EoSs for homogeneous hot matter in proto-neutron stars. To be usable in astrophysical simulations, the EoS has to encompass a wide range of densities, temperatures and isospin asymmetries. Such "general purpose" EoSs are much rarer; there exist only about 40. They not only have to cover a huge range of thermodynamic conditions but also include a description of clusterised and/or inhomogeneous matter at subsaturation densities. General purpose EoSs are of great importance for astrophysics, as they can be used in simulations of neutron star mergers or core-collapse supernovae. The final outcome of stellar evolution (remnant and nucleosynthesis ejecta) and the neutrino and gravitational wave signals are also sensitive to the EoS.

As a sub-class of "general purpose" EoSs, unified EoS for cold neutron stars are those that describe matter from the surface to the centre of the NS in a unified manner, i.e., on the basis of the same interaction model, including a description of inhomogeneous matter in the crust. This is important for detailed predictions of NS radii and for dynamical properties. Only a few such unified NS EoSs exist.

All of the available "general purpose" EoSs are based on phenomenological approaches. Even at this level, several of them are clearly ruled out by experimental or astrophysical observations and no presently existing model is consistent with all available constraints.
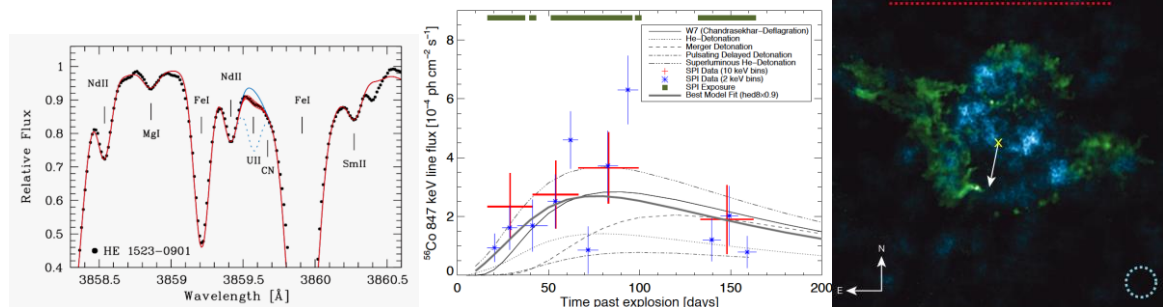
Astronomical Observations

Observations of characteristic lines in stellar spectra have been the backbone of determining elemental abundances in stars in great detail; different stars thus have taught us about the cosmic variations of elemental abundances. The isotopic composition of winds and ejecta, and their kinetic and radiative feedback, makes stars the key agents that drive the evolution of interstellar gas and their entire host galaxies. These nucleosynthesis imprints can be observed in various ways: the photospheres of single stars; characteristic lines from interstellar gas; collective spectra of entire populations of stars

or galaxies; and even in dust grains collected in meteorites. Understanding how characteristic spectral features arise is key to interpretations of astronomical spectra in terms of the composition. Additionally, often, many sources contribute and are superimposed, making the decomposition challenging due to the complex, non-linear and often stochastic processes involved. Therefore, it is very challenging to relate observational abundance data directly to nuclear reactions in cosmic objects. Instead, models of stars and explosions are combined with ejecta propagation, and with the frequency of their occurrences over time, to be composed into sophisticated galactic chemical evolution models. These serve as tools to validate the underlying physics assumptions against astronomical observations. Often still, models are constructed around simplifying assumptions such as instantaneous recycling of matter between stellar generations, or assumption of spherical symmetry of the explosions. This may often have been a necessary simplification owing to the high dynamic range in the spatial and temporal scales that are involved in stellar evolution. But advances in our theoretical understanding, combined with availability of adequate computing power, helps to learn and provide tighter and tighter constraints to nuclear processes in cosmic environments.

Elemental abundances have been the foundation of nuclear astrophysics. One of the recent findings was the detection of Uranium with ESO's Very Large Telescope (left). Much better data are now becoming available for a vast number of stars in our Galaxy, thanks to ESA's Gaia space satellite instrumentation, and new and planed multi-object spectrographs such as WEAVE and 4MOST. These enable us to discriminate abundance pattern systematics for stars of different origins and ages, "Galactic archaeology", and the test of modern descriptions of chemical evolution of cosmic gas in and between galaxies.

Multi-messenger data complement the astronomical observations. Meteorites and stardust embedded therein had been essential for isotopic ratios, from solar system material, and also tracing dust from nucleosynthesis sources (AGB stars, novae, supernovae) with characteristic nuclear reaction products. Astronomical observations at other wavelengths, from radio and sub-mm molecules to X- and gamma-ray nuclear lines also carry isotopic information. X and gamma-ray space observatories allow measurements directly at individual nucleosynthesis sources. So, supernova gamma-rays from the ^{56}Ni decay chain have been discovered for the first time from a supernova of type Ia (center). With SN2014J at a distance of 3.5 Mpc, such a supernova occurred sufficiently close for current telescopes. Similarly, the Cas A supernova remnant at only 3.4 kpc distance allowed analysing, and even imaging, the ejection of nucleosynthesis products. The ^{44}Ti image of the spatial distribution within the remnant is a recent breakthrough (right). ^{44}Ti is expected to be produced near to the boundary between the material falling back onto the collapsing core and that ejected into the surrounding medium. Its spatial distribution directly probes the explosion asymmetries. Key nuclear reactions, including ^{44}Ti(α,p), determining the production are being studied in several European labs.

Identifications of metal-poor stars in different varieties have founded a field now called Galactic Archeology, as metal content reflects stellar age, and thus the history of enrichment of Galactic matter, with different elements, can be studied. In recent years, large surveys (both photometric and spectroscopic) have been conducted, which by now provide spectra for millions of stars in our Galaxy, and thousands of metal poor star spectra. From this, different populations of stars in our Galaxy have been recognised, i.e. the different enrichment histories tell us if stars were born in unusual environments, if they reflect what we expect from the evolution of stars in our Galaxy across its ten gigayear history, or if they may have been formed from material outside our Galaxy that merged with the Milky Way Galaxy at some point. The detection of uranium is a recent achievement, which allows dating, independently of cosmological model assumptions, and improved constraints on pollution from r-process ejecta. With Gaia and Kepler, now it is possible to add precision to secondary parameters that are key to such study, namely the distance to the sources of stellar photosphere spectra, and the age of the parent star. Even larger spectroscopic surveys based on high-multiplex spectrographs are underway in order to complement the Gaia information with detailed chemistry and radial velocities (e.g. WEAVE and 4MOST).

Beyond stellar spectra, several 'new astronomies' have been arising since the advent of radioastronomy in the 1930s. Some of these are sufficiently matured to also use them in the study of evolving cosmic matter composition. Most importantly, meteories provide us with material from the history of our solar system, which can be analysed for its isotopic composition in terrestrial laboratories. The isotopic composition of the sun thus has been established, complementing spectroscopy of the sunlight. Within those meteorites, inclusions of extrasolar material

have been recognised about 40 years ago, and have been associated with stardust from stars, novae, and supernovae outside our solar system. The isotopic composition measured in such stardust grains have led to important constraints on nuclear reactions, in particular for AGB stars, and more recently also for supernovae.

Radio astronomy has matured to provide both spatial and spectral resolution to measure molecules and their isotopic variants even in distant galaxies. Although the variety of species observed in radio and sub-mm spectroscopy leaves a task of species identification, and chemistry in interstellar space is required to interpret such data, new constraints on cosmic nucleosynthesis arise from measurements with, e.g., SOFIA, ALMA and IRAM.

Towards the higher energy end of the electromagnetic spectrum, X-ray and gamma-ray telescopes have added spectroscopy of hot plasma. Since nucleosynthesis sources and in particularly supernovae are very energetic and eject nucleosynthesis ashes in the form of hot plasma, this allows the study of sources of nucleosynthesis directly, thus complementing the information contained in stellar spectra about their cumulative action before such a star was formed. Recent progress here involves, e.g., constraints on the morphology of nucleosynthesis ejecta in the Cas A supernova remnant with different X-ray and gamma-ray telescopes. Chandra measurements had shown that in different atomic recombination lines the structure of the remnants appears different, with surprises from iron appearing outside regions of silicon emission. NuSTAR imaging of the same remnant in ^{44}Ti radioactivity measured at ~70 keV then showed a set of different emission clumps. This is surprising in that it shows the non-sphericity of a supernova even from messengers of its innermost regions. On the other hand, a qualitative similarity to recent 3-dimensional simulations is encouraging, confirming that instabilities of the inner burning regions are at the origin of the observed clumping. A second example is the direct proof that ^{56}Ni radioactivity powers supernova light, from INTEGRAL/SPI observations of the gamma-ray lines characterising the ^{56}Ni radioactive decay chain through ^{56}Co lines leaking out after several weeks. With detailed observations of diffuse nucleosynthesis in ^{26}Al gamma-rays, a new and independent access has been opened to massive star feedback and cosmic matter recycling, making use of this radioactive clock with a million year characteristic decay time of the radioactive by-product of massive star nucleosynthesis that can be measured in interstellar space. ^{60}Fe gamma rays have also been seen, yet instrument sensitivities are insufficient to similarly exploit these much fainter gamma-ray lines towards constraining the s-process in massive star shell burning.

Finally, the detection of first gravitational wave events, even though from different objects, show that also this astronomical window is ready, to witness gravitational wave signatures of neutron star mergers or a nearby core collapse supernova in our Galaxy., Constraints on the explosion dynamics, and on the formation of a neutron star and its equation of state are among the prospects of such measurement

Requirements for Nuclear Experiment, and Theory

Experimental opportunities

Accelerator facilities

Radioactive beam facilities

Box 3: Experimental constraints on astrophysical reactions involving exotic nuclei

One of the major challenges in modelling nucleosynthesis in explosive environments is the fact that the nuclear properties of the many nuclei involved are not known experimentally. This is particularly the case for the r process that requires neutron captures and beta-decay rates for neutron-rich nuclei. Beta-decay experimental data for r process nuclei has dramatically contributed to improve theoretical calculations. The situation is different for neutron capture rates. However, recent experimental developments offer the possibility of constraining neutron capture rates far from stability.

S. N. Liddick, et al., Phys. Rev. Lett. 116, 242502 (2016)
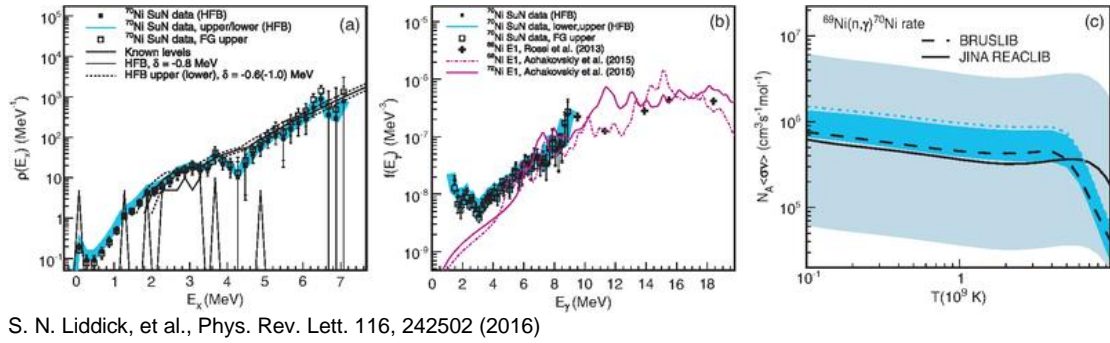
New radioactive beam facilities in Europe, such as FAIR at GSI, SPIRAL2 at GANIL, HIE-ISOLDE at CERN, SPES-INFN and ELI IGISOL at ELI-NP, will provide unprecedented opportunities to study exotic nuclei of interest for nuclear astrophysics. In particular major steps on the production of nuclei of interest for the rp-, i- and r-processes will be realised. This breakthrough, coupled to the next-generation detector systems and the new experimental techniques, will allow more precise and new experimental measurements of nuclear inputs relevant for astrophysical models, particularly for supernovae, mergers and X-ray bursts. Moreover, the study of nuclear properties and reactions far from stability will provide much needed experimental data to test and constrain the nuclear models, which still provide the majority of nuclear input to explosion models.

In the immediate future, rp-process nuclei can be explored e.g. employing beams from SPIRAL1 and new facilities, such as S3 at GANIL and MARA at JYFL. In the lower-mass region, reaction studies in inverse kinematics employing intense radioactive beams will increase our knowledge of reaction rates needed for the astrophysical reaction network calculations. Surrogate (d,n) proton-transfer reactions have shown to be promising candidates for determining the relevant states and resonance strengths for (p,γ) reactions. In combination with the state-of-the-art detectors, such as the high-resolution gamma-ray detector AGATA, these will lead to a significant improvement in the knowledge of key reactions

for the rp-process. Direct reaction studies as well as Coulomb dissociation reactions performed at the R3B facility at FAIR (GSI) are also essential for the rp-process. New kinds of experiments become available at the NESR storage ring facility at FAIR. The first proof-of-principle experiments have already been performed for nuclear astrophysics at ESR storage ring at GSI.

The masses of the involved nuclei determine the path of the rp-process and have a strong effect on the X-ray burst light curves and final abundances. Penning-traps have revolutionised the possibilities of high-precision mass measurements of radioactive isotopes. New techniques, employing phase imaging or Fourier-transform ion cyclotron resonance mass spectrometry, make it possible to do measurements faster or with lower yields than ever before. Penning traps at future RIB facilities, such as MATS at NUSTAR/FAIR and MLLTRAP (coupled to PIPERADE in some cases) at SPIRAL2 will provide new opportunities and complement/support the work done at the existing ISOLTRAP, SHIPTRAP and JYFLTRAP facilities. Multi-reflection time-of-flight mass spectrometers (MR-TOF) have shown to be efficient, yet not so precise, tools for mass measurements of shorter-lived nuclei. New MR-TOF mass spectrometers are planned for most new facilities, such as for the low-energy branches of MARA at JYFL and S3 at SPIRAL2

Beta-decay properties of nuclei along the rp process path are also necessary input to X-ray

bursts models. Here, both Penning traps and MR-TOF-MS devices are very useful for providing isotopically or even isomerically pure beams for decay spectroscopy experiments. As low-energy isomers can be thermally excited at the peak temperature of the bursts, isomeric states can play a critical role in X-ray busts, making their identification and study relevant for the modelling of the rp-process. Beta-delayed particle decays have yielded much information on the resonance strengths and states in the lower mass region. New active target time projection chamber detectors, such as ACTAR, will help in detecting lower proton energies than previously possible, often a critical requirement for astrophysics studies. Total Absorption Spectrometers will yield better understanding of the Gamow-Teller strength distribution and electron-capture decay probabilities. Furthermore, complementary studies employing charge-exchange reactions will enable detailed comparisons of the Gamow teller strengths.

For the production of heavy elements in supernovae and mergers, the three European ISOL facilities (HIE-ISOLDE, SPES and SPIRAL2) will soon provide more intense beams of some nuclei located along the r-process path (fission products of uranium). In the future, a major step will be made with the FAIR-NUSTAR facility, which is expected to give access, for the first time, to many of the r-process path nuclei at N=126 by means of fragmentation of high-intensity and high-energy ^{238}U-beam. Thus, a change of paradigm can be expected in the near future, providing first experimental data in a yet unknown region of the nuclear chart, and very stringent constraints for the r-process nucleosynthesis of the heaviest stable nuclei.

Recent developments at LNL and GANIL have demonstrated also the suitability of multi-nucleon transfer reactions to produce large yields of N=126 nuclei. In particular the low neutron binding energy of neutron-rich species can be used to produce extremely neutron rich target-like fragments. Transfer reactions on a lead target using e.g. high intensity ^{94}Rb beams feasible at HIE ISOLDE or SPES can be used to produce very neutron-rich heavy nuclei around the N=126 region. Fragmentation and nucleon transfer are rather complementary production mechanisms, and one can expect first-hand access to many of the r-process nuclei directly at N=126 as well as to those involved in the freeze-out phase. Advanced instrumentation capable of coping

with the severe background conditions is being developed and tested in existing facilities such as ALTO, GANIL, GSI, or LNL in Europe and abroad at NSCL (USA) and RIKEN (Japan). These advanced detection systems with high sensitivity and selectivity will allow one to experimentally determine masses, beta-decay half-lives and beta-delayed neutron-emission of the most exotic neutron-rich nuclei. It is worth mentioning that almost all the nuclei to be discovered are expected to be beta-delayed neutron emitters. Beta-delayed neutron emission has a two-fold impact in the final r-process abundances, as on one side it shifts the mass-distribution towards lower values, and on the other hand it may induce a reactivation of the r-process in its later stages.

Apart from the ground state and decay properties, one of the ingredients influencing the final r-process abundance pattern are the neutron capture reaction rates on the neutron-rich unstable nuclei involved. Stellar neutron capture reaction rates are also of relevance for the recently proposed i-process mechanism of nucleosynthesis.

These cross-sections cannot be directly measured and thus, alternative indirect approaches need to be investigated. In this respect, a leap forward can be expected in the near future due to ongoing developments on different, complementary, experimental approaches. One such approach is based on detailed studies of the electric dipole response of exotic nuclei, which include a high energy resolution over a broad energy spectrum enabling the identification of low-energy gamma-ray strength distribution, so-called Pygmy resonances. Measurements of the Pygmy resonance in stable and unstable nuclei have been found to represent a rather large influence on the neutron capture stellar rates and correspondingly on the final r-process abundance pattern. Advanced detection systems such as AGATA and R3B-LAND at NUSTAR will allow the mapping of the electric dipole nuclear response on very neutron-rich nuclei, and using it to infer more realistic neutron capture cross sections.
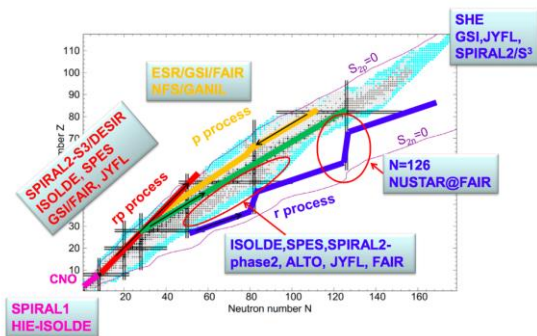
Figure 8 European radioactive beam facilities offer unprecedented and complementary capabilities to study exotic relevant for the evolution and nucleosynthesis in explosive environments.

Other approaches, still under development, employ transfer reactions as surrogates for neutron capture. Two different innovative techniques are being developed in this field. One of them induces transfer reactions employing radioactive ion beams in inverse kinematics, exploiting the high beam energy resolution, high luminosity and target purity attainable in storage rings like ESR/CRYRING at FAIR-NUSTAR. Present studies have shown the feasibility of surrogate methods for determining fission cross sections, whereas a successful methodology for radiative neutron capture has yet to be developed and validated.

Other techniques intend to exploit the high secondary beam intensities provided by the SPES facility in combination with high-resolution measurements, which employ high-granularity particle and gamma-ray tracking detectors. This methodology could help to constrain the s-wave component of the neutron capture, which is in most cases one of the main contributions to the overall stellar neutron capture rate.

Finally, Total Absorption Spectroscopy (TAS) beta-decay measurements, which are sensible to the γ-ray strength distribution beyond the neutron separation threshold of the daughter nucleus, in combination with high-resolution neutron-spectroscopy measurements, using new time-of-flight spectrometers, like MONSTER, can also help to experimentally constrain the neutron capture rates in the relevant stellar energy range.

New laboratory experiments and experimental facilities such as RIKEN, FRIB, FAIR, NICA, and SPIRAL2 are also essential to provide new constraints on the equation of state, a crucial ingredient for compact stars and supernovae models. In order to reduce current uncertainties in the values of the symmetry energy parameters, novel experimental data with improved accuracy are needed. In particular, this includes parity violating electron scattering on nuclei, which provides model-independent measurement of the root mean square radius of the neutron distribution in the nucleus. Other approaches necessary to provide complementary constraints for the symmetry energy with improved accuracy include isovector multipole transitions, in particular, complete dipole transition spectra including pygmy strengths, isovector giant dipole resonances and respective dipole polarizability. Future experiments on novel charge-exchange transitions, such as the anti-analog giant dipole resonances, also represent a promising approach to determine the symmetry energy parameters.

In the next 5-10 years, with several new RIB facilities operational in Europe, one can expect to remarkably push forward the border of knowledge of the nuclear chart, particularly in the heavy mass region, while gaining a wealth of new data (masses, half-lives, neutron branchings, reaction cross sections) that will be direct input for r-process model calculations. A very complete assembly of different detection systems and even new techniques are being developed and tested at existing facilities in order to get as much and accurate information as possible, once the new RIBs become accessible.

Underground nuclear astrophysics

The LUNA (Laboratory for Underground Nuclear Astrophysics) collaboration celebrating its 25th anniversary in 2016 has shown the tremendous advantages of a deep underground location for an accelerator in experimental nuclear astrophysics. Indeed, the extremely low laboratory background has allowed, for the first time, nuclear physics experiments with very small count rates, down to a couple of events per month. This way, the important reactions responsible for the hydrogen burning in the Sun could be studied down to the relevant stellar energies. Although LUNA is still the only deep underground accelerator facility, several new similar projects are planned or under construction in many places of the world. In order to keep the world-leading role of Europe in this area and compete successfully with the Chinese or USA initiatives, the future European underground accelerator facilities must receive strong support.

The next phase of the LUNA collaboration, mainly devoted to helium and carbon burning,

is already in preparation at the Gran Sasso deep underground laboratory in Italy. This so-called LUNA-MV project will benefit from a new high current single-ended 3.5 MV accelerator able to provide hydrogen, helium and carbon (also double ionized) beams. Based on the energy range and beam intensity of this machine, several key reactions of nuclear astrophysics are on the ambitious list of the LUNA-MV scientific program. These include the neutron source reactions of the s-process ($^{13}C(\alpha,n)^{16}O$, $^{22}Ne(\alpha,n)^{25}Mg$), the "Holy Grail" of nuclear astrophysics ($^{12}C(\alpha,\gamma)^{16}O$), the $^{12}C+^{12}C$ fusion, and several hydrogen and alpha burning reactions.

An underground accelerator is also proposed at the Canfranc underground laboratory in Spain. The planned CUNA (Canfranc Underground Nuclear Astrophysics) project aims first at the measurement of the neutron source reactions of the s-process ($^{13}C(\alpha,n)^{16}O$, $^{22}Ne(\alpha,n)^{25}Mg$).

A 5MV pelletron accelerator is under installation in the shallow underground laboratory "Felsenkeller" in Dresden, Germany. The accelerator will serve as an open user facility and studies of the reactions of the H, He and C burning processes are planned.

Stable beam accelerator facilities
The very fact that nuclear reactions in stars occur at extremely low energies means that in many cases the important reactions can be studied at small accelerators providing low energy beams. Such accelerators are often found at small scale facilities which have therefore been one of the main driving forces in experimental nuclear astrophysics over the years. More recently, extensive nuclear astrophysics research, particularly on explosive scenarios, has been developed at large scale facilities, but small scale facilities remain a key workhorse of the field.

When direct measurements of astrophysical cross-sections close to or in the Gamow peak are not achievable, indirect methods can be used advantageously. For physics cases involving nuclei only a few units from the valley of stability, indirect studies can be performed at small scale facilities operating stable beams. In this context it is important to highlight the need to preserve electrostatic machines like TANDEMs from possible shut-downs in the near future. Magnetic spectrometers (Enge Split-pole and Q3D) are an instrumentation of choice to perform high resolution spectroscopic studies, to determine the parameters of key nuclear excited states. Europe currently maintains a high profile in these studies, but with several magnetic spectrometers coming online in the U.S. in the next five years, it is crucial that European facilities support and invest in these instruments.

Although most of the reactions in quiescent burning processes of stars have already been studied experimentally, the rates of these reactions are not yet known with the high precision now required by improved astrophysical models and observations. The fast development of astronomical observation techniques triggers the continuous improvement of stellar models. The sophisticated stellar models, therefore, require high precision nuclear physics input. The improved precision required by future nuclear astrophysics experiments will be achieved through several means. New techniques like higher intensity ion sources and accelerators or improved quality targets are certainly needed. Studying a reaction with complementary methods such as in-beam gamma-detection, activation, accelerator mass spectrometry (AMS) or various indirect methods like Trojan Horse or ANC can significantly increase the precision and reliability of data. Measuring the cross section of a reaction in a wide energy range may aid the theory-based extrapolation of the data to low energies.

Accelerator mass spectrometry (AMS) is a very sensitive tool to measure long-lived radionuclides at very minute concentrations. This technique has been used for nuclear astrophysics research primarily in two ways. Firstly, in dedicated experiments, where the nuclear reaction for the production of the radionuclide is studied, AMS is able to detect the often small number of produced atoms of the radionuclide in the target material after the reaction process. These measurements complement techniques that detect prompt reaction products (e.g. at n_TOF facility) or the measurements of shorter-lived radionuclides via decay measurement after the irradiation (activation measurements). In particular, long-lived nuclides that are difficult or impossible to detect via decay measurements (e.g. ^{41}Ca with a half-life of about 10^5 years, is virtually impossible to detect otherwise). Mainly s-process reactions have been studied with irradiations at neutron facilities preceding the AMS measurement, but also some charged particle reactions (e.g. $^{25}Mg(p,\gamma)^{26}Al$).

Secondly, the superb sensitivity can be used to detect traces of recent nucleosynthesis events. Some long-lived nuclides have no significant sources in our Solar System and on Earth, but are produced in significant quantities during nucleosynthesis and are emitted into the interstellar space during supernova explosions. ^{60}Fe (halflife of 1.3 My) and ^{244}Pu (81 My) are the two candidates that have been studied via AMS. The finding of a clear signal from 2-3 million years ago in a deep-sea FeMn crust points to a direct deposition of recently produced ^{60}Fe from a nearby supernova and complements space-based observation of ^{60}Fe by γ-ray astronomy. The measured abundance of the r-process nuclide ^{244}Pu (in total only 5 atoms were detected) is about two orders of magnitude below the value expected from continuous production in our Galaxy. This information adds a piece to the puzzle of the possible site(s) of the r-process. The measured low ^{244}Pu abundance might be the result of rare but high-yield events that produced the heaviest elements (actinides), in contrast to supernovae that are likely to be responsible for the main r-process nuclides.

AMS is generally based on electrostatic tandem accelerators that provide the elimination of molecular interference in the mass spectrometric analysis. For identification of the rare radionuclide in the presence of intense isobaric interference (e.g. ^{60}Fe with interference of stable ^{60}Ni), rather high ion energies are required (terminal voltages above 10 MV). In Europe there is currently only the accelerator facility in Garching of the Technical University in Munich that can perform such challenging measurements. It is important for the field that at least one large tandem accelerator facility is capable of doing AMS at high energies; many other long-lived nuclides that do not require the identification within the isobaric background, can be done with less effort and higher precision and efficiency at smaller accelerator facilities (e.g. at the 500 kV TANDY at ETH Zurich or the 3 MV VERA facility in Vienna).

Extensive experimental nuclear astrophysics programmes are planned in many small scale facilities all over Europe. Many reactions of quiescent hydrogen-, helium- and carbon-burning processes are to be studied with various methods including novel techniques. Moreover, stable beam experiments are also important for the better understanding of some explosive nucleosynthesis processes like e.g. the p-process and in binary objects such as classical novae and type I X-ray bursts. These experiments will provide crucial progress in nuclear astrophysics in the forthcoming years.

Europe has long played a leading role in experimental nuclear astrophysics due to the many complementary facilities contributing to the success of the field in the last decades. However, a full understanding of those reactions, which can be studied with stable beam accelerators, has still not been achieved. Therefore it is crucial to continued European success in the field that small scale facilities are recognised and receive the necessary support for continuing and improving their nuclear astrophysics research. Forming and strengthening the nuclear astrophysics network of European small scale facilities is important in order to exploit the complementary techniques in various institutions, and to support critical existing equipment

Neutron beam facilities

Neutron production via (p, n) reactions at low-energy electrostatic accelerators was the initial source of information on stellar cross sections. Fast pulsed electrostatic accelerators are important because they are complementary to white neutron sources due to a combination of unique features, i.e. the possibility to tailor the neutron spectrum, low backgrounds and competitive flux at sufficient TOF resolution. Neutron spectra can be restricted to the immediate region of interest for s-process applications by the proper choice of the proton energy and the thickness of the neutron production target.

For the example of the ^{7}Li(p,n)^{7}Be reaction, which represents the most prolific and commonly used (p, n) source, neutrons in the energy range from a few to 220 keV are produced by bombarding layers of metallic Li or LiF with typical thicknesses of 10 to 30 μm. With proton beams 30 and 100 keV above the reaction threshold at 1881 keV, continuous neutron spectra with maximum energies of 100 and 225 keV, respectively, are obtained, where the first choice offers a significantly better signal to the background ratio at lower neutron energies. The neutron production target consists only of a thin Li layer on a comparably thin backing without any moderator, thus allowing for very short flight paths down to a few centimetres.

An examples of such a setup realized with a Van-de-Graaff accelerator is at JRC, Geel, Belgium and with a 3 MV Tandem Pelletron at

CNA, Sevilla, Spain, in the framework of the HISPANOS initiative. Recent developments gear towards increased proton beams using RFQ-type LINACS. Examples are SARAF (Soreq, Israel) with a liquid lithium target, LENOS (INFN Legnaro, Italy) or FRANZ (Goethe University Frankfurt, Frankfurt, Germany).

Future approaches might include inverse kinematics in the neutron production, such lithium beam on hydrogen target (LICORN, Orsay, France) or even inverse kinematics during the experiment (ion beam on neutron target).

The highest neutron yields are obtained in spallation reactions of high-energy beams. As spallation neutrons are very energetic, a moderator near the neutron production target is needed to shift the spectrum to the lower neutron energies of astrophysical interest. The only TOF facility at spallation neutron sources are presently operating in Europe is n_TOF at CERN. At n_TOF, intense 20 GeV pulses of 7×10^{12} protons are producing about 2×10^{15} neutrons per pulse in a massive lead target, corresponding to 300 neutrons per incident proton. The target is cooled with water, which acts also as a moderator. The resulting neutron spectrum ranges from thermal energies of 25 keV to a few GeV. Two flight paths of 20 m and 185 m and the proton pulse width of 7 ns offer a very good energy resolution.

Electron accelerators have been used for neutron production via bremsstrahlung-induced (γ,f) and (γ,n) reactions by irradiation of high-Z targets with pulsed electron beams. GELINA at Geel/Belgium is the only electron-driven, moderated facility for neutron studies in the energy regime of the s-process. The accelerator delivers a 140 MeV electron beam with a pulse width of 1 ns onto a rotating Uranium target, and the water-moderated neutron spectra from 25 keV up to 20 MeV can be accessed at 10 flight paths from 10 to 400 m.

At the ELBE accelerator at Dresden-Rossendorf a 40 MeV electron beam on an unmoderated liquid metal target is used to operate a very compact neutron source characterized by a remarkably high TOF resolution. Applications in astrophysics are hampered, however, by the hard neutron spectrum that is concentrated in the energy range from 0.2 to 10 MeV with an intensity

maximum around 1 MeV, too high for most astrophysical (n, γ) measurements.

High resolution γ-beams
The availability of high-brilliance narrow-bandwidth gamma beams, such as the beams that will be available at ELI-NP, will provide new opportunities for photonuclear reaction studies with high resolution. One flagship study is that of the important $^{12}C(\alpha,\gamma)^{16}O$ reaction. Understanding and modelling the evolution and explosion of massive stars requires a 10% uncertainty on the $^{12}C(\alpha,\gamma)^{16}O$ reaction cross section at helium burning energies around 300 keV. Due to the extremely small cross section at such low energies, the $^{12}C(\alpha,\gamma)$ reaction has been studied experimentally only down to energies around 1 MeV. The detailed measurement of the reaction cross section and angular distributions for the inverse photodisintegration reaction $^{16}O(\gamma,\alpha)^{12}C$ is one of the high priority experiments at ELI-NP. One of the advantages of measuring the photo-dissociation of ^{16}O is a gain in cross section due to detailed balance. The measurement of cross section and angular distributions with precision better than 3% at higher energies, all the way to 14 MeV excitation energy reduce the uncertainty of cross-section extrapolations.

Laser driven reactions
A major challenge in experimental nuclear astrophysics is the direct reproduction of the astrophysical conditions in the laboratory, accessing the finite temperature and screening corrections of the stellar plasma. Experimental studies of nuclear reactions in controlled plasma conditions become possible nowadays with the availability of high-power lasers. A new laser acceleration mechanism, namely radiation pressure acceleration (RPA), promising production of accelerated bunches at solid-state density, is predicted at laser intensities achievable at ELI-NP. One proposed exploitation of these high-density accelerated ions is to fission heavy nuclei and induce the fusion of the light fission fragments, producing this way unstable neutron-rich nuclei in the region of N ~ 126 r-process waiting point.

Nuclear astrophysics with indirect techniques
Indirect methods, such as the coulomb dissociation, the asymptotic normalization coefficients (ANC), and Trojan Horse (THM), have been introduced as alternative approaches for determining cross sections of astrophysical interest. They make use of

Box 4: Heavy element nucleosynthesis in core-collapse supernova

The determination of the heavy elements produced in core-collapse supernova requires accurate predictions for the spectral differences between electron neutrinos and antineutrinos. These differences are related to the nuclear symmetry energy at sub saturation densities. A combination of nuclear experiments and theory and astronomical observations have greatly contributed to constrain the density dependence of the symmetry energy. This puts strong constrains on equations of state used in core-collapse supernova simulations and furthers contributes to determine the neutron richness, Y_e, of the ejected material. This is the main parameter affecting the nucleosynthesis in the ejected material.
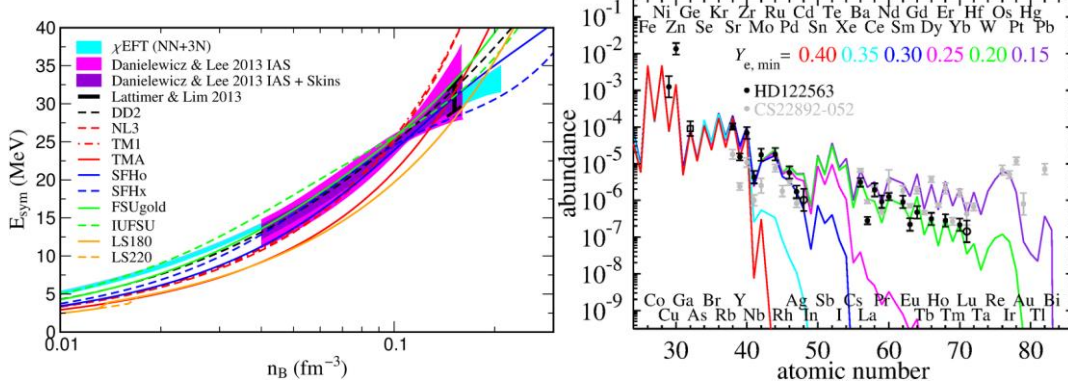
indirect reaction mechanisms, such as transfer processes (stripping and pick-up) and quasi-free reactions (knock-out reactions). The astrophysically relevant direct reaction is found with the help of nuclear reaction theory. It is essential to factorise the cross section into a contribution that can be calculated from theory and a quantity that is related to the cross section of the astrophysically relevant reaction. This exploits the fact that the reaction mechanism is dominated by peripheral processes where only the asymptotic part of the wave functions is relevant. Recently, the capabilities of THM have been exploited with radioactive beams. Moreover, indirect methods are unique tools to investigate neutron captures on very short-lived radioactive nuclei, such as $^{26}Al^*(n,p)$ and $^{26}Al^*(n,\alpha)$ $^{26}Al^*(n,\alpha)$, involving the isomeric state of ^{26}Al and not accessible via direct measurements.

Developments in nuclear theory

The present status of "general purpose EoS" at finite temperature and various densities and asymmetries is not satisfactory. There is still need for new general purpose EoSs, that employ modern energy-density functionals (or even beyond) with good nuclear matter properties, that tackle the problem of additional degrees of freedom at high densities and temperatures, and that give a detailed description of clustering at subsaturation densities. All available "general purpose" EoSs

are based on phenomenological approaches due to the computational and conceptual complexity of more microscopic methods. In the future, the increase in computational power is likely to allow the latter to provide EoSs suitable for astrophysical simulations, too.

There is also a need for new unified neutron star EoSs, especially if accurate radius measurements will become available in the future. Besides thermodynamic quantities, it would be advantageous to include pairing in a self-consistent description, e.g., relevant for neutron star glitches and cooling. In addition, also the transport properties should be calculated consistently with the EoS model. Regarding high densities, the predominant degrees of freedom should be identified, or at least constrained better, both by the forthcoming astrophysical observations and constraints from experiments, and also by robust theoretical studies. For the hyperon puzzle it is a key aspect to provide more experimental data about hyperon interactions.

If phase transitions are considered, e.g., to quark matter, it is important to treat them correctly, especially if multiple conserved charges are involved. At best, Coulomb and surface energies should be taken into account explicitly leading to finite-size structures and Pasta phases when one reaches the regime where matter is "frustrated".

In recent years we have seen tremendous progress in ab initio approaches for nuclear structure calculations and descriptions of nuclear matter, particularly neutron matter. Using different many-body techniques these approaches have been applied up to medium mass nuclei and for selected heavy nuclei. Their extension to the description of nuclear reactions relevant for astrophysics is in progress. Applications for Big Bang Nucleosynthesis and hydrogen burning reactions have already taken place and further progress for intermediate mass nuclei is expected particularly involving alpha induced reactions. It becomes fundamental to determine the highest densities that ab-initio approaches can reliably describe to put constraints on the EoS of uniform matter at all relevant isospin asymmetries.

Global microscopic calculations of nuclear masses have reached a precision comparable to more phenomenological approaches. Further extensions are necessary to improve the description of nuclear masses in regions with sudden changes in nuclear shapes by including beyond mean field effects. Those regions have been shown to play an important role in the determination of r-process abundances. An important challenge is the treatment of odd and odd-odd nuclei at a level similar to even-even nuclei.

An important extension of these approaches is the description of beta-decay rates and electromagnetic excitations. Global microscopic calculations of beta-decay rates for r-process nuclei have recently become available. They consistently account for both Gamow-Teller and first-forbidden transitions and provide an improved description of available experimental data. First-forbidden transitions are found to play an important role in the beta decay of r-process nuclei around N=126 and above in agreement with recent experimental evidence. Further improvements involve the description of deformed nuclei and a consistent treatment of odd and odd-odd nuclei.

The developments of improved astrophysical models for r-process requires an improved description of neutron capture rates. Current estimates are based on statistical model approaches. Giving the extreme neutron rich conditions reached in neutron star mergers, it becomes fundamental to assess the range of validity of statistical approaches near the neutron dripline and develop alternative reaction models.

Gamma strength functions are one fundamental ingredient for the statistical description of radiative capture rates. Neutron rich nuclei are known to develop a low lying dipole excitation mode known as pygmy dipole mode. This mode has been experimentally identified in many nuclei in photo absorption reactions. In astrophysical applications, it is fundamental to understand how this mode evolves with neutron excess and nuclear excitation energy. Reliable theoretical description of these excitations require subtle effects such as couplings with complex configurations to provide fine structure of excitation spectra that allow a direct comparison with measured data. Experimental determinations of gamma strength functions involving excited states by the so-called Oslo method show evidence for the existence of an upbend at low gamma energies. The nature of the upbend (M1 vs E1) has not yet been identified. In the nuclear astrophysics context, this result shows that gamma strength functions involving excited states could be substantially different from those obtained based on ground state data. It becomes important to address the nature of the upbend, its dependence on excitation energy and its impact on radiative capture reactions.

Fission is expected to play a fundamental role in the description of r process nucleosynthesis in mergers. However, there are many uncertain aspects regarding fission that need to be addressed for an accurate determination of r-process yields. The region of the nuclear chart where fission sets in has not yet been conclusively identified. This may even depend on the dominating fission channel (neutron induced, beta-delayed, spontaneous,…) during different phases of the r-process. In particular before freeze out of neutron capture neutron induced fission is expected to be the main fission channel. It becomes important to extend recent advances for the description of spontaneous fission rates and yields to neutron induced fission.

An important aspect in constraining the EoS properties and in general nuclear physics input for astrophysics simulations is assessing the uncertainty quantification of the models (including uncertainties in the predicted nucleosynthesis abundances). This necessitates development of reliable strategies to provide statistical error estimates. Since the models are often based on parameters that were fitted to sets of experimental data, the quality of that fit is an indicator of the statistical

uncertainty of the model's predictions. Bayesian statistical methods provide the insight into the uncertainties of model parameters and their inter-dependencies to determine if the model employed and dataset used to constrain the model are adequate. The systematic uncertainties are associated to the spread of the calculated values due to various underlying foundations and/or parameterisations of the models that are often subject to deficiencies due to missing physics. Possible strategies include analysis of residuals, inter-model dependence, estimates using comparison with the experimental data, etc.

Nuclear reactions and stars are intimately related. A better knowledge of stars thus depends on a better knowledge of the key reactions that shape energy generation and nucleosynthesis processes. Given the very high cost of experimental measurements, priority lists of reactions that have the largest impact on stellar nucleosynthesis calculations are highly desirable. The process of establishing such lists using comprehensive approaches guided by theory have recently started and will yield these priority lists in the coming decade. This will be key to maximise the return on the large investments in nuclear facilities.

Observational developments

While masses of neutron stars can be measured rather precisely, present radius determinations are subject to many assumptions and uncertainties. Significant observational effort is focused on neutron star radius measurements, e.g. by determining quantities that depend on mass and radius. One approach is based on the measurement of the moment of inertia that could be achieved in five years for the PSR J0737-3039A double pulsar system. Assuming that we know the equation of state up to saturation density a measurement of the moment of inertia will constrain the radius of a neutron star within ± 1 km.

Future high-precision X-ray astronomy, such as proposed, e.g., by the projects NICER or ATHENA+ promise rich information from binary accretion and X-ray bursts regarding the inner neutron star structure and the EoS at high densities from which the nuclear interaction in the medium can be inferred. These missions are finally allowing the study of hot intergalactic gas and the question of the cosmic baryon budget, i.e. why we can see

(through their electromagnetic interaction with photons in stars and interstellar/intergalactic gas) is only half of the baryon amount created by big bang nucleosynthesis.

Proposals such as GRIPS and recent eAstrogam have been made to establish a successor to INTEGRAL's gamma-ray spectrometer, for observing nuclear lines from interstellar gas in nearby galaxies, or from supernova and nova explosions. These compete with other (similarly-expensive) space mission proposals, and the scientific community will have to set priorities.

At long wavelengths, ground based ALMA and NOEMA instruments and their observations will continue to exploit cold gas in star forming regions, measuring composition and kinematics through molecular lines. Here, some specific isotopic discriminations are possible (e.g. $^{13}C/^{12}C$, $^{16,17,18}O$ in spectra from CO molecules), thus providing access to nuclear information in molecules, as a complement to isotopic measurements of atomic or ionised gas at higher energies.

The SKA radio telescope, which is currently under construction, is expected to detect several thousands of new pulsars. This has the potential to identify the real maximum mass, by finding neutron stars with precisely determined masses significantly above $2\,M_\odot$ and/or a cut-off in the mass distribution. If the real maximum mass is around $2.5\,M_\odot$, it would represent an extremely stringent constraint for the behaviour of matter at high densities. The astrometric project THEIA might also contribute to the search of high mass neutron stars and help the radius determinations by determining the distance to X-ray binaries.

Gravitational wave astronomy represents a new observational window into the astrophysical processes in the universe. It has the potential to give new and completely independent insights about compact stars and their underlying EoS. It is only a matter of time until the first gravitational wave signal of a neutron star merger will be detected, with the potential to constrain neutron star radii and their maximum mass.

The neutrino signal of the next galactic core-collapse supernovae will provide an incomparable insight into the supernova explosion mechanism and will lead to constraints for the EoS of neutron star matter and the possible existence of a phase transition at high densities. It will be possible to

determine the total energy emitted in neutrinos and the proto-neutron star deleptonization time. In some favourable cases one could even observe the transition to a black hole.

Developments in astrophysical modelling

In the section "Lives of Stars" the necessity of modelling the long-term evolution of stars under the assumption of spherical symmetry (1D) by considering the time scales involved was briefly touched upon. These kinds of models, although very successful in many respects on their own, contain too many assumptions, approximations, parameterisations and inverse-modelling recipes to possess the predictive power that is so desired.

The current challenges are to test the accuracy and validity of the 1D approximations to astrophysical phenomena in various relevant regimes, and thus improve or replace certain ingredients of the models or equations with something more accurate, or rather, something that produces results closer to what is observed in nature. Observational data is crucial for many validation efforts of stellar models, but is often limited to the core hydrogen- and helium-burning phases of the evolution that comprise the vast majority of the star's life. Additionally, observational data cannot always help to distinguish the cause of a process, so to speak, only an effect.

Multidimensional hydrodynamic simulations, on the other hand, start from the relevant set of equations of fluid dynamics and can provide the missing information concerning the physical processes operating in the region of interest. Specific problems that should be addressed include the mixing process in AGB stars that creates the ^{13}C pocket fundamental to the main s-process production. How this pocket is formed is the most important question of the main s process and yet is still an unsolved problem. Rotation-induced mixing (shear, meridional circulation, etc) and the transport of angular momentum inside stars are other very important physical processes that can be constrained observationally from the rotation rates of white dwarf stars. Now that there has been an emergence of the kind of simulations that are needed to begin to answer some of these questions, a new challenge has arisen: how to apply the knowledge gained from 2D and 3D hydrodynamic simulations to 1D stellar models in order to make better predictions of the long-term evolution of stars?

Lastly, the elephants in the room of stellar modelling are the magnetic fields. At present, the effects of magnetic fields are considered using simple recipes. Unfortunately, 3D magneto-hydrodynamic simulations with a sufficiently high resolution to resolve magnetic fields amplification or destruction processes with a stellar context will still be out of reach within the next ten years. These simulations remain a long term goal of stellar astrophysics in the coming decades.

Even when all this is done, the application of stellar models is much broader than the theory of stellar evolution. The results of stellar evolution and nucleosynthesis calculations are key input for galactic chemical evolution and binary population synthesis calculations. Ideally, these calculations would like to have data from a multitude of stellar models that span a large range of parameter space in several dimensions: initial mass, initial composition, initial rotation rate, initial binary mass ratio and initial binary separation, with a fine resolution in each parameter.

Modelling the explosions of stars is an essential part of astrophysics. It is required to understand the origin of nuclei heavier than H and He, the formation of compact objects, the emission of gravitational wave and neutrino signals, and to determine the cosmological parameters of our Universe. These explosions take place in the transonic regime of fluid dynamics and therefore, as opposed to stellar evolution processes, conventional codes apply. The challenge is to resolve all scales relevant to the problems and to model the source terms and the transport processes adequately. The goals are to devise a complete description of the dynamic explosion phase with direct links to the evolution of the stellar progenitor and to the remnant. A goal of particular interest is to understand the role of supernovae in cosmic nucleosynthesis.

Over the past years, multi-dimensional dynamical simulations have become the standard in supernova theory. These models, however, have not yet reached the state of reproducing all observables in a satisfying way. Earlier parametric one-dimensional approaches were more successful in this respect, but only by means of tweaking free parameters that had to be introduced due to the limited realism of the modelling approach. Future developments will focus on improving multi-dimensional approaches. The main challenges are to realistically model details of

the explosion mechanism and to define realistic initial conditions for the simulations, i.e. multi-dimensional structures of the progenitor stars.

All kinds of stellar explosions models have several main goals in common, namely: i) understanding the physical mechanism of the explosion; ii) link the explosion phase consistently to the progenitor evolution; determine the impact of progenitor parameters (mass, metallicity, etc.) on observables and nucleosynthetic yields, and clarify the contribution of different stellar explosion processes to galactic chemical evolution.

Specifically, for **thermonuclear supernova explosions**, the dominant scenario for producing normal Type Ia supernovae has to be identified. This is urgently needed because of the prominent role these events play as distance indicators in observational cosmology. The main challenge is to identify the progenitor system because it sets the initial parameters for the explosion process. The explosion physics has been modelled in detail, although several aspects such as ignition of the combustion wave, the possibility of deflagration-to-detonation transitions and the resolution of burning fronts remain challenging.

Box 5: Mergers and r process nucleosynthesis

The direct detection of gravitational waves by the LIGO collaboration has opened a new window to the Universe. A future observation of the gravitational signal from a neutron star-neutron star or neutron star-black hole system will provide valuable information about the merger dynamics, which reflects neutron star properties such as its compactness. The peak frequency in the signal is directly correlated with the radius of a cold neutron star, providing a model independent determination of this fundamental property. Mergers are discussed to be a major source of r process elements. The frequency at which mergers occur in the present Universe will be also determined by Gravitational wave detections providing constrains on the amount of material ejected in individual events. The radioactive decay of r-process material ejected in the merger could be responsible for an electromagnetic transient known as kilonova. An observation of a kilonova light curve will provide direct evidence that the r process has indeed taken place in the merger. . Other astronomical messengers (MeV gamma-ray bursts, GeV gamma-rays, positron annihilation emission) will contribute to understand such events and their aftermath. An improved description of the properties and reactions involving neutron rich exotic nuclei is fundamental to confront our predictions for the nucleosynthesis and light curves with observations.
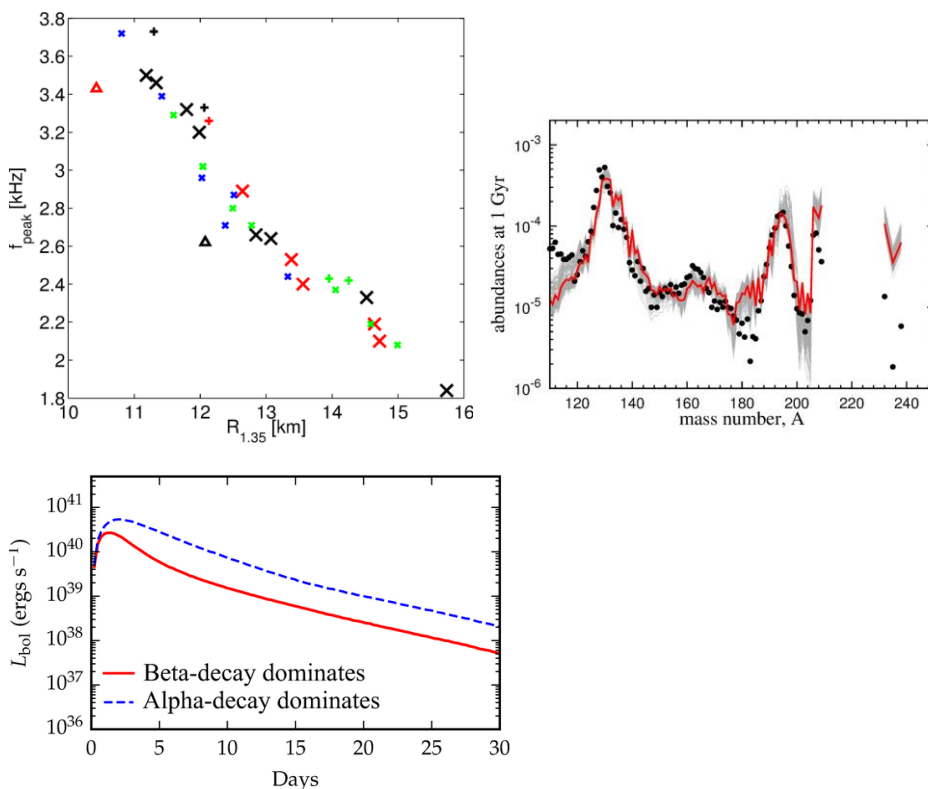
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A breakthrough on the observational side would be the astronomical identification of a Type Ia supernova progenitor system. Lacking such an observation, however, progress has to be made in an interplay of theoretical modelling of the evolution of possible progenitor systems, corresponding hydrodynamic explosion simulations, the prediction of observables from such models, and detailed comparison with astronomical data. It is of particular interest to determine systematic trends of observable properties with parameters of the progenitor. This requires to explore the parameter spaces in extended sequences of simulations. Efficient numerical tools for such studies are available and they can be carried out given sufficient access to computational resources.

In contrast to Type Ia supernovae, progenitors of **core collapse supernovae** have been observationally identified. This, however, does not imply that the progenitor problem does not introduce uncertainties. As initial conditions for the explosion simulations, the detailed structure and multidimensional shape of the star prior to the onset of core collapse has to be known to high accuracy. Thus, a main field of activity will aim at devising realistic multidimensional progenitor models that accurately capture the impact of rotation and convection. An important question is how the outcome of the collapse (neutron star or black hole) depends on the detailed properties of the progenitor star. There are indications that early ideas of a sudden transition in mass from producing neutron stars to black holes may be incorrect. We may well be dealing with islands of explodability surrounded by regions of non-exploding models. It becomes fundamental to understand the progenitor properties that determine the feasibility of an explosion and their dependence with metallicity.

We further need to be able to identify the lower limit in mass at which core-collapse supernova are expected. For the lightest massive stars (8 to 10 solar masses) we expect two different outcomes: a thermonuclear explosion of the core or an electron capture' supernova are possible in principle. The realization of either of these possibilities depends sensitively on a turbulent flame front in the core of the star that has to be treated carefully in multidimensional simulations, couple with an accurate description of nuclear burning and electron capture processes.

The main challenge in the field of core collapse supernova modelling, however, remains the unknown explosion mechanism. Further studies in extended multidimensional hydrodynamic simulations are required to settle this problem. These have to take into account the details of neutrino-matter interaction as well as multidimensional flow instabilities. Additional parameters that will be explored are magnetic fields and the equation of state of the forming neutron star. Such simulations will predict precise neutrino and gravitational wave signals. Measuring these in detail would be an observational breakthrough in the field providing new insight into the explosion physics. Another goal is to determine the role core collapse supernovae play in the synthesis of heavy elements. Modelling more exotic objects, such as gamma-ray bursts, pair instability supernovae and magnetorotational supernova will remain of great interest given the forthcoming extended observational surveys of transient astrophysical sources.

The severe scale problem astrophysical simulations have to face becomes most pronounced in the simulations of supernova explosions. The energy input in thermonuclear burning fronts and nuclear interactions take place on very small scales compared to the dimensions of the exploding stars. This, together with the demonstrated importance of multidimensional modelling, challenges numerical simulations. Sufficient access to high-performance computational resources, further efforts in the development of numerical techniques, and the continuity of expertise in code development are prerequisites for future progress. As nuclear processes are the most important source terms in the hydrodynamic description of the explosions, a fluid connection to the latest experimental and theoretical nuclear physics advances is essential.

Within the next years the understanding of the GW emission from compact object mergers will continue to grow by means of numerical simulations that will allow for the construction of improved parametric models. The long-term goal of using GWs from compact object mergers to constrain the high-density matter EoS will require intense efforts to connect the results of simulations with data analysis strategies to extract the relevant parameters from a future measurement. It will be advantageous to restrict the possible parameter range by future computer calculations using candidate EoS. These surveys will crucially rely on nuclear physics input for the equation of state models which

take into account already available constraints on properties of nuclear matter. In turn, this approach promises to provide tighter constraints on parameters describing nuclear matter at and above nuclear saturation density, which is the density range probed by compact object mergers. Moreover, numerical models of compact object mergers may explore finite-temperature effects in nuclear matter, which may then be compared to future GW detections. This, however, requires to extend the currently available set of temperature-dependent EoS models.

A combination of future GW measurements and theoretical models promises to unravel the role of compact object mergers for the enrichment of the universe by heavy r-process elements and thus to answer the question whether or not compact object mergers are the dominant source of heavy r-process elements. The key steps towards an answer are a clarification of the merger rate, of the average amount of ejecta per merger event and of the robustness and details of the r-process in the merger outflows.

A better constraint of the local merger rate will be provided by the frequency of GW detections when the advanced instruments reach their design sensitivity within the next years. The robustness of the r-process will be settled by network calculations based on improved hydrodynamcal models including advanced methods of neutrino transport physics. The exact thermodynamical conditions are relevant in order that nuclear network studies can identify the detailed path of the r-process and the most relevant nuclear reactions, clarifying for instance the role of fission processes. Challenges are the development of improved numerical tools and the availability of sufficient computational resources as well as progress in the description of reaction rates from a theoretical as well as experimental point of view.

Progress in fixing the expected amount of ejecta per merger event will emerge from improved hydrodynamical models, further theoretical and/or experimental/observational constraints on the neutron-star EoS, and possibly the detection of electromagnetic counterparts. The interpretation of the latter and the extraction of physical parameters rely on detailed numerical models of the outflows and nuclear network calculations. Additional insights into the role of mergers will arise from population synthesis models and chemical evolution models, which will in particular shed light on the early enrichment. This may clarify if compact object mergers are responsible for the early enrichment of the Galaxy by heavy elements or if alternative sites like for instance MHD jets in core-collapse supernovae should be invoked as explanation for the observed abundance of heavy elements in metal-poor stars.

Hydrodynamical simulations face challenges in modelling the exact conditions in the prompt ejecta and the secular ejecta. High-resolution hydrodynamical calculations with an appropriate treatment of neutrino transport physics are required to reveal the exact thermodynamical conditions, which are crucial to determine the nucleosynthetic yields produced in those outflows. The initial conditions of the neutron star-torus system or black hole-torus system forming after the merger depend on the preceding dynamics of the merger. From these remnants additional matter becomes unbound on secular time scales by neutrino winds or magneto-hydrodynamical effects and contributes to the total nucleosynthesis yields of compact object mergers. Thus, it will be particularly important to consistently connect hydrodynamical merger calculations with long-term evolution models of the secular ejecta that include neutrino transport and magneto-hydrodynamical effects. Neutrinos as well as magneto-hydrodynamical effects also play a role during the dynamical phases of the merger and thus affect the details of the prompt-ejecta nucleosynthesis and associated electromagnetic counterparts.

Recommendations and priorities

Due to the great diversity and strong interdisciplinary character of the field, nuclear astrophysics requires a wide span of experimental facilities ranging from major international laboratories to smaller university-based centres. Many of the European research centres maintain a strong research program in nuclear astrophysics. At the same time, much of the progress achieved in recent years is due to university groups. Both, the activities at large research centres and university

laboratories need to be continued and extended.

Theory plays a unique role in Nuclear Astrophysics. Nuclear Theory is necessary to connect the experimental observables to astrophysically relevant quantities such as reaction rates, etc. Furthermore, it becomes fundamental to describe properties of nuclei that are not accessible due to current experimental limitations. Moreover, to combine advances in experimental and theoretical nuclear physics with improved astrophysical models, access to supercomputer facilities is often required.

We strongly support the completion of the FAIR facility. Its worldwide unique multifaceted approach, exploited by its four experimental pillars APPA, CBM, NUSTAR and PANDA, opens a new era for nuclear astrophysics and promises to deepen our understanding of the Universe and the objects therein. FAIR and the instrumentation of the NUSTAR collaboration will provide unparalleled access to unstable nuclei far from stability, in particular to the heavy neutron-rich r-process nuclei around N=126. CBM will study the properties of matter at the high densities achieved in neutron stars and will constrain the supernova equation of state. With its ability to produce high rates of hypernuclei PANDA will contribute to our understanding of the nucleon-hyperon and NN-hyperon interactions. The APPA collaboration will explore the behaviour of matter, in storage ring experiments, under the extreme electromagnetic fields achieved on neutron star surfaces and, in ion-beam and laser experiments under the astrophysical conditions expected in stellar plasma and in gaseous planets.

We strongly support the completion of the next generation of radioactive ion beam facilities, including SPIRAL2, SPES-INFN. For HIE-ISOLDE, which is completing in 2018 its phase 2, we highly recommend the implementation of the phase 3, enabling capture reactions of astrophysical interest and the installation of a new storage ring at HIE-ISOLDE. The complementary capabilities of these facilities will guarantee European leadership in nuclear astrophysics and supplement the strong European efforts in astrophysics, cosmology and astroparticle research. Furthermore, we recognise the necessity for the ISOL facilities to expand their coordinated approach to beam development, as lack of specific radioactive species of sufficient intensity is a major

limitation. In the longer term, progress towards EURISOL-DF is vital.

The Laboratory for Underground Nuclear Astrophysics (LUNA) at Gran Sasso is a world-leading facility, which has performed high impact nuclear reaction studies of astrophysical importance, at the relevant stellar energies. We strongly support the upgrade of LUNA with a multi-MV accelerator allowing the access to a new range of nuclear reactions.

The improvements in observations and astrophysical models have highlighted the need for high precision cross section measurements. These, and other high impact studies, reflect the strong programme of nuclear astrophysics research carried out at small facilities. We strongly recommend to continue and to extend the dedicated nuclear astrophysics programs at universities and small research centres, and maintain access to such facilities through the transnational access programme.

The ELI-NP facility at Bucharest, which will become operational as a user facility in 2019, will provide high-power laser pulses and high-intensity narrow-bandwidth gamma beams. Studies of laser-driven nuclear reactions in controlled plasma conditions will become possible together with measurements on photodissociation reactions with unprecedented precision. This will provide new research opportunities for the nuclear astrophysics community in Europe. We strongly recommend that the instrumentation needed for the implementation of this research program be built and the suggested experiments are performed with high priority.

Both small and large scale facilities educate the next generation of researchers on the broad range of techniques necessary to run and analyse experiments. We strongly recommend the continuation and extension of the training efforts to guarantee enough skilful people at future facilities.

Nuclear Astrophysics requires an extensive contact and exchange of ideas between theoretical and experimental nuclear physicists, astrophysicists and astronomical observers. We recommend a strong initiative to develop a European centre for nuclear astrophysics that coordinates specific nuclear astrophysics needs such as up-to-date and exhaustive databases of nuclear reactions, astrophysical models and observations. This

should follow the successful example of the JINA Center for the Evolution of the Elements and extend available but geographically limited initiatives like the Nuclear Astrophysics Virtual Institute in Germany or COST Actions NewCompStar and ChETEC, complementing these networks with funding for cross-disciplinary research projects and students.

A key issue in experimental nuclear astrophysics research is the availability of high quality target material, tailored for the special envisaged experiment. Especially radioactive targets require big efforts in production of the isotope, its chemical separation and purification as well as elaborated target manufacturing and handling. The establishment of a target preparation network and a strong support of target producing research groups will be a precondition for successful future experiments.

Scientific support is necessary of astronomical observation facilities which are aimed at, or include, information on nuclear physics and processes in cosmic objects. While nuclear astrophysics is a small part in the wide range of astrophysical themes, nuclear astrophysics arguments need to be made more aggressively and in a more accessible way, so that the relevant science connections are clear also to decision bodies that have to evaluate the promises and effectiveness of billion Euro investments into major new or enhanced astronomical facilities. While cosmology and search for life on other planets are obviously convincing drivers of new investments, the more complex and deep meaning of nuclear processes in cosmic objects needs dedicated efforts to communicate its scientific merits.

Theoretical nuclear astrophysics deals with extrapolations of experimental advances to the astrophysical relevant energies or temperatures. Those are coupled with large nuclear networks and sophisticated astrophysical modelling to allow for the full exploitation of the possibilities offered the experimental facilities. Given the broad range of techniques needed and the access to powerful computers it becomes fundamental to have a comprehensive education program to train the next generation of researchers. The above recommended European Centre can play a leading role coordinating such education, supplementing activities already carried out at ECT* Trento.