White Paper on Nuclear Astrophysics

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2 Executive Summary

This white paper is the result of a nuclear astrophysics town meeting, organized by the Joint Institute for Nuclear Astrophysics, and held on October 9-10, 2012 in Detroit, Michigan. 150 scientists attended the meeting that comprised of 22 plenary talks and 13 working groups. The goal of this meeting was to develop a vision for nuclear astrophysics, in light of the recent NRC decadal surveys in nuclear physics (NP2010) and astronomy (ASTRO2010). The program, talks, working group summaries, and other notes and comments can be found at `https://extwiki.nscl.msu.edu/astrotown2012` and the Twitter feed @NucAstroTown12.

This white paper should also inform the nuclear physics community and funding agencies about the scientific directions and priorities of the field with the goal of providing input for the 2014 Long Range Plan. The answer of many questions in nuclear astrophysics can be found in the physics of nuclear structure and fundamental symmetries which will be highlighted in the context of this paper.

Nuclear astrophysics is a modern and vibrant field addressing fundamental science questions at the intersection of nuclear physics and astrophysics. Broadly these questions can be grouped into three themes: What is the origin of the elements? What is the nature of neutron stars? How do stars evolve and explode? Some of the questions are long standing such as the origin of the heavy elements made in the slow and rapid neutron capture process, the mechanism that explodes core collapse supernovae, the interior composition of neutron stars, or the specific amounts of elements made in each type of stars. Others have only been raised more recently, driven by new results or observations, such as the origin of the elements in the Sr - Te range, the nature of the first stars, the mechanism to explode super X-ray bursts, or the contribution of proton rich neutrino driven winds or intermediate neutron capture processes to the origin of the elements. In some areas, progress enables the field to move beyond qualitative questions. Examples include the Big Bang or the Sun, where the thrust has turned towards precision measurements of nuclear reaction rates that enable the use of these scenarios together with neutrino physics to answer questions related to new particles, the nature of the universe, and the properties of neutrinos.

With technological advances in experimental nuclear physics, astronomy, and computational physics, and the developments outlined in the ASTR2010 and NP2010 decadal reviews, the field is in an unprecedented position to answer many of the open questions in the next decade. With the Facility for Rare Isotope beams (FRIB) most of the rare isotope produced in stellar explosions and neutron stars finally become available for laboratory studies. Upgrades of stable beam facilities at university laboratories will enable unprecedented precision measurements of stellar reaction rates. This will be complemented by the development of high intensity low background accelerator facilities that for the first time will allow a direct cross section measurement at stellar energies. Major efforts in building new high flux neutron facilities for studying nuclear reactions critical for the slow neutron capture process are being underway in Europe. New initiatives in nuclear structure, weak interaction, and nuclear reaction theory will help to decipher the nature of all nucleosynthesis processes which so far is mostly based on phenomenological description. New efforts have emerged at fusion physics facilities such as OMEGA and NIF that for the first time allow a direct study of the impact of the stellar plasma effects that are crucial for low temperature burning in stars and the ignition of fusion driven bursts in the core of white dwarfs or the crust of neutron stars. Large scale surveys of metal poor stars and high resolution spectroscopic followup with the largest available telescopes is providing a fossil record of chemical evolution that reaches back to the very first supernova explosions after the big bang opening links to cosmology and galaxy formation. New observational initiatives such as PAN-STARR and LSST will open up time domain astronomy with the prospect of discovery of new explosive astrophysical scenarios. And with advanced LIGO there is a realistic chance to detect for the first time gravitational waves from merging neutron stars that directly link to fundamental nuclear astrophysics questions related to neutron stars and high density matter.

In the following we summarize the findings and recommendations of the nuclear astrophysics community to enable the exploitation of these opportunities towards transformational advances in nuclear astrophysics:

`Recommendations will be placed here`

3 Scientific Challenges in Nuclear Astrophysics

3.1 What is the Origin of the Elements?

3.1.1 Introduction for non experts

The origin of the elements is one of the fundamental questions in science. How did the universe evolve from a place made of hydrogen and helium with spurious traces of lithium to a world with the incredible chemical diversity of 84 elements that are the building blocks of planets and life? Our understanding of the answers to this basic question is incomplete in major aspects. What we do know is that a wide variety of nuclear reaction sequences in stars, stellar explosions, and, possibly, collisions of neutron stars, build up the elements step by step. Some of these reactions involve the fusion of stable nuclei over millions of years, others use extremely unstable nuclei as stepping stones to build up new elements within seconds. For some of these reaction sequences experiments have provided data on reaction rates that allow to predict what elements they may have created. For most however, nuclear physics knowledge is still very limited. Some processes have only very recently been discovered, and some may still await discovery. And for some of the well known processes, the astrophysical sites have not been identified with certainty. The answers to all these questions will not only inform us about the origin of the basic building blocks of nature, but will also address questions about the formation of galaxies, about the formation of stars and planets, about the interiors of stars and stellar explosions, and about the properties of neutrinos.

3.1.2 Current open questions

- What was the nature of the first stars, what are their nucleosynthetic signatures, and can we find these signatures today?
- What are the rates of the key nuclear reactions in stars that define the sequence of stellar evolution and characterize the patterns of stellar life?
- How can the observations of solar and supernova neutrinos be exploited toward a deeper understanding of stellar burning mechanisms?
- What defines the relative abundances of carbon and oxygen in our universe that determine the fate of stellar evolution, define the seed for stellar explosions, and provide the base for the origin of life on Earth.
- What is the origin about half of the 54 elements beyond iron traditionally attributed to a rapid neutron capture process (r-process)?
- Why is the r-process so robust, producing similar abundance patterns event by event?
- What is the contribution of neutrino driven winds in core collapse supernovae to nucleosynthesis? And what role do neutrino properties play?

- What is the origin of the unexpectedly highly abundant light isotopes of molybdenum and ruthenium traditionally attributed to a p-process?
- How can we use element abundance observations in stars and presolar grains to validate complex stellar models?
- What is the quantitative contribution of different types of stellar sites to the origin of the elements (initial mass function), how does this evolve with time or galaxy type, and what is the effect of most stars being binaries?
- What are the limits of chemical variability for stars hosting exoplanets?

3.1.3 Context

Nuclear astrophysics has come a long way in explaining the origin of the elements ever since Fred Hoyle in 1946 first summarized the gradual creation of elements beyond lithium in stellar environments. In the classical picture nuclear fusion reactions in stars, as well as capture reactions of protons, neutrons, and α-particles released in these fusion reactions, synthesize elements up to the ”iron peak”. The pattern of abundances of heavier isotopes point to four processes, a weak slow neutron capture process (s-process) known to occur in massive red-giant stars, a main s-process known to occur in lower mass, thermally pulsing red giant stars (TP-AGB stars), a rapid neutron capture process (r-process) and a photodissociation driven process (p-process) producing the rare neutron deficient isotopes of some elements. The sites of the r- and p-process are not known with certainty. However, a p-process occurs naturally in models of core collapse supernovae, and in some models of thermonuclear supernovae (type Ia). On the other hand, it has been a challenge to come up with possible models for the r-process - possibilities include various sites in core collapse supernovae and merging neutron stars, but all these sites have problems explaining the entirety of observational data.

On the nuclear side, decades of laboratory efforts have succeeded in measuring directly many of the relevant neutron capture cross sections for the s-process. Stellar s-process models can therefore be compared with confidence to the observed abundances of s-process isotopes in the solar system, in stars, and in meteoritic grains thought to originate from the condensed ejecta of ancient red giant stars elsewhere in the Galaxy. Critical issues still remain with neutron capture reactions on long-lived radioactive nuclei that determine the branching points of the s-process. These are of particular interest since a detailed analysis of isotopic abundances of nuclei associated with branching points in meteoritic inclusions can be used as thermometer pygnometer for determining the internal conditions of the actual s-process sites. Also of interests are neutron capture associated with the presumed s-process endpoint in the Pb and Bi range as a tool for distinguishing between r-process and s-process based production of Pb isotopes.

Despite huge developments in accelerator and detector technology, however, experimental determination of the rates in stellar fusion, the p-process, and the r-process still remain largely elusive - in the case of stellar fusion because of the small cross sections that determine the stellar evolution timescales, in the case of the r- and p-processes in fast explosive environments because the nuclei involved are unstable and difficult to produce in laboratories.

In addition to these challenges, with advances in observations and stellar modeling a more complex picture of the origin of the elements is emerging. Observations of the composition of old, chemically primitive stars in the halo of the Galaxy (so called metal poor stars) provide snapshots of the compositional evolution of the Galaxy forming a ”fossil record” of chemical evolution. These observations indicate that elements above Ge, maybe up to Te, previously attributed to the r-process are instead produced by multiple processes of unknown nature with distinct compositional signatures. The observations also indicate that stellar nucleosynthesis yields have changed over time, as the initial metal content of a star can dramatically alter its evolution and nucleosynthetic output. At the same time advanced stellar models have led to predictions of hithero unknown nucleosynthesis processes, including extended reaction sequences in first stars, proton rich neutrino driven winds in core collapse supernovae - the so called νp-process, and an intermediate neutron capture process (i-process) in low metallicity stars. The jury is still out as to which extent these processes occur, and whether they may explain some of the unanticipated observational signatures. Nuclear data are urgently needed to predict their characteristic abundance patterns.

3.1.4 Origin of the Elements Thrust Area 1: The Nuclear Physics of Element Synthesis and Model Validation

For the understanding of the origin of the elements the knowledge of the underlying nuclear reactions is of fundamental importance. Only with reliable nuclear physics can one predict the abundance signatures of various nucleosynthesis processes and unravel their contributions to the elements found in nature. And only with reliable nuclear physics can nucleosynthesis models be validated against observations. Once a nucleosynthesis process is identified, detailed observations of produced abundances in connection with reliable nuclear physics open the door to validate stellar models and constrain conditions inside stars and stellar explosions that are otherwise not accessible. For example, thanks to decades of careful experimental work the s-process is now used as a sensitive probe of mixing processes in stellar interiors. The goal for the coming decade is that other nucleosynthesis processes can be used in a similar fashion.

However, experimental information on the element producing nuclear reactions in nature is surprisingly sparse. Reactions among stable nuclei occur in stars at relatively low densities and temperatures on timescales of millions or billions of years. Measuring these very slow reactions is a huge experimental challenge, and has only been achieved in rare cases of fusion or capture reactions in the pp-chains between low Z nuclei. Expanding the scope of experiments to hydrogen and helium induced reactions on higher Z-nuclei requires the development of new facilities with high intensity beams and increased background reduction capabilities above and underground (see section 4.1). On the other hand, when conditions produce faster reactions, such as in stellar explosions, the nuclei involved are unstable, because reactions on unstable nuclei can occur before the nuclei decay. Measurements are then equally challenging, as it is extremely difficult to produce sufficiently intense beams of unstable nuclei to study these reactions. Again, measurements have only succeeded in a very small number of cases. In the coming decade we will be able to address these challenges with the advent of a new generation of radioactive beam facilities (see section 4.2).

The critical reactions for stellar nucleosynthesis include the reactions influencing stellar evolution (see section 3.2), including the $3\alpha \rightarrow ^{12}$C and ^{12}C($\alpha$,$\gamma$)^{16}O reactions that alter nucleosynthesis throughout the evolution of a star since they determine the carbon/oxygen ratio, a seed for multiple subsequent burning events in the later phases of stellar evolution. In addition, there are a number of reactions that are not critical for energy production, but nevertheless have a strong impact on nucleosynthesis. These include neutron producing reactions, including ^{13}C(α,n) and ^{22}Ne(α,n). These reactions determine strength and extent of the weak s-process, and, because they serve as seeds for the p-process, the nucleosynthetic outcome of the p-process. Of similar importance are the neutron capture rates on abundant nuclides that absorb neutrons, so called neutron poisons. During advanced burning stages and during explosive nuclear burning triggered by the shock wave passing through the star when it explodes as a supernova, proton, neutron, and ^{4}He induced reactions on heavier stable and unstable nuclei become important.

Masses, β-decay properties, and neutron capture rates on hundreds of unstable nuclei are critical for modeling various r-processes and the i-process. In the case of the r-process the nuclei are very far from stability and many have not yet been produced in laboratories so far. Nevertheless, progress has been made. A wide range of mass measurements for increasingly unstable nuclei have been successfully carried out using time-of-flight and Penning trap techniques. β-decay measurements now reach beyond the N=50 shell in Ga-Ge region covering the beginning of the r-process, and similar measurements at RIKEN are now verging on the r-process waiting points in the Rb-Zr region. FRIB will be essential in expanding the reach of r-process experiments to cover a significant portion of the r-process path (see section 4.2). Neutrino interactions play an important role in the r-process and can also produce some rare isotopes in the so called ν-process.

For the i-process, a neutron capture process with time scales intermediate to the s- and r-process, the critical nuclei are close to stability. However, accurate neutron capture rates are needed, which are very difficult to determine experimentally for unstable nuclei. Techniques to carry out such measurements, such as the surrogate approach using (d,p) and other transfer reactions, are critical. Pioneering measurements have been carried out, for example in the ^{132}Sn region. Promising progress has also been made in utilizing inverse photodissociation or Coulmob breakup processes as in the case of ^{60}Fe, but all these techniques need to be developed further through experimental and theoretical work. β-decay, proton capture, (p,α), and (n,p) reactions on unstable neutron deficient nuclei need to be understood for models of the νp-process as well as nucleosynthesis in nova explosions.

p-process models require reliable (γ,n), (γ,p), and (γ,α) reactions on 100s of stable and unstable neutron deficient nuclei. The need for experimental data is underlined by findings of large discrepancies between statistical model predictions and measurements of reactions that involve α-particles. Measurements can be performed γ-beams (see section 4.1) or, taking advantage of quasi-virtual photons, Coulomb breakup. However, in many cases, a measurement of the inverse particle induced capture reaction is preferable and is currently a standard tool for p-process studies.

Nuclear theory is critical to complement experimental information (see section 4.6). Even with new facilities expected to fill in much of the missing information in the coming decade, theory is needed to reliably predict properties of nuclei out of experimental reach, and to determine corrections to the measured nuclear data due to the extreme stellar environments. Nuclear theory is also essential when using indirect experimental approaches to determine neutron induced reactions on unstable nuclei, which are a particular challenge as both, target and projectile, are unstable. Of particular importance is reaction theory, to extrapolate experimental reaction data into yet unexplored regions of stable beam reactions or to translate nuclear structure data into cross section predictions for far off-stability processes. Renewed effort is required also for the application of statistical model reaction theory which is critical for the analysis and conversion of Coulomb dissociation and transfer reaction data into reaction rates.

Finally it will be important to carefully assess and characterize the uncertainties of experimental and theoretical data. Recently, the community has begun to develop techniques to describe and use uncertainties of astrophysical reaction rates in nuclear astrophysics models (see section 4.10).

3.1.5 Origin of the Elements Thrust Area 2: Advancing models of individual nucleosynthesis processes

The understanding of individual nucleosynthesis processes in a variety of scenarios will directly benefit from advances in models of the various nuclear driven astrophysical environment such as stars (see section 3.2), core collapse supernovae (see section 3.3), and thermonuclear explosions (see section 3.5). However, progress in the quest for the origin of the elements requires additional model work that is discussed in this section. There are many reasons for this. For many nucleosynthesis processes, the conditions needed to create new elements in accordance with observations, are not always produced naturally in stellar models. In other instances, state of the art models are not including the regions, or phases, where nucleosynthesis occurs. In addition, computational limitations often prevent the use of state of the art stellar models for anything but very crude nucleosynthesis estimates. Finally, there are a number of processes where a stellar site has not been identified and site independent parameter studies are needed to complement attempts to adapt specific stellar models. Nucleosynthesis research therefore needs specific model approaches tailored to reliably predict element synthesis based on complete sets of nuclear data (see section 4.7).

Massive Stars Our current understanding of the nucleosynthesis contribution of massive stars and core collapse supernovae is based on 1D explosions induced by a parameterized piston or parameterized thermal energy deposition. Work in the past decade has highlighted the shortcomings of this approach. 3D simulations for the last phases of stellar evolutions have demonstrated the likely existence of deep convective dredge up and mixing processes that disperse the ”onion shell” structure of a late star modifying the conditions for supernova shock front driven nucleosynthesis. 3D simulations of stellar explosions indicate the development of high velocity nickel ”bullets” and other observed features that one dimensional simulations fail to match. Simulations of neutrino-powered explosions, using spectral neutrino transport, result in nucleosynthesis products qualitatively different in composition from either the parameterized bomb/piston nucleosynthesis models or older models using gray neutrino transport. These models have shown the importance of neutrino captures in the supernova ejecta that significantly alter nucleosynthesis predictions and result in better agreement with observations.

Given the importance of these findings, it is essential that we follow 3D, first-principles core collapse supernova models that employ spectral neutrino transport and other essential supernova physics through not just the explosion phase, but until the supernova shock breaks out from the surface of the star, and further until the supernova remnant forms (see section 4.8). Only from such extended models can we fully understand the impact of the core collapse supernova engine on the isotopic composition and velocity distribution of the ejecta. As a second step we must use these first-principles models, which will be limited in number because of their computational cost, to calibrate simpler, parameterized models as a replacement for the bomb/piston models. These new parameterized models must be computationally frugal, to enable explorations in a wide parameter space of stellar masses, metallicity and progenitor physics, yet capture the essential impact that the neutrino-heated, convectively active central engine has on the nucleosynthesis.

Neutrino driven winds: Reliable models of neutrino transport in core collapse supernovae are critical to the understanding of neutrino driven winds. These winds occur in the wake of the outgoing shock wave driving the supernova explosion. The large neutrino flux emerging from the forming proto-neutron star drives ejection of very hot material. Recent research shows that even small changes in the neutrino physics can alter nucleosynthesis drastically and make the difference between proton and neutron rich winds, the former being candidates for explaining some p-process abundances, the latter for a weak r-process. Either way, neutrino driven winds are the prime candidates for producing heavy elements in the germanium-tellurium element range.

s-process Nuclear physics data for n-capture rates (see section 4.4) as well as β-decay rates, both at stellar temperatures are also needed for the important s-process branchings that provide detailed probes of many advanced nuclear production sites in the late stages of stellar evolution. New radioactive beam facilities (see section 4.2), paired with appropriate theory effort need to address this nuclear data need. Predictions of such branchings can be combined with isotopic data from pre-solar grains (see section 4.9.10) to provide powerful validation scenarios.

p-process The p-process is responsible for the origin of 35 neutron deficient isotopes of elements in the selenium to mercury range. These isotopes are very rare in nature. The favored process is a γ-induced process that occurs when the outgoing shockwave in a core collapse supernova passes through oxygen and neon burning layers of the exploding star. The sudden heating triggers removal of neutrons, protons, and α-particles of the heavy nuclei existing in these layers, producing neutron deficient isotopes. The scenario is unavoidable to occur in a supernovae, but it does not produce enough nuclei in the $A = 92 - 98$ and $150 < A < 165$ mass range. While the origin of the latter may be explained through (underestimated) contributions from other processes such as the s-process, neutrino processes, or even the rp-process, the former represents a major challenge for nuclear astrophysics. Either the initial composition of the O-Ne layers is very different from what has been assumed, the γ-process occurs in a different environment such as thermonuclear supernovae, or an entirely different process such as the νp-process or the rp-process are responsible for the origin of neutron deficient $A = 92 - 98$ isotopes. Reliable nuclear physics for the p-process and the seed producing s-process are needed to solve this puzzle.

r-process: The r-process is thought to be responsible for the origin of about half of the heavy elements beyond germanium, and is the sole production site for uranium and thorium. The major challenge for the field has been to understand the nuclear physics of the extremely neutron rich exotic nuclei involved in the process, and to come up with a credible theoretical scenario where the necessary extreme conditions (free neutron densities of the order of grams per cm^3 and more) occur frequently enough to explain the rather gradual heavy-element enrichment of the Galaxy observed in the abundance signatures of very metal poor stars.

There are indications from stellar abundance observations that the lighter heavy elements from strontium to maybe tellurium are produced in several different sites. There is now an opportunity to understand the origin of these elements: 1) Observations of ultra metal-poor stars are improving and their numbers are increasing. 2) The conditions necessary to produce these elements are less extreme than for producing heavy r-process nuclei. Nucleosynthesis studies based on current simulations and models show that these lighter heavy elements can be synthesized in neutrino-driven winds and in fast rotating stars. 3) In both cases the nuclear reactions and nuclei involved are not very far from stability, and most of them can be constrained in the coming years by experiments and theoretical models. It is thus crucial to identify the key nuclei and reactions that need to be measured. A recent effort has been successful in identifying the most critical nuclei with respect to mass measurements, decay studies, and neutron capture measurements. 4) Chemical evolution models together with stellar abundance observations will show the relative contribution of the astrophysical sites (see section 3.8).

The origin of heavy r-process elements remains a challenging problem. The neutrino-driven wind was thought to be the appropriate site, however current simulations show that it is not possible to reach the extreme conditions that the r-process requires. In addition, observations of Europium scatter at low metallicities indicates that heavy r-process elements cannot be produced in every core-collapse supernova. The origin of these elements must therefore be linked to a rare event. Possibilities include neutron star mergers, jet-like supernova explosions, He rich layers in stars irradiated by neutrinos from a collapsing core, and accretion disks around neutron stars or black holes. The next 10 years are critical to develop better models of these astrophysical environments and (with help of chemical evolution) to constrain the contribution of different r-process sites. This is especially true in the cases of neutron star mergers and collapsars, where the physical fidelity of current models trails that of the iron core and oxygen-neon core collapse models, in part because of the geometric disadvantage of these events being far removed from spherical symmetry (see section 4.8).

3.1.6 Origin of the Elements Thrust Area 3: Nucleosynthesis Yield Grids

Over the last decades many important aspects of stellar evolution and associated nucleosynthesis have been investigated and clarified. A goal for the next decade will be to enhance the fidelity, accuracy and completeness of large, internally consistent nucleosynthesis yield sets. These yield sets describe the isotopic composition a star contributes to the interstellar medium during its evolution and through its final stellar wind or supernova phase as functions of stellar mass, initial stellar composition and other parameters. They are an essential input in models of galactic chemical evolution (see section 3.8) and enable to use these models to constrain nucleosynthesis sites and galaxy formation and merger processes (”near-field cosmology”). Initial versions of such data sets have become available in recent years. However, completeness in both covered elements and mass- and metallicity-range, as well as the input physics needs to be further improved. The computational tools for such large-scale yield calculations are available (see section 4.8), and can be used to systematically explore uncertainties in all contributing areas of input physics, including in particular the two most important areas - nuclear physics rates and hydrodynamic mixing processes. This capability will ensure that future progress in both areas can be readily confronted with the increasing body of stellar abundance observations.

The new yield sets need to incorporate progress in the quantitative understanding of stellar mass loss made possible through observations and simulations. However, other basic input physics aspects, such as stellar opacities, need to be updated as well. In the latter case, the way abundance mixtures in stars are approximated is outdated and expertise at the national labs could make critical contributions through accurate and flexible microphysics modules that are commensurate with today’s computational resources (see section 4.8).

3.1.7 Origin of the Elements Thrust Area 4: Observations of Element Production Signatures

Observations of ancient, metal-poor stars found in the Milky Way provide the only available diagnostics for studying the nucleosynthesis in the early Galaxy, including the very first stars that lit up the Universe after the Big Bang. Metal-poor stars preserve the chemical fingerprint of the integrated nucleosynthesis events that occurred before these stars formed. Major breakthroughs from these observations have been the discovery of r-process stars that provide information individual r-process events, the identification of new heavy element producing processes such as the Light Element Primary Process, and the potential discovery of the signatures of the very first supernovae after the Big Bang. However, observational data at the lowest metallicities are still sparse.

Searches for these stars have been ongoing for decades, including through large scale surveys that involve millions of stars such as Hamburg-ESO, SDSS-SEGUE, and LAMOST. Ongoing large scale surveys such as APOGEE, SkyMapper, GALAH, FunnelWeb, Dark Energy Survey, and Gaia will provide abundance and metal contents constraints on many more stars (see section 4.9.4 and 4.9.5). It will be important to significantly increase he volume of detailed stellar abundance data at the lowest metallicities through spectroscopic followup studies of promising candidate stars with the world's largest telescopes, such as Magellan, the VLT, Subaru, Gemini, Keck, and HST. A larger sample is critical to discover the full range of nucleosynthesis processes operating in the early Galaxy, and to determine event-to-event variations that provide clues on the nature of the events. These data will also provide large statistically significant samples of stellar abundances for a smaller number of key elements that provide information on the compositional evolution of the early Galaxy and are essential for comparison with modern chemical evolution models (see section 3.8)

While the detailed spectroscopic observations of the chemical evolution of the elemental composition of our Galaxy constitutes a major breakthrough for the field, ambiguities remain because of the lack of isotopic information. For example, the observed signatures of a new process producing strontium, yttrium, and zirconium can be explained by a novel proton capture process, or a weak r-process - while isotopic composition would be very different, both types of processes can produce similar elemental abundance patterns.

Observations of isotopic abundance would therefore be extremely important. Spectroscopically, isotopes can in principle be distinguished through the isotope shift of spectral lines. However, the shifts are very small, and so far only very crude determinations have been made for a few heavy elements such as europium or barium. The observation of characteristic γ-rays from long-lived radioactive nuclides can in principle provide such isotopic abundance information (see section 4.9.7). However, there are only a few isotopes that have suitable half-lives and decay properties. Furthermore, the field is currently lacking an observatory with enough sensitivity. COMPTEL and INTEGRAL have detected ^{60}Fe and ^{26}Al, which had been breakthroughs for the field, but both isotopes are too long-lived to be uniquely attributed to specific nucleosynthesis events. COMPTEL made a marginal detection of ^{44}Ti decay radiation in one supernova remnant, which has provided extremely valuable constraints on supernova models, and FERMI and NUSTAR are expected to provide additional ^{44}Ti data on a wider range of remnants taking advantage of the particularly low γ-energies emitted by the decay of this isotope.

On the other hand, pre-solar grains can provide precise isotopic information about the environment where they formed (see section 4.9.10). These grains are thought to have formed in extra-solar stellar environments, have travelled through space, and have been incorporated into the pre-solar nebula making it possible to find them today in primitive meteorites. Information is limited to stellar environments that do form such grains, and identifying the origin of the grains is difficult and requires initial knowledge of nucleosynthetic signatures. The approach has been very successful in construing s-process nucleosynthesis in AGB stars, where observations support grain formation in stellar winds, and abundance signatures clearly indicate the origin of the grains. Grains from supernovae and novae have also been found, though their identification is less certain.

3.1.8 Impact on other areas in nuclear astrophysics

Nucleosynthesis in connection with abundance observations creates a pathway to validate models of stars and stellar explosions. Often nucleosynthesis processes probe conditions deep in a stellar environment where no other probes are available and therefore provide unique astrophysical insights. To use nucleosynthesis as a stellar probe requires a good understanding of the nuclear physics. Examples are CNO neutrinos, that would provide an independent tool to determine the solar metallicity or the s-process branching point abundances that are used to characterize temperature and density conditions, as well as mixing processes in AGB stars. In connection with chemical evolution, nucleosynthesis offers opportunity to probe birth and evolution of our Galaxy. With observations of the composition of the universe at very early times, for example in very old stars, or the interstellar medium at high redshifts, the Big Bang and the cosmological environment of the first stars can be probed. Nucleosynthesis also affects the formation and evolution of planets. For example, type and properties of planets depend on the chemical composition of the host star and evolve with the chemical evolution of the universe. The incorporation of long lived radioactive nuclei strongly affects evolution of planets and may make the difference between water and desert worlds.

3.2 How do stars work?

3.2.1 Introduction for non experts

Stars are the most obvious manifestation of nuclear processes in the universe, deriving their power exclusively from an enormous natural nuclear fusion reactor in their cores. During the course of their evolution they produce the majority of elements found in nature. Despite of the first stellar models being created in the 19th century and the hydrogen burning nuclear reaction sequences being delineated by the mid 20th century, stars are still poorly understood. This begins with the best studied star, our Sun, where the amount of metals in its core is still an open question. One difficulty in understanding stars are the unknown rates of the very slow nuclear reactions in their interior. The slowness of the reactions enables stars to exist for extended periods of time, but also makes experimental measurements extraordinarily difficult. Other poorly understood aspects of stars are convection, rotation, magnetic fields, and mass loss through winds. It is now becoming clear that these effects cannot be adequately modeled in one dimension. As multi-dimensional models are developed, validation of the more complex models using nucleosynthesis and abundance observations becomes critical. This requires a much improved understanding of the underlying nuclear reaction rates that are determined by the low energy nuclear cross section and the plasma conditions in the stellar interior.

3.2.2 Current open questions

- What are the rates of the capture reactions (e.g. ^{3}He(α, γ)^{7}Be, ^{12}C(α,γ)^{16}O, ^{14}N(p,γ)^{15}O, ^{17}O+p)), heavy-ion reactions (e.g., ^{12}C+^{12}C, ^{12}C+^{16}O, ^{16}O+^{16}O), and neutron sources and neutron poison reactions (e.g., ^{13}C(α,n)^{16}O, ^{22}Ne+α, ^{17}O+α) in stars, and what are pathways to determine these rates at stellar energies?

- Is there a truly unique nucleosynthetic signature of the first stars, and can we infer their properties from low-metallicity stellar abundances?

- How do low metallicity stars, including the first stars, evolve and how do convective processes impact their evolution and nucleosynthesis?

- What is the composition and low energy neutrino flux of the sun?

- What is the nucleosynthetic yield of stars as a function of mass, metallicity, and rate of rotation?

- How do 7-10 solar mass stars evolve and what delineates the boundary between the most massive white dwarf remnants and the lowest mass, most frequent supernova explosions?
- How does the binary nature of most stellar systems affect stellar evolution and nucloeynthesis?
- What is the origin of carbon enhanced metal poor stars that do not show any signatures of the s-process?
- How do massive stars loose mass, and how much do they loose?

3.2.3 Context

One of the biggest accomplishments of nuclear astrophysics is the precision prediction of the solar neutrino flux owing to detailed laboratory measurements of the relevant nuclear reaction rates. This enabled in connection with an accurate solar model the discovery of neutrino oscillations. Since this discovery, the quest to improve the precision of the solar neutrino flux measurements and to detect neutrinos from other nuclear processes in the Sun continues. In addition to the improved 3% precision of the ^{8}B neutrino flux measurement by SNO, BOREXINO has now measured the ^{7}Be neutrino flux with 4.6% precision, and has detected first hints of pep neutrinos. The best 90% confidence upper limit on hep neutrinos from SNO is close to the predicted flux. The accuracy of the corresponding standard solar model flux predictions has steadily improved due to continued progress in measurements of the nuclear reaction rates.

In that context improved reaction models have been developed which allow a much better interpretation of the reaction mechanisms that contribute to the stellar reaction rate. This significantly reduces the uncertainties in the theoretical extrapolation of the reaction cross sections towards the stellar energy range.

New initiatives have emerged to study the impact of stellar plasma conditions on the reaction rate, an aspect that was neglected for decades but will affect in particular fusion rates in high density environments. First experiments at the Nation's high density plasma facilities such as OMEGA and NIF have successfully been performed to directly measure the plasma impact on the fusion rate of light elements.

Over the past decade several groups have significantly expanded capabilities in stellar evolution and nucleosynthesis modeling. One-dimensional stellar evolution simulations are now routine for all phases of the evolution of stars that are suitable for spherically symmetric simulations. Simulations have enabled many detailed investigations of how nuclear physics uncertainties are propagating through multi-physics simulation codes and impact astronomical observables. These investigations have demonstrated the importance of many nuclear reactions, including the ^{14}N +p, triple-α and ^{12}C+α reactions, as well as ^{12}C+^{12}C fusion and show in detail the significant, and sometimes dominant, contribution of nuclear physics uncertainties to the overall uncertainty budget. At the same time progress in accelerators and experimental techniques have enabled many new measurements of these and other reaction rates that have in some cases significantly reduced uncertainties. The resulting nucleosynthesis signatures have been successfully compared with the compositions found in certain metal poor stars providing validation for the stellar models. For example, through this work it was possible to verify that the C-enhanced metal-poor stars with enhancements of slow-neutron capture elements are polluted by a former giant star companion that is now a white dwarf.

A lot of effort has been devoted in the past decade towards calculating models for low-metallicity stars, all the way down to zero metal contents (i.e. those stars that formed out of pure Big Bang material). As a result first predictions of the synthesis of elements in the first generations of stars have been developed to the point where the confrontation with observed abundances of metal-poor halo or extra-galactic stars starts to provide intriguing constraints on cosmological structure formation models.

The quantitative interpretation of isotopic ratios from measurements of pre-solar grains has also made tremendous progress. This observational access to the nucleosynthesis and mixing processes in interiors of stars and stellar explosions is complementary to astronomical observations and provides extremely powerful constraints for fluid mixing and nuclear physics in the interior of stars that directly determine element synthesis. The role of rotation and magnetic fields is now understood much better, although a significant uncertainty in this area remains.

Several groups are now investigating convection and convective mixing in stellar interiors through three-dimensional hydrodynamics simulations. This new development has only started in earnest in the past decade, and takes full advantage of the substantially increasing computational resources. The simulation-based findings are converging in that the conventional treatment of convection via the mixing-length theory (MLT) in stellar evolution models needs urgently to be updated. In particular, the important behavior of fluid motion at convective boundaries is poorly described by MLT. This poses significant limitations to further progress toward predictive simulations of the origin of the elements.

In the coming decade, there is an opportunity for a significant advance in stellar models. Multi-dimensional computational hydrodynamics efforts have now reached a level that they can inform one dimensional stellar models, offering the opportunity to develop hybrid models that use results from 3D models to enhance the fidelity of 1D models and adequately model critical aspects of stars such as mixing, convection, and better understand the impact of rotation and magnetic field. This is especially important for models of low metallicity stars, that to date have been largely inadequate. At the same time, new experimental capabilities offer the opportunity for significant improvements of the underlying nuclear physics.

As a byproduct of several transient-method based exo-planet search missions a significant amount of data for asteroseismology has been collected over the past decade, notably through the CoRoT and KEPLER missions (see section 4.9.11). This data provides another independent avenue to constrain stellar physics for nuclear astrophysics simulations. In this way our understanding of the internal rotation profiles of giant stars and the role of turbulent mixing and diffusion in stars has been significantly improved.

3.2.4 Stars Thrust Area 1: Constraining the rates of nuclear reactions in stars

The structure and evolution of stars depends very sensitively on the rates of key nuclear reactions. The reaction rates define the timescale for the stellar evolution, dictate the energy production rate, and determine the abundance distribution of seed and fuel for the next burning stage. Recent work has reinforced these well known facts by demonstrating that in some cases even small changes of reaction rates at the 10% level can dramatically change the location and duration of various convection zones inside stars, affecting the internal structure of the burning zones. Some of the poorly known nuclear reactions that are of particular importance for stellar evolution are capture and fusion reactions (e.g., ^{3}He(α, γ)^{7}Be, ^{14}N(p,γ)^{15}O, ^{17}O+p), ^{12}C(α,γ)^{16}O, heavy-ion reactions (e.g., ^{12}C+^{12}C, ^{12}C+^{16}O, ^{16}O+^{16}O) that characterize the subsequent evolutionary stages of massive stars. A number of these reactions involving stable targets (e.g., ^{14}N(p,γ)^{15}O, ^{12}C(α,γ)^{16}O, ^{13}C(α,n), and ^{22}Ne+α, have a tremendous impact on stellar explosions, since these reactions determine the seed abundance distribution for core collapse, thermonuclear runaway, and the p-process. Other reactions such as the ^{12}C+^{12}C) fusion process dictate the ignition conditions for thermonuclear explosions in dense environments such as white dwarf core or neutron star crust. Dedicated and more sensitive measurements using new techniques (see section 4.1) are needed to experimentally determine these and many other stellar reaction rates.

3.2.5 Stars Thrust Area 2: Fundamental Advances in Stellar Models

Major progress in modeling convection induced mixing in all its forms during various stages of stellar evolution can be expected to derive from high-fidelity multi-dimensional simulations that are now becoming available (see section 4.8). Such simulations are tackling the simmering phase in supernova type Ia explosions as well as shell convection zones of C- and O-burning in pre-supernova massive stars and of He-shell flashes in late stages of low- and intermediate mass stars. The emerging simulation capabilities provide a huge potential to significantly improve the accuracy of stellar models, and provide an indispensable complement to the upcoming new nuclear physics data for nucleosynthesis off the valley of stability. Simulations may be performed on new systems, like Blue Waters, on grids of 20000 or even 30000 which has been shown to be sufficient to converge key properties of interior convection properties such as mixing at and across convective boundaries. However, fully demonstrating numerical convergence for all applications, and balancing microphysics detail with the need to manage computational cost in resolved hydrodynamic simulations will remain an issue in this decade. But with appropriate effort the basic properties of the stellar interior convection and nuclear burning problem in the late stages of stellar evolution can now be resolved.

Such progress would enable generating more realistic 3D initial models for core-collapse supernova simulations. Another important area for progress would be a thorough investigation of the H-He convective-reactive phases of evolution that are especially prominent in stellar modeling attempts for the lowest metallicity and zero-metallicity stellar generations. In such events protons and primary ^{12}C from a He-burning layer are reacting and releasing energy on the convective time scale of the order of 5 – 60 minutes. Spherically symmetric convection theories (such as the MLT, see above) have been shown to be unreliable under these conditions.

Even in standard convection scenarios, assumptions of the presently adopted spherically symmetric convection theory have to be revisited through simulations of stellar hydrodynamics. The goal is that stellar evolution simulations with such enhanced mixing models will provide more reliable yield predictions for nuclear astrophysics. In the context of mixing processes in stars, rotation also plays an important role. Multidimensional models of fast rotating stars from different groups are needed to address this.

While the evolution of low- and intermediate mass stars will remain a focus area of stellar evolution, research in the mass range between 7 and 10 solar masses needs to receive the most attention now. Some recent investigations have addressed the shell burning properties of super-AGB stars and shown that most uncertainties are again due to a lack of understanding of convection and mass loss. The transition from the initial mass range that form ONe white dwarfs to the initial masses that provide the progenitors of the lowest-mass supernova remains a poorly charted territory. Basic properties of the evolution of convective shells inside electron-degenerate cores, the interaction of turbulence, unusual nuclear reaction chains under extreme conditions and neutrino losses form a delicate balance that does not allow much room for error. This regime is particularly important as the initial-mass function favors lower-mass supernova progenitors in numbers. It has been suspected to be the nuclear production site for a number of exotic processes, such as the r process or other high neutron-density processes associated with convective-reactive regimes, that may play a role in some of the poorly understood observational phenomena of the metal-poor universe, such as the C-enhanced metal poor stars with s and r process signature. Light-curves from supernova from this mass range may be constrained by time-domain surveys (see section 4.9.4) and provide pivotal constraints for the underlying physics responsible for the evolutionary fate of stars in this mass range.

Most stars are binaries and many will at some point in their lives interact in one way or another with their companion. These interactions, such as tidal interactions, the common envelope phase, mass transfer and double degenerate mergers involve non-spherically symmetric hydrodynamic processes that pose significant challenges to our understanding. Binary evolution may be the most important source of rapidly rotating stars, and despite promising progress in recent years the quantitative understanding of the detailed evolution, nucleosynthesis and final death of such interacting binaries remains a challenge.

3.2.6 Stars Thrust Area 3: Nucleosynthesis as validation tool

With major advances in stellar models within reach, and with the expected dramatic increase in model complexity, model validation will become a center stage issue. Direct observations offer one possible pathway. Data expected from GAIA and KEPLER are revolutionizing the field (see section 4.9.4). For a very limited set of stars it is now possible to obtain some constraints on their interior structure with astroseismology (see section 4.9.11). However, the by far most powerful tool to validate stellar processes are their nucleosynthetic signatures. The available data on the composition of metal poor stars are growing rapidly providing information in individual nucleosynthesis events and their evolution over time (see sections 4.9.4 and 4.9.5). A prerequisite for this approach are precise nuclear data on the processes involved. Given the increased need for model validation, advances in the understanding of stellar reaction rates are particularly urgent (see section 4.1).

In addition it will be necessary to establish sound validation procedures for yield predictions so that improvements in modeling accuracy can be measured and assessed. Such a validation framework needs to apply simultaneously the constraints from well-defined and orthogonal observational tests that are directly relevant to the various aspects of input physics. The framework would include multi-wavelength stellar observational data from well-understood astronomical sources, as well as isotopic data from grains. The goal would be to test individual physics models, e.g. of nuclear reaction rate sets or mixing physics simultaneously in different stellar environments with a variety of observational tests to allow breaking the degeneracy that most individual constraints are plagued with. Without such a systematic validation effort it is difficult to see how yield predictions based on different uncertain physics assumptions can be evaluated in order to fully support the interpretation of observational data for a more general range of astronomical questions.

3.2.7 Stars Thrust Area 4: Solar Neutrinos

Since the detection of the first solar neutrinos in 1965 the field has come a long way. With the understanding of neutrino oscillations, and the construction of ever more sensitive detectors the field is now transitioning into a precision era, where solar neutron detection can be used as a precision tool to understand the interior structure of the sun as well as the physics of neutrinos. Recent milestones were the first detection of neutrinos from the rare pep process and a 4.6% precision measurement of the ^{7}Be neutrino flux by BOREXINO. SNO has presented its final data on ^{8}B neutrinos that provides already strong constraints on solar metallicity and Θ_{12}.

Open questions that remain to be addressed in the future include (1) What is the solar core metallicity? (2) What is the total solar luminosity measured with neutrinos (need to measure pp or pep neutrinos)? (3) Are there non-standard neutrino oscillations? (4) What is the Sun's CNO neutrino flux? (5) Can we see a day/night effect due to interactions with matter?

Major new opportunities for the next decade emerge from advanced neutrino detection experiments (see section 4.9.13). Super Kamiokande and Borexino continue to operate. Plans at Borexino include improvements of purity to reduce backgrounds and enable the first detection of neutrinos from the CNO cycle. SNO+ is under construction and promises detection of pep and CNO neutrinos. The detection of CNO neutrinos together with further constraints from precision measurements of the ^{8}B neutrino flux offer the most promising pathway to determine the metal content of the sun that is still under debate. LENS and CLEAN are detector projects that are currently in the exploratory stage with small scale prototypes. Full scale experiments have the potential to measure the pp solar neutrino flux and therefore the total solar neutrino luminosity to better than a few percent.

To exploit these opportunities the critical task for nuclear astrophysics is to improve the precision of the underlying nuclear reaction rates that connect neutrino observations with solar and neutrino physics (see section 4.1). Important reactions include the $^{3}\mathrm{He}+^{4}\mathrm{He}$ reaction, and the radiative capture reactions in the CNO cycle that affect the abundance of the neutrino emitters ^{13}N, ^{15}O, and ^{17}F. In addition to provide better experimental data, a consistent theoretical analysis of various data sets is crucial to better understand the strength of the various reaction components and mechanisms that affect the low energy extrapolation of the laboratory reaction cross sections.

3.2.8 Impact on other areas in nuclear astrophysics

Understanding stars is essential for understanding the origin of the elements. Stars are also the progenitors of core collapse supernovae, and supernova models are sensitive to the structure of the progenitor star. Addressing the supernova problem therefore requires reliable progenitors with better nuclear physics and astrophysics. The Sun plays a special role as neutrino laboratory providing insights into particle physics that also impact our understanding of the role of neutrinos in nucleosynthesis, supernovae, and neutron stars.

3.3 How do Core-Collapse Supernovae and Long Gamma Ray Bursts Explode?

3.3.1 Introduction for non experts

Massive stars develop in their centers a core of nuclear ashes. This core eventually collapses under its own weight. What happens then is subject of intense research efforts. Observations indicate that in many cases a supernova explosion is triggered. Just how a core collapse initiates an explosion remains unknown, and so are the outcomes of the core collapse event for various types of stars. Possibilities include the formation of black holes or neutron stars, bright or faint supernovae, or long gamma ray bursts. The understanding of core collapse supernovae is of central importance in nuclear astrophysics, as they are the main sites responsible for the origin of the elements, and as their energy output is the primary driver of the galactic mixing processes that are fundamental for chemical evolution.

3.3.2 Current open questions

- What is the core collapse supernova (CC SN) mechanism?
- Which stars become failed, subluminous, normal, or hyper CC SNe, and which ones result in long Gamma Ray Bursts (GRB)?
- What is the neutrino and gravitational wave signal from CC SNe?
- Are CC SNe the sites of the r- or LEPP nucleosynthesis processes?

3.3.3 Context

There has been much recent progress in the modeling of massive star collapse. The community agrees that spherically-symmetric (1D) models of core-collapse supernovae (CCSNe) do not lead to explosions regardless of their level of sophistication. The challenge is to find a mechanism that is able to transfer about a percent of the enormous energy released in the collapse to the outer layers of the infalling matter, with the remainder of the energy being emitted as neutrinos. Various groups agree that multi-dimensional effects, in particular convection and the standing accretion shock instability (SASI), are crucial for driving an explosion. Two-dimensional (2D; axisymmetric) simulations with spectral (i.e., energy-dependent) neutrino transport are now available and have demonstrated that the explosion mechanism based on neutrino heating can work for 2D CCSNe, if all relevant multi-physics components are included, in particular, Boltzmann neutrino transport, general relativity, and a detailed treatment of electron capture and a neutrino interactions with coupling of energy bins. However, resulting explosion energies are generally lower than observed.

Progress has also been made in identifying key physics ingredients that affect supernova explosion models: instabilities, neutrino-matter interactions, neutrino oscillations and transport, general relativity effects, progenitor, nuclear equation of state, and magnetic fields. The goal of the next decade is to improve the understanding of this input physics, and to find ways to incorporate the critical aspects into the most sophisticated supernova models.

The connection of long GRBs and extreme CCSNe is now well established observationally, but how and under which conditions a GRB central engine forms in a dying massive star is uncertain. Modeling such extreme events and understanding their nucleosynthetic consequences is tremendously difficult. It will require bringing together CCSN simulation techniques with the methods of numerical relativity to address the general-relativistic dynamics associated with black hole formation, rapid rotation, and ultra-strong magnetic fields important in GRB central engines.

3.3.4 CCSNe Thrust Area 1: Towards adequate 3D Models

Computational advances are expected to make true 3D simulations of core collapse supernovae possible in the next decade. Studies indicate that this will be an important if not decisive step towards identifying the supernova explosion mechanism. Computational advances will also allow modelers to implement the full underlying nuclear physics that significantly affects supernova model characteristics and observables.

First 3D hydrodynamical simulations of core-collapse supernovae with a simple neutrino transport are becoming available. One of the big challenges of next decade is to improve the microphysics in such simulations which will provide new insights about supernova explosions. Taking detailed first-principles neutrino radiation-hydrodynamics simulations to three dimensions (3D) is a major challenge, but will be necessary to robustly model the turbulence behind the shock and fully assess the roles of convection, Standing Accretion Shock Instability (SASI), magnetic fields, and rotation. While first 3D simulations with gray (i.e. energy-averaged) transport have been carried out, spectral transport simulations will be crucial to ascertain the explosion mechanism, its multi-messenger signatures, and nucleosynthetic impact. Developing, running, and validating these simulations will require a broader workforce with interdisciplinary training, access to the necessary computational resources (a single spectral-transport simulation requires $\sim$200 million CPU hours), and code comparisons between groups (see section 4.8).

3.3.5 CCSNe Thrust Area 2: Improved Nuclear Physics

Neutrino interactions, electron capture reactions, high temperature partition functions of nuclei and the nuclear equation of state play an important role in CC SNe. CC SNe are primarily neutrino explosions (99% of the energy is emitted as a neutrino burst). Understanding the properties and interactions of neutrinos with nuclei, electrons, or other neutrinos, is essential for interpreting the observable neutrino signal from CC SNe. Neutrino interactions also play a central role in transferring energy to the ejecta and in modifying the ejecta composition, especially the neutron richness, enabling (or prohibiting) particular nucleosynthesis processes such as the νp-process or the r-process (see section 3.1). Fundamental neutrino properties such as mixing parameters, mass hierarchy, and the existence or non existence of additional sterile species, have shown to influence supernova explosions and nucleosynthesis. Of particular importance is the flavor evolution of the neutrino flux throughout the supernova, and during travel to terrestrial neutrino detectors, as neutrino energy transport, deposition, and detection is flavor dependent. Studies show that despite the small neutrino mass differences collective flavor transformation can take place deep in the supernova.

The nuclear equation of state directly determines the dynamics of the core bounce and the resulting outward bound shock wave that is thought to be the initial step of the explosion mechanism. It also affects neutrino interactions within the proto-neutron star, and therefore influences neutrino energetics, which is a supernova observable and a key ingredient in the explosion mechanism and nucleosynthesis (see sections 3.6, 4.2, and 4.6).

Electron capture reactions play an important role during the initial collapse phase, where electrons provide the pressure support that controls the core collapse. Improved electron capture rates and realistic estimates of remaining nuclear uncertainties are now available for the important stable nuclei up to the iron/nickel region. This has been achieved by a coordinated effort of systematic shell model calculations and targeted experiments that measure cross sections for charge exchange. The challenge for the next decade is to extend this improvement to heavier nuclei and nuclei far from stability, which are also present in significant quantities in collapsing supernova cores (see section 4.2).

In the next decade many groups will begin implementing true higher-order multi-dimensional neutrino transport schemes. These higher order schemes will be able to use more a more detailed description of neutrino interactions and their coupling to the nuclear equation of state. Advances in computing power will allow to more accurately follow compositional changes and to implement more detailed weak interaction processes with various nuclei. There is therefore a growing need for better models of neutrino interactions, weak interaction processes with nuclei, and the nuclear equation of state.

Improved nuclear physics is also needed in the stellar models used to calculate the structure of the pre-supernova progenitor stars (see section 3.2).

3.3.6 CCSNe Thrust Area 3: More realistic progenitor models

A major deficiency of current CCSN models is the reliance on spherically-symmetric models of the presupernova star as initial condition for collapse simulations. Progress in the 3D modeling of convective burning suggests that presupernova stellar structure may be significantly different from what current purely 1D models predict. In addition, the rotational structure of the pre-supernova star, its magnetic fields, and its mass, determined by mass loss processes during its previous evolution, turn out to be crucial parameters determining the outcome of the supernova explosion. Robust 3D CCSN models will thus crucially depend on advances in multi-D stellar evolution (see section 3.2).

Connected to this is the challenge to predict the ultimate outcome of stellar collapse (and its various observational signatures, including nucleosynthetic yields) as a function of zero-age-main-sequence mass, metallicity, and rotation. This will require the generation of an extensive grid of stellar presupernova models as a function of various initial parameters, and taking into account astrophysical and nuclear uncertainties.

An often neglected aspect of this problem is the fact that most stars are part of a stellar binary system. The evolution of such stellar binary systems, such as common envelope phases where one star is located inside the other star, and various mass transfer episodes must therefore be taken into account when determining the pre-supernova properties of a star.

3.3.7 CCSNe Thrust Area 4: Multi-messenger observations

Multi-messenger studies imply observing supernovae not only with photons at different wave lengths but also with gravitational waves and neutrinos. The combination of these observations and their associated communities is key to make advance in understanding these complicated and fascinating environments.

The advent of wide-field optical surveys, with spectroscopic follow-up, has greatly increased the observational catalog of supernovae (thermonuclear SNe and CCSNe), revealing peculiar events and rare features. This includes timely observations of shock breakout, which provides powerful constraints on the progenitor star's structure. Comparisons with archival data from Hubble and other sources has revealed several progenitors in their presupernova state, allowing correlations between CCSN observables and progenitor features, thereby furnishing extremely valuable constraints on stellar evolution and CCSN modeling. Optical spectropolarimetric observations of supernovae and X-ray compositional maps of supernova remnants have revealed wide-spread, but moderately strong, asymmetry in the ejecta, providing insight into the morphology of the central engine. Studies of the afterglows of γ-ray bursts have confirmed the association of long duration bursts with CCSNe while establishing that short duration bursts do not share this association. Our ability to simulate the photon radiative transfer that produces the visual display of all of these events has also improved, with 3D time-dependent light curve and spectrum calculations now possible, including the far-from-equilibrium conditions that occur during shock breakout.

Despite this myriad of new observations that provides crucial constraints of CCSNe, observations of explosive astrophysical events have been limited in terms of sky coverage and cadence. Improving our supernova census and determining the a more complete morphology of all types of supernova events will require high cadence surveys with near full sky coverage and through follow-up across all wavelengths (see section 4.9). Rapid follow-up at X-ray and UV wavelengths are particularly important to maximize the information we can glean from shock breakouts and γ-ray bursts (in particular in combination with gravitational-wave observations). Expanding the catalog of presupernova progenitor observations will require highly-resolved, deep multi-band imaging of a multitude of galaxies. To bridge the gap between these new observations and modeling of the central engines and nucleosynthesis, further improvements in light curve and spectral modeling are needed.

γ-ray observations allow one to determine the yields of radioactive isotopes produced in supernovae offering unique opportunities to probe the deepest layers of nucleosynthesis. Model predictions of ^{44}Ti yields do vary signifcantly. NUSTAR will be able to provide ^{44}Ti yields and spatial distributions for a number of historic supernova remnants in the Galaxy, including 1987A. There is also a $\approx$50% chance to directly observe a core collapse supernova during the expected instrument lifetime. Other radioactive isotopes expected to be produced in supernovae cannot be detected directly with NUSTAR owing to the higher γ-ray energies, but will contribute to the low energy γ-ray flux due to down scattering processes, that will however need to be modeled to provide useful constraints.

Much progress has been made in predicting the neutrino signal seen by neutrino detectors and the gravitational-wave signal seen by Advanced LIGO and its partner observatories from the next galactic CCSN. Understanding these signals is crucial for observationally probing the dynamics and thermodynamics in the core, but most predictions still come from 1D (for neutrinos) and 2D (for neutrinos and gravitational-waves) simulations. Detection of a Galactic supernova with Advanced LIGO would provide unique information about asymmetries, rotation, and convective flows in the supernova engine.

Observing supernova neutrinos is currently restricted to events in our Galaxy or nearby satellites such as the Small or Large Magellanic Clouds. A number of detectors are currently operating and would provide detailed information on the neutrino signal from a Galactic supernovae. The most sensitive detector is Super Kamiokande, with KamLand, Borexino, LVD, ICEcube, and MiniBoone also being expected to detect of the order of 100 neutrino events. Planned larger detectors such as the LBNE water Cerenkov detector or Gadzooks would provide much improved sensitivity to Galactic supernova neutrinos. With such detectors it might also be possible to detect a few events from a supernova in Andromeda, slightly increasing the chance of detecting a supernova during the detector lifetime.

In addition, neutrino detectors are sensitive to the cumulative relic neutrino background from all supernovae having occurred in our Galaxy to date. Detecting this relic neutrino flux would provide information on the Galactic supernova rate and the average neutrino fluxes and energies of core collapse supernovae. So far only upper limits have been detected, and a next generation of neutrino detectors will be needed to provide useful constraints, or a detection.

3.3.8 Impact on other areas in nuclear astrophysics

Advances in supernova modeling directly impact our understanding of the origin of the elements. The r-process has been shown to be sensitive to ”fallback”, where material might be almost ejected only to fall back onto the proto-neutron star, where can become re-energized to finally be fully ejected. Clearly the nucleosynthesis conditions are very different for such a scenario, compared to a simple straight ejection in a one dimensional model. Similarly, multi-D supernova models indicate that the electron fraction, a key parameter determining nucleosynthesis outcomes, is evolves highly anisotropically in the deepest layer of the supernova. Clearly 1-D models are not adequate to predict the nucleosynthesis of the deepest ejected layers where the electron fraction plays a critical role. Finally, multi-D models and observations indicate that supernova ejecta are asymmetric and anisotropic, including the formation of clumps and filaments. Existing and future observations of element distributions in supernova ejecta can be a powerful tool to validate supernova models, but require advanced supernova models in 3D with reliable microphysics, in particular the nuclear physics that determines the nucleosynthesis outcomes.

Realistic supernova models are also needed to predict the properties of the remnants, in particular mass and velocity distributions of neutron stars.

3.4 Compact Object Binary Mergers and Short GRBs

3.4.1 Introduction for non experts

Compact stellar objects such as white dwarfs, neutron stars, and black holes are remnants of stars that have run out of nuclear fuel. As many stars exist in pairs, so called stellar binary systems, pair of compact objects that orbit each other are also common. Gravitational wave emission and other mechanisms lead to a reduction of the distance over time, eventually ending in the collision and merging of the two compact objects. Predictions are uncertain but indicate that such mergers should occur at least a few times to a hundred times per Million years in our Galaxy alone, making it a very common phenomenon in the universe. Of particular interest for nuclear astrophysics are the mergers that involve neutron stars. Such events are associated observationally with the occasionally observed short gamma ray bursts. During the merger neutron rich neutron star material is ejected or blown off by neutrinos, providing a possible site for the r-process (see section 3.1). The decay heat produced by the large amount of r-process radioactivity may explain the so called ”kilo novae”, afterglows that are sometimes observed following a short gamma-ray burst. Finally, mergers that involve neutron stars are prime candidates for emitting detectable levels of gravitational waves, and the observations of such waves during the merging process with future gravitational wave detectors may provide insights into the structure of neutron stars.

3.4.2 Current open questions

- What are the rates of neutron star neutron star and neutron star - black hole mergers and how has the merger rate changed over the history of the Galaxy?

- What are the gravitational wave signals from merging neutron stars, and what would they tell us, if detected, about the properties of neutron stars?

- What is the nucleosynthesis output of neutron stars - neutron star and neutron star - black hole mergers and how is it affected by neutrino physics?

- How long does the hyper massive neutron star formed by the merger of two neutron stars survive and does its neutrino-driven wind delay or prevent a GRB due to baryon loading?

- How massive is the accretion disk that is formed when the hyper massive neutron star collapses and how massive is it in BHNS systems?

- Can, and if so, how does the postmerger state evolve to a short GRB?

- What is the photon signature of the early merger afterglow?

3.4.3 Context

The past decade has seen a breakthrough in numerical relativity, enabling for the first time long-term simulations of merging binaries of black holes and neutron stars in full general relativity with microscopic equations of state and neutrino emission. These events are thought to be the progenitors of the frequently observed short gamma ray bursts, and are also a candidate site for the rapid neutron capture process (r-process) (see section 3.1). r-process nucleosynthesis in neutron star mergers is now modeled by multiple groups using trajectories of material ejected in multi-D merger models. The robustness of the resulting r-process has renewed interest into neutron star mergers as sites of the r-process.

The connection between gamma ray bursts and heavy element synthesis has recently been strengthened through the observations of optical and near infra red (near IR) afterglows following a short gamma ray burst, so called kilo novas. The properties of the kilo nova event agree well with predictions based on the decay of ejected long lived r-process nuclei. In addition the first generation of laser interferometer gravitational-wave (GW) observatories reached design sensitivity. While no detection was made, interesting upper limits were obtained. This has triggered progress in theory linking neutron star properties such as the neutron star radius and the nuclear equation of state to the expected gravitational wave signals.

3.4.4 Compact Mergers Thrust Area 1: Advanced Models

Merger simulations using Newtonian gravity or various approximations to general relativity already include realistic nuclear EOS, but use treatments of neutrino interactions and transport too crude for reliable predictions of nucleosynthetic yields. More importantly, they lead to unreliable predictions of the survival time of the HMNS and ejecta masses. Full numerical relativity simulations, on the other hand, capture the general-relativistic aspects of the problem, but generally employ polytropic NS models, which are not useful to study the postmerger evolution. Since Advanced LIGO will be taking data within a few years, relativistic merger simulations must urgently be improved to theoretically underpin Advanced LIGO observations and the follow-up observations in the electromagnetic spectrum. Collaborations between numerical relativists and CCSN modelers will be necessary to incorporate nuclear EOS, spectral and angle-dependent neutrino transport, and neutrino and nuclear interactions into relativistic merger models. This effort will therefore directly benefit from advances in our understanding of the nuclear equation of state through experiment (see section 3.6) as well as X-ray and radio observations of neutron stars (see section 4.9). The structure of the neutron star crust may also play an important role (see section 3.6). Methods need to be developed to accurately follow the long-term evolution of the merger remnant and robustly predict its nucleosynthetic yields and determine the viability of mergers as short GRB central engines and r-process sites. To predict the lightcurve and spectrum of the early merger afterglow in photons, non-LTE radiative transfer simulations will be needed. These, in turn, will require reliable photon opacities for the range of possible exotic and neutron rich nucleosynthesis products of the merger. Resulting advanced merger models need to be extended to cover the critical phases of nucleosynthesis and must then be coupled to nuclear reaction networks to predict the composition of the freshly synthesized nuclei that are ejected and contribute to the chemical evolution of the Galaxy.

3.4.5 Compact Mergers Thrust Area 2: Multi-messenger observations

Advanced LIGO is expected to turn on in 2015 (see section 4.9.14). When it reaches its design sensitivity within a few years, it will have horizons of $\sim$200 Mpc and $\sim$600 Mpc for neutron-star – neutron-star (NSNS) and neutron-star – black-hole (NSBH) binaries, respectively (see section 4.9.14). Depending on population synthesis models, these ranges correspond to conservative estimates of *tens of observations per year*. Observations at low signal-to-noise ratio will yield constraints on the total system mass and possibly the mass ratio of the components. Rarer closer events will yield detailed information on the individual masses of NSNS and NSBH binaries and the spin of the BH in BHNS binaries. In the last hundreds of orbits before merger, the tidal interaction (which depends on the nuclear equation of state [EOS]) of the components has an influence on the GW signal. In BHNS systems, the NS may be disrupted and the GW frequency at which this occurs can be connected to NS structure. In NSNS systems, a hypermassive NS (HMNS) is formed whose long-term survival and the GW signal emitted in the postmerger phase depend on the system mass, on the nuclear EOS, and neutrino cooling.

More observations of optical/near IR afterglows of short gamma ray bursts, so called kilo novas, with current and future wide-field observatories such as Pan-STARRS, DECam, Subaru, or LSST will also be important (see section 4.9). These observations may directly constrain the amount of radioactive r-process nuclei ejected in a neutron star merger event.

3.4.6 Impact on other areas in nuclear astrophysics

Compact object mergers may play a central role in the origin of the heavy elements as sites for the r-process. A better understanding of the merger process and the associated neutrino physics is therefore important. In addition, neutron star mergers offer an opportunity to probe neutron star structure and the nuclear equation of state through future gravitational wave observations.

3.5 Explosions of White Dwarfs

3.5.1 Introduction for non experts

White dwarf stars are the cores of nuclear ash left over at the end of the lives of low mass stars. If they are formed in a stellar binary system, mass transfer can induce a very wide range of nuclear phenomena, ranging from explosions of accreted fuel on the surface, giving rise to classical novae, to the thermonuclear explosion of the entire white dwarf, giving rise to a type Ia supernova. Many other phenomena, some possibly still undiscovered, some currently classified as anomalous or sub luminous type Ia supernovae, may occur. The most common explosions - novae and regular type Ia supernovae are observed frequently, but what exactly determines their evolutionary pathways and which pathway is the one leading to a type Ia supernova remains unclear. Novae and type Ia supernovae are important contributors to the elements in the cosmos - SN Ia produce many elements around iron, and novae may be responsible for the origin of a number of rarer isotopes such as ^{15}N, ^{17}O as well as radioactive ^{26}Al. A successful model for type Ia supernovae is also important to address cosmological questions about the expansion of the universe, as calibrated SN Ia are the prime distance indicators for cosmological distances. Models are needed to reliably estimate systematic errors that might arise, for example, from a dependence of the explosion mechanism on age or environment.

3.5.2 Open questions

- What are the most common origins of type Ia supernovae? What determines whether an accreting white dwarf becomes a type Ia supernovae, and/or a classical nova system?
- What is the reason for the diversity of type Ia supernovae? How common are unusual events?
- How does the nature of type Ia supernovae depend on the environment, and how can type Ia supernovae be used as probes of galactic environments at very high redshifts?
- How robust is the calibration of type Ia supernovae as standard candles?
- What are best potential observational indicators of type Ia environment or explosion mechanism?
- What are suitably accurate computational methods for modeling combustion in full-star explosion simulations, and how can their uncertainty be quantified?
- Does the Urca electron capture / positron decay process play an important role in single degenerate ignition of type Ia supernovae?
- Why do classical Novae eject more mass than expected? Is there a problem with the expectations, the measurements, or both?
- How is interior white dwarf material mixed into a classical nova explosion? And what is its role as an accelerant and in nucleosynthesis of distinctive nuclides?
- What is the contribution of classical novae to the origin of stable and radioactive nuclei in the Galaxy?
- Are there pre-solar grains from Novae?
- What other explosive or non-explosive thermonuclear phenomena occur on white dwarfs, how do they relate to the variety of observed types of explosions, and can we predict so far unobserved phenomena and their observational signatures?

3.5.3 Context

Over the past decade numerous supernova surveys have amassed a huge observational data set on type Ia supernovae, that spans from nearby explosions to the most distant objects at redshifts around 1.9. An important conclusion is the large diversity of type Ia supernovae with large variations in maximum brightness and numerous peculiar subclasses. There are also hints of a correlation of the observed properties with the characteristics of the respective host galaxies.

However, these observations have not allowed conclusive identification of the correct progenitor model and very few observations have identified pre-explosion objects. While based on nucleosynthesis arguments it is robustly believed that type Ia supernovae originate from the incineration of a white dwarf star, it is unclear how the thermonuclear explosion of the white dwarf is triggered. All proposed scenarios have severe shortcomings. Among the most studied scenarios is the so called ”single degenerate” model, where a single white dwarf accretes matter from a companion star until gravitational collapse sets in, which in turn triggers the thermonuclear explosion. In the ”double degenerate” approach that has gained more interest recently, two white dwarfs merge or collide (possibly explaining the fact that in some cases the observationally inferred mass exceeds the maximum mass of a single white dwarf, and explaining the general absence of companion star relics). Various variations involving different details of ignition and explosion within these types of progenitors have also been explored.

One challenge of the single degenerate models is that under most circumstances matter accreted onto a white dwarf results in the thermonuclear explosion of a surface layer after 10s to 100,000s of years of accretion, giving rise to a classical nova explosion. These explosions are thought to eject more material than has been accreted, hence leading to a decrease of white dwarf mass over time. Classical novae are critical testing grounds for stellar physics and are regularly observed at all wavelengths both within our galaxy and in nearby galaxies. This has allowed measurements of approximate ejected masses as well as abundances of elements in the ejecta. Recent radio observations show multiple mass loss episodes in novae, perhaps indicating multiple outbursts.

One dimensional nova models have been very successful in explaining the typically observed composition of the ejecta that comprise of a mixture of mixed in white dwarf material and the ashes of thermonuclear burning. However, the inputs necessary (in particular, enrichment of the H envelope) do not match observations. There is also a significant discrepancy between inferred and predicted ejecta masses. Multi-dimensional models have focused on the role of convection in producing the necessary enrichment, and have shown some success. Nova models predict nova ejecta to be enhanced in some otherwise rare isotopes such as ^{15}N, ^{17}O, and radioactive ^{26}Al. Novae may therefore be at least in part responsible for the origin of these isotopes in nature. Enhancements of these isotopes are found in a number of pre-solar grains extracted from meteorites, which may have been formed in nova ejecta. If confirmed, such nova grains could be analyzed in terms of other isotopic characteristics that may help to constrain nova models.

While most studies of supernovae and novae attempt to explain observed events, there has been some work on predicting rare and novel event types based on the observed population of binary systems. An example are so called .Ia (”point one a”) events where a thick helium layer explodes on the surface of an accreting white dwarf without triggering the ignition of the white dwarf star itself. Another example are rare classical nova events, where relatively cold white dwarfs are expected to accumulate more massive hydrogen and helium rich layers that lead to novae that may produce heavier elements through a more extended rapid proton capture process.

There has been tremendous progress in the understanding of the underlying nuclear physics of explosions related to accreting white dwarfs. This is critical for constraining and validating various theoretical possibilities, for predicting compositional and nucleosynthetic signatures, and for exploring environmental effects. For type Ia supernovae carbon and oxygen induced fusion reactions are critical and have been shown to affect ignition conditions, the strength of the detonation, and the ejected composition. Experiments have shown that the uncertainty on fusion reactions is much larger than previously thought. In addition to the well known effect of sub-barrier fusion enhancement, there is now evidence from fusion reactions with heavier nuclei for significant sub-barrier fusion suppression. It is not clear to which extent such a suppression is present, for example in the ^{12}C+^{12}C fusion, but together with the possibility of rate enhancement through unknown resonance, the possibility of this effect dramatically increases the rate uncertainty. Weak interaction rates, such as electron captures, also play an important role in type Ia supernovae. Experiments with charge exchange reactions in the last decade have provided enough experimental data in weak interaction strength in nuclei to guide the development of effective interactions in shell model calculations, and to characterize quantitatively the remaining uncertainties.

Progress in understanding the underlying nuclear physics has been even more impressive in the case of Nova explosions. Novae are a fortuitous case in that temperatures are high enough for reaction cross sections to be large enough so they can be measured directly. On the other hand temperatures are still low enough so that the reaction sequence only includes stable nuclei, or unstable nuclei located close to stability where reasonably intense radioactive beams can be developed in many cases. As a consequence, Novae are the only astrophysical explosions where most of the nuclear reaction rates are known experimentally. A few exception remain, where beam development has been particularly difficult.

3.5.4 WD Explosions Thrust Area1: Advancing the models

Type Ia Supernovae: Chandrasekhar mass single degenerate models for type Ia supernovae are relatively mature. Prediction of nucleosynthetic yields of sufficient quality for detailed observational comparison to sequences of spectra still requires further refinement of computational techniques for both detonation and deflagration modes of combustion (see section 4.8). Gross yields of, for example, ^{56}Ni are modestly accurate ($\sim 10\%$), but this may not be sufficient to distinguish between alternative models. Large parameter studies with 3D simulations are possible, which allows observational questions relating to the population of supernovae to addressed, but this must be pursued in parallel with improvements in computational techniques. Performing radiative transfer calculations is only possible for a few groups currently, and suffers from computational challenges to run effectively on modern massively-parallel supercomputers.

Models of double degenerate systems are also fairly mature though they received less attention in the early 2000's than Chandrasekhar mass models. Some areas of necessary refinement are similar, such as accurate computation of the dynamics and products of detonation, while others are different, such as the treatment of the mass transfer process, which utilizes a particle rather than a grid method for computing hydrodynamics. The division between violent mergers, which may lead to explosions, and non-violent ones that likely lead to collapse to a neutron star requires further investigation as computational methods tailored for this problem continue to be refined (see section 4.8).

Relevant to all channels, theoretical work on binary stellar populations, and specifically short-period binaries containing white dwarfs, is important for understanding the frequency at which various possible scenarios might be realized. Producing the right rate of events is typically a challenge for candidate scenarios. Computing these rates for comparison to observed rates depends critically on the understanding of the short period white dwarf binary population.

A particularly important challenge is the incorporation of the latest nuclear physics advances into supernova models. This does not just require updating of nuclear data inputs, but for example in the case of weak interactions extensive nuclear model calculations that use experimental constraints to determine improved rate sets with uncertainties that can be used in supernova models (see section 4.6). Extensive post processing calculations are needed to take advantage of progress in nuclear physics to obtain nucleosynthetic signatures, that can be used to validate (or falsify) models. Of special importance is the incorporation of nuclear uncertainties that now become available for various reaction rates (see section 4.10).

A well understood physical model of type Ia supernova would be a major breakthrough and would open up possibilities to explore potential systematic errors in standard candle calibration, to understand the contribution of SNIa to the chemical enrichment of galaxies, and to exploit environmental dependencies to constrain the properties of the oldest, most distant galaxies such as their star formation properties.

Classical Novae: Multi-dimensional models of Novae have so far not been possible, though aspects such as the onset of the explosion have been modeled in 3D. This is a severe limitation as many of the current open questions likely require the reliable modeling of multi-D effects (see section 4.8). One critical open question is the mixing of white dwarf material into the explosion. Not only does the mixing process affect ignition conditions, and nature of the explosion and nucleosynthesis, but it is also critical in determining whether continued nova explosions lead to growth or erosion of the underlying white dwarf. One challenge here is the low speed of convection compared to the sound speed, which necessitates more sophisticated and complex numerical hydrodynamics methods. Refined multidimensional models may be key to understanding the dynamics of the mixing, but algorithms can have trouble right at the H envelope boundary since numerical mixing may artificially enhance the burning. Algorithmic sensitivity studies are needed to understand what is real and what is unphysical. Other important questions that require multi-D modeling include the role of the companion in the ejection process, the impact of the explosion on the accretion process, or the impact of magnetic fields.

With the complexity of models the need for validation will also increase. The produced abundance distribution provides an important pathway for such validation. Reliable nuclear physics will be essential to take advantage of this opportunity. In addition it will be important to constrain the basic model parameters such as accretion rate and white dwarf mass independently through observational means.

Other types of explosions: In general it will be important to expand the parameter space considered in supernova and nova modeling to capture the full variety of observed phenomena and to be able to predict unknown types of transients. In particular for novae it has been shown that low accretion rates and low core temperatures can lead to much more powerful explosions with drastically changed nucleosynthesis. Another explosion regime are thick helium layers that lead to .Ia supernovae. So far, self consistent sensitivity studies to explore the critical nuclear physics that take into account mixing and the impact of reaction rate changes on energy generation through the production of radioactive isotopes have not been carried out - neither for standard classical nova models, nor for the range of rarer phenomena. Such sensitivity studies will be critical to guide future efforts in nuclear physics. This is especially important as most of the nuclear physics can probably be determined experimentally as long as it is clear what is needed. Similar efforts will be needed for type Ia supernova models.

3.5.5 WD Explosions Thrust Area2: Multi-wavelength observations

The biggest observational need related to type Ia supernovae is to provide constraints on the progenitor. This is difficult due to the rarity of these events. New surveys such as the Palomar Transient Factory (PTF) find large numbers of transients, including more events close to Earth that provide richer observables. Rapid followup observations at all wavelengths are key (see section 4.9). For example, radio observations with EVLA only two days after PTF found a type Ia supernova have led to significant constraints on total ejected mass and therefore on the possible nature of progenitors. New telescopes will also open windows in the IR. This is interesting because SN Ia are more similar in the IR and distinct lines can be seen there. More observations of polarization can help distinguish between models (for example, mergers may be expected to have high polarization). It is also possible that isotopic information can be obtained from these observations.

For novae, more detailed observations of the composition of ejecta and radio constraints on ejected masses will be needed to validate models. A severe limitation in this context is the lack of UV spectroscopic capabilities (see section 4.9). Of critical importance are also observational constraints on system parameters such as accretion rate, nature of the companion star, and mass of the white dwarf. Such observational constraints would greatly tighten nova model validation through abundance observations, enabling modelers to take full advantage of the advances in our understanding of the nuclear physics of novae.

The observation of nuclear γ-rays would be of particular importance for both, type Ia supernovae and novae. γ-rays provide information on the produced abundance of a specific isotope, and are largely free of radiation transport issues that plague the traditional elemental abundance observations. The time evolution of γ-radiation can also provide a handle on distinguishing various progenitor scenarios. NUSTAR is expected to detect one to two type Ia supernovae per year in low energy γ radiation (see section 4.9). However, its limitation to the hard X-ray band enables only detection of down scattered higher energy γ-ray lines and therefore relies on detailed hard X-ray models of type Ia supernovae. A future γ-ray mission with enhanced sensitivity in the few MeV energy range compared to existing instruments would provide powerful diagnostics for type Ia supernovae and novae. In novae, detection of decay γ-rays from ^{22}Na and, if the instrument can be pointed early, ^{18}F may also be possible.

New time domain surveys (like PTF and soon LSST) will find a large number of transients, possibly in novel recurrence time regimes (see section 4.9). Questions that will arise will include: Are these new objects or extreme examples of our existing models? Detailed observations on these new transients will be needed. This will have tremendous impact on nuclear astrophysics, with new types of objects likely requiring new nuclear physics investigations.

3.5.6 WD Explosions Thrust Area3: Pinning down the nuclear physics

Novae and type Ia supernovae are thermonuclear events and nuclear physics naturally plays a critical role for ignition, energy generation, and nucleosynthesis. An important problem are the huge uncertainties associated with carbon and carbon-oxygen fusion reactions. These are among the most uncertain thermonuclear rates in astrophysics limiting models of the ignition process of type Ia supernovae. The carbon and oxygen fusion reaction rates also affect the strength of the detonation in the most common deflagration - detonation models impacting directly the composition of the supernova ashes. Multiple strategies are needed to address this problem (see section 4.1). While measurements need to push to lower energies to reach the relevant astrophysical energy range, a better understanding of fusion reactions in general is also needed. This requires work in reaction theory (see section 4.6), which then has to be validated with cross section measurements for a range of different types of reactions. Improved rates for charged-particle rates on ^{48}Ca are also needed—this can be a possible discriminator of progenitor models.

While much progress has been made over the past decade in measuring weak interaction strengths mainly through the use of charge exchange reactions on stable nuclei, the steps of converting this experimental data into the products that can be used by modelers is incomplete. Systematic studies of weak interaction strength on unstable nuclei, in conjunction with shell model calculations, will become possible at facilities that offer fast radioactive beams, such as FRIB in the US, FAIR in Germany, or RIBF in Japan (see section 4.2).

Temperatures in novae are much more moderate than in SN Ia. In fact, in terms of the feasibility of experimentally determining reaction rates on unstable nuclei in stellar explosions, novae provide a somewhat ideal case. Temperatures are high enough to make cross sections accessible with moderate beam intensities (unlike reaction rates in stars) while temperatures are still sufficiently low to confine the reaction sequence to lighter nuclei up to $Z \sim 20$ close to stability. As a consequence, many of the important rates in Novae are already experimentally determined. There are a few remaining reactions, that remain unmeasured and strongly limit predictions of radionuclide production or interpretation of abundance signatures to validate models. Key reactions include ^{18}F(p,γ)^{15}O, ^{25}Al(p,γ)^{26}Si, and ^{30}P(p,γ)^{31}S. Measurements with low energy beams at the Facility for Rare Isotope Beams should be able to determine the majority of the nuclear reaction rates needed to understand nova nucleosynthesis (see section 4.2).

Much work has been done on identifying the critical nuclear physics in standard SNIa and nova models. Such sensitivity studies provide critical guidance for the improvement of the underlying nuclear physics and also provide estimates for the nuclear uncertainty component of observables. In the future it will be important to carry out such sensitivity studies along with changes and improvements of astrophysical models. For novae it will be important carry out sensitivity studies that take into account feedback from reaction rate changes on the hydrodynamical evolution and nuclear uncertainties 4.10).

In addition, sensitivity studies are needed for the rarer events, such as .Ia supernovae, other sub luminous SNia, as well as for rarer classes of classical novae, such as the recently predicted explosions on white dwarfs with particularly low temperatures and accretion rates. For the latter systems it has been shown that breakout from the CNO cycles and a much stronger rapid proton capture process into the iron region and beyond ensues. In general, reaction sequences can vary widely depending on the system parameters, and for each case reliable nuclear physics is needed to predict observational signatures.

3.5.7 Impact on other areas in nuclear astrophysics

Type Ia supernovae are important nucleosynthesis sites - they are responsible for the origin of a significant fraction of iron and near iron elements, and may also be a site of the p-process. Novae may contribute to the origin of ^{17}O, ^{15}N, and ^{26}Al. In addition, type Ia supernovae play a primary role in cosmology as standard candles on very large cosmic distances and are one of the pillars of the modern paradigm of an accelerating, dark energy driven universe. Progenitors and properties of type Ia supernovae need to be understood to gauge for example systematic errors in distance measurements through environment dependencies of the luminosity calibration.

3.6 Neutron Stars

3.6.1 Introduction for non experts

Neutron stars are formed in supernova explosions as the remnants of the collapsed cores of massive stars. They are essentially 10 kilometer sized blobs of nuclear matter floating through space, with masses of the order of the sun. Neutron stars offer the unique opportunity to study the properties of macroscopic quantities of nuclear matter through astronomical observations. The goal is to reveal the equation of state of nuclear matter (the relationship between energy density and pressure) related to the neutron star mass and radius relationship, and signatures of nucleon superfluidity, or the various possible phases of cold dense nuclear matter such as pion, kaon, or quark condensates. Neutron stars are also interesting astrophysical objects in themselves, exhibiting radio pulsations, X-ray bursts, strong star quakes, and, in the case of magnetars, some of the strongest magnetic fields observed anywhere in the cosmos. Many of these phenomena are not understood and link directly to open questions in nuclear, neutrino, condensed matter, and plasma physics at extreme conditions.

3.6.2 Current open Questions

- What are the values and limits for masses and radii of neutron stars?
- What do observations of cooling neutron stars tell us about the interior? Is there really evidence for enhanced cooling in massive neutron stars?
- What is the origin of the intense surface magnetic fields as large as 10^{15} Gauss found in magnetars, and the origin of observed flares and their Quasi Periodic Oscillations?
- What phases are there in the phase diagram of dense matter at low temperatures? How can we use neutron star observations to learn about those phases? How do we make good theoretical predictions about those phases?
- What is the nature of absorption features detected from isolated and from accreting neutron stars?
- Is there a limit to the spin frequency of milli-second pulsars? If so, why?
- What precisely controls the durations, shapes, and frequency of X-ray bursts and why is the transition to stable burning at a much lower accretion rate than expected?
- What is the origin of burst oscillations, and what do they tell us about the underlying neutron star?
- Is unstable burning of carbon the cause of all super bursts? What is the inferred unknown shallow heat source in the neutron star ocean that seems to be required to ignite super bursts and to explain the early light curve of cooling transients?
- What are glitches and why do they occur? What is the trigger that couples the superfluid to the crust over a timescale of less than one minute? What are the relevant dissipative processes?
- How does one link the microphysics of transport, heat flow, superfluidity, viscosity, vortices/flux tubes to neutron star phenomenology?

3.6.3 Context

Mass and radius measurements: Neutron stars are observed in a variety of different environments at a wide range of wavelengths. Significant progress has been made in quality and quantity of observational data, in developing the theoretical tools to interpret them, and in obtaining experimental data on the underlying nuclear physics. Rapidly spinning neutron stars with magnetic fields are observed as radio pulsars, and precision observations of the pulse trains arriving on earth allow for rather accurate neutron star mass measurements. A major breakthrough was the recent discovery of a 1.97 ± 0.04 solar mass neutron star in the radio pulsar PSR J1614-2230 with the NRAO Green Bank Telescope (GBT) using the Shapiro delay technique. This is the most massive neutron star found to date. Its existence provides a lower limit for the maximum mass of a neutron star, which already excludes a range of theoretical possibilities for the nuclear matter equation of state.

X-ray observations of thermal emission from neutron stars, in particular in globular clusters where distances are known, and in transients where atmospheres can be modeled more reliably, now put constraints on neutron star radii. In addition observations of pulse profiles from radio millisecond pulsars have placed the restriction that the radius of a 1.4 solar mass neutron star is greater than 10.7 km. This is important as many equations of state for nuclear matter predict a very narrow range of radii for the wide range of typical neutron star masses. Radii can therefore provide very stringent limits on the equation of state.

Pulse train analysis from X-ray pulsars - highly magnetic neutron stars where accretion onto hot spots leads to bright X-ray pulsations - can in principle be used to constrain neutron star masses and radii. This approach requires bright sources and modeling of spectral emission and probation of radiation in the gravitational field of a possibly deformed neutron star. Current constraints indicate that a 1.4 solar mass neutron star should should have a radius of at least 12.7 km. Better observational data with larger telescopes are needed to improve statistical and systematic errors.

Clearly combined mass radius constraints, which are essential to fully constrain the nuclear matter equation of state, are still very limited, but the field has now arrived at a stage where a detailed analysis of the systematic errors, guided by more observations, experiments, and theoretical progress, becomes possible and could lead to a significant breakthrough in the near future.

Cooling neutron stars: Cooling of neutron stars can be observed with X-ray telescopes and puts strong constraints on the neutron star interior structure as many neutrino emission processes are sensitive to the existence of superfluidity and exotic phases. Typically neutron stars are relatively old and cool slowly, so X-ray observations of their thermal emission together with an age determination provide a single data point on a particular neutron star cooling curve. However, it has now become possible to observe an actual change in temperature in a few systems. The most spectacular case is the recent observation of rapid cooling of the 330 year old neutron star in Cassiopeia A from 2.12×10^6 K to 2.04×10^6 K over a period of 10 years, which was interpreted as confirmation of the occurrence of neutron superfluidity and proton superconductivity in the dense interiors of neutron stars.

In accreting neutron stars the crust is heated separately from the core and can cool on timescales of years once accretion shuts off. This has now been observed in a number of X-ray transients using long term observations with Chandra and XMM. The results confirmed the theoretical prediction that neutron stars have crusts, but are also beginning to shed light on the elastic and transport properties of crystalline structures in neutron star surfaces. Significant progress has been made in identifying the nuclear processes responsible for crustal heating during accretion, but the lack of knowledge about weak interaction strengths, masses, the location of the neutron drip line, and fusion cross sections of extremely neutron rich nuclei limit reliable predictions.

X-ray bursts: Accreting neutron stars exhibit a range of thermonuclear bursting behavior - ranging from regular X-ray bursts lasting 10-100 s with recurrence times of hours to days, to intermediate long bursts, to the rare, but 3 orders of magnitude more energetic superbursts. The frequent regular X-ray bursts have been found to exhibit a variety of phenomena, including variations in burst duration, multi-peaked bursts, and unexpected changes in recurrence time. Mapping out this phenomenology with X-ray observatories such as XMM, Chandra, RXTE, Swift, and INTEGRAL is one of the major accomplishments of the last decade. The MINBAR burst archive now contains thousands of bursts setting the stage for future efforts to understand the observations theoretically.

A major limitation of detailed and systematic comparisons between model bursts and observations is the uncertain nuclear physics of the αp- and rp-processes that power X-ray bursts, and determine light curve shapes, recurrence time behavior, and the peak luminosity of sub-Eddington bursts. While huge progress has been made in measuring β-decay half-lives and nuclear masses, in particular high precision mass measurements with Penning traps and storage rings, experimental information on proton and helium induced reaction rates is still very limited.

Progress has also been made in further developing X-ray burst models. 1D hydrodynamic burst models have now been extended to simulate the deeper occurring super bursts together with the shallow regular bursts shedding light on the interplay between the two burst modes. Ultimately however 3D models will be necessary, in particular to describe anisotropies in burning that are often observed as quasi periodic oscillations during bursts. The necessary codes are under development and already indicate the importance of rotation in localizing the burning.

These advances have inspired a number of groups to revisit the question whether burst observations can be used to constrain the mass and radius of the underlying neutron star. Interesting constraints have been obtained, especially when combining information from X-ray bursts with cooling transients, though systematic errors remain to be investigated in detail. It has also been shown that burst profiles are in principle dependent on the neutron star surface redshift, opening additional avenues to constrain neutron star compactness.

The nuclear matter equation of state (EOS): Neutron star observations and their interpretation are complemented by laboratory studies that independently attempt to constrain the nuclear matter equation of state. Of great importance is the behavior of the energy of a system of unequal number of neutrons and protons, the so-called symmetry energy. The density dependence of the nuclear symmetry energy not only determines the structure (particularly the radius) of a neutron star, but also governs its thermal evolution (detected in multi-wavelength photon emissions) through various neutrino emitting processes which relentlessly cool the star.

Many recent laboratory experiments have provided initial constraints on the density dependence of the nuclear symmetry energy and on the EOS of neutron-rich matter at near-saturation and sub-saturation densities. These constraints have been extracted from measurements of nuclear masses and excitation energies of isobaric analog resonances; energies and strength functions of giant monopole and dipole resonances; electric dipole strength functions and electric dipole polarizability sum rules; energies and strengths of pigmy electric dipole resonances; and measurements of neutron skin thicknesses. Experiments have also probed the differential flows of neutrons and protons during nuclear collisions to constrain the symmetry energy at sub-saturation densities. Relevant observables are the diffusion of isospin between projectile and target nuclei in binary collisions, and comparisons of the spectra and flows of mirror nuclei, such as neutrons vs. protons, or tritons vs. helions (^3He).

Impressive accomplishments have been made on the theoretical front both in first principle calculations and in applications to neutron star phenomenology. Areas of significant progress include ab-initio calculations of neutron matter highlighting the role of three-nucleon forces on the density dependence of the nuclear symmetry energy; application of effective field theory methods to calculations of low density superfluid and solid matter of practical importance in calculating transport (particularly thermal conductivity) and elastic properties (shear and bulk modulii) of a neutron stars crust; Using a maximally compact EOS, model-independent upper limits to thermodynamic properties in neutron stars, such as energy density, pressure, baryon number density and chemical potential, which depend upon the neutron star maximum mass, have been established; and Classical and quantum molecular dynamical simulations of neutron star crusts and their transport properties have been performed.

3.6.4 Neutron Star Thrust Area 1: Observations

The maximum neutron star mass has profound implications for the minimum mass of a hadronic-material black hole (and the total number of black holes in our Universe, of much concern to Cosmology), the mass of the progenitor star that gave birth to it, and the equation of state of hadronic matter. The minimum neutron star mass raises questions about stellar evolution and how low mass neutron stars can be formed within the current paradigm of core collapse supernovae. A concerted effort in astronomy to increase the sample of neutron stars with measured masses is therefore very important. Radio observations of pulsars require sensitive radio telescopes such as the Green Bank Telescope (GBT) and Arecibo; future facilities such as the Square Kilometer Array (SKA), MeerKAT, ASKAP, and ATAwill are expected to provide many more mass measurements (see section 4.9). Observations with these advanced radio telescopes will also give a more detailed picture of pulsar glitches, including time resolved data on the glitch, to the point where models can be tested. Continued measurements of the double radio pulsar system (PSR J0737-- 3039) over the next 5-10 years offer the prospect of a direct measurement of the moment of inertia of pulsar A in this system.

In order to delineate the interior composition of neutron stars and the associated neutrino emission processes, we need a future generation of time and energy sensitive X-ray observatories (see section 4.9.6). In particular, precise measurements of the masses and radii of several individual stars would revolutionize this field. Theoretical techniques to invert the structure equations from mass-radius information to obtain the pressure-energy density relation are in place waiting for data to emerge. Obtaining such measurements from X-ray pulsar observations requires significantly larger X-ray telescopes with excellent timing resolution such as NASA's Neutron Star Interior Composition ExploreR (NICER) International Space Station (ISS) payload and ESA's LOFT. The GAIA mission will also be important in this context as it will greatly improve distance measurements reducing one of the main uncertainties in determining neutron star radii from quiescent neutron stars, and increasing the number of systems with reasonably known distances that can be used for such measurements.

To address the open questions concerning neutron stars in X-ray binaries and related phenomena such as X-ray bursts, superbursts, and quasi-periodic oscillations will require continued X-ray observations to increase statistics and time domain coverage, especially on burst oscillations and their time-resolved spectral evolution, on accretion flows onto milli-second X-ray pulsars, and on phenomena related to super bursts. In addition new predictions that are the result of the better understanding of the nuclear physics and astrophysics of bursts, such as predicted oscillations triggered by the ^{15}O(α,γ) reaction in the tails of super bursts, or absorption edges in X-ray spectra due to ejected material, need to be searched for. In the near future these observations have to be continued with existing instruments such as XMM/Chandra, Swift, INTEGRAL, while at the same time burst catalogues need to be expanded and fully analyzed. Future missions of importance are LOFT (ESA) , NICER (NASA), ASTROSAT (India), ASTRO-H (Japan), and eROSITA (Germany/Russia) (see section 4.9.6). A particularly important feature of LOFT is the timing resolution that will enable the study of various oscillatory modes on the neutron star surface that are directly related to composition and therefore to nuclear processes, as well as other time dependent effects such as the spreading of the nuclear burning front during the early stages of an X-ray burst. A long standing quest in the field is high sensitivity and high resolution X-ray spectroscopy of accreting neutron stars. This has the potential of identifying the composition of material burned by X-ray bursts or superbursts, and would provide very stringent constraints on the surface redshift and therefore on neutron star compactness. Because many systems show rapidly rotating hot spots, time resolved spectroscopy has the greatest potential. In this context the planned IXO/Athena mission would represent a major advance for the field.

3.6.5 Neutron Star Thrust Area 2: Rare Isotope Physics of Bursts and Crusts

Nuclear processes on accreting neutron stars span extremely neutron deficient isotopes during the rp-process in X-ray bursts to crustal electron capture and fusion reactions that involve extremely neutron rich nuclei at and beyond the neutron drip line.

X-ray bursts: In X-ray bursts, nuclear properties affect the shape of the burst light curve, the composition of small amounts of material that might be ejected, and the composition of the burst ashes which sets the stage for re-ignition in superbursts and the composition of the neutron star crust. The critical nuclear physics governing the rp-process in X-ray bursts are β-decay half-lives, nuclear masses, and the rates of proton and helium induced reactions along the proton drip line up to $A \approx 108$. All the β-decay half-lives and many of the relevant masses are now measured. Precision mass measurements with Penning traps or storage rings are needed for a number of remaining nuclei in the path of the rp-process, many of which can be reached with some improvements at current accelerator facilities (see section 4.2).

The biggest challenge for the future are the measurements of the reaction rates. Here a multi-accelerator approach is essential. Of highest importance are direct measurements of critical (p,γ) and (α,p) reactions with intense, low energy radioactive beams on windowless hydrogen and helium gas targets using recoil separators and detector arrays. A major limitation is the difficulty of realizing such beams in the laboratory and as a consequence only a handful of reactions have been measured so far, mostly at ISOL facilities. This problem is being addressed in the US through the development of a new, complementary, radioactive beam production technique, the reacceleration of radioactive nuclei that have been produced by fragmentation at intermediate energies, and have then been stopped in a gas cell system. This technique will be available at the new ReA3 facility at NSCL, and later at FRIB, and will enable in concert with the SECAR recoil separator and the JENSA gas jet target the direct measurement of many critical rp-process reaction rates (see section 4.2).

Indirect studies of reaction rates on unstable nuclei, such as measurements of direct capture Asymptotic Normalization Coefficients (ANCs) and the properties of resonances, are complementary to direct measurements. They are needed as preparation to the more difficult direct measurements, and they provide information on reaction rate components that are too weak to be measured directly. In some cases, transfer reactions with stable beams can reach the unstable nuclei in the rp-process, especially below calcium where the rp-process proceeds closer to stability. Stable beam facilities with high resolution spectrometers such as TU-Munich (Germany), RCNP (Japan), and i-Themba (South Africa), or high resolution gamma arrays such as GAMMASPHERE at ATLAS are necessary for such experiments (see section 4.1). These types of measurements need to be exploited to the fullest extent possible, so the more difficult and more resource intensive radioactive beam experiments can be optimized.

For most rp-process reactions, transfer reactions with unstable beams are needed to reach the relevant nuclei. At the next generation radioactive beam facilities, and especially at FRIB, it will be possible to reach all rp-process nuclei to study excitation energies and other properties of resonances. Proton transfer reactions with radioactive beams such as (d,n) or (^{3}He,d) (or neutron transfer reactions on mirror nuclei) as well as α-transfer reactions such as (^{6}Li,d) have the advantage to populate preferentially the critical states and offer the additional opportunity to directly constrain proton and α spectroscopic factors, ANCs and widths (see section 4.2).

While theoretical predictions of rp-process reaction rates are not sufficiently reliable for X-ray burst models, the combination of theoretical information with indirect experimental data on excitation energies and other level properties can result in reaction rate uncertainties that are acceptable for some of the less critical reactions, and that provide much more reliable data until further experiments become feasible. Expanding shell model spaces and developing new effective interactions so that calculations in the region of the deformed nuclei ^{64}Ge - ^{74}Sr become possible would be important.

Crust processes: The nuclear properties of the neutron star crust determine its mechanical, electrical, and thermal structure. This is especially true for accreting neutron stars, where the crust is replaced by X-ray burst ashes, greatly expanding the range of possible non equilibrium compositions, and where ongoing accretion continuously drives electron capture reactions, β-decays, neutron captures and releases, and fusion reactions. These reactions determine crustal heating and cooling during accretion and are therefore directly related to observations of cooling transients. Electron capture induced density discontinuities have also been predicted to give rise to gravitational wave emission provided the neutron star spins rapidly and exhibits temperature anisotropies.

The relevant nuclei are neutron rich and range from near stable isotopes to rare isotopes beyond the neutron drip line. Most of these nuclei have never been observed in a laboratory. The location of the neutron drip line itself is of prime interest as it defines the depth in the crust where neutrons appear. Currently the neutron drip line is only known experimentally up to oxygen. Here FRIB with its unique reach to produce the most neutron rich isotopes will have a significant impact (see section 4.2). It is possible that FRIB experiments will delineate the neutron drip line up to around $A \approx 100$ (depending on where the drip line turns out to be located) covering essentially the range needed for modeling of accreted crusts. Mass measurements of neutron rich nuclei with $A < 100$ at next generation radioactive beam facilities are needed to define the location of electron capture transitions, and charge exchange reactions and β-decay studies can constrain the weak interaction strengths, in particular the excitation energies of the lowest lying transitions that can directly affect heat deposition and cooling. Experiments with low energy beams of very neutron rich nuclei can be used to explore the dependence of fusion reaction cross sections on neutron richness.

For the foreseeable future, neutron star crust models will have to rely on a combination of experimental and theoretical data (see section 4.6). Especially modifications to masses and effects such as superfluidity, pasta phases, and neutrino emissivity will have to be calculated using nuclear theory. An important development are mass and drip line predictions by modern Density Functional Theory, which can provide estimates for theoretical uncertainties that can be taken into account in astrophysical models. Shell model calculations can provide relatively reliable electron capture and β strength, but the effective interactions need to be tested with data on neutron rich nuclei, especially in the electron capture direction. A major challenge are predictions of weak interaction strength in neutron rich nuclei that are heavier than current shell model spaces. QRPA approaches are frequently employed in astrophysical model calculations, but have been shown to be unreliable in predicting the strength in a few isolated low-lying states needed for neutron star crust models.

3.6.6 Neutron Star Thrust Area 3: The nuclear matter equation of state

The nuclear matter equation of state is a fundamental aspect of matter, yet, it is not well known. Neutron star properties depend sensitively on the equation of state of cold nuclear matter in a density range of 0.1 to 10 times the nuclear saturation density (2.7×10^{14} g/cm^3). Particularly uncertain is the density dependence of the symmetry energy - the energy difference between nuclear matter with protons and neutrons, and pure neutron matter. The symmetry energy determines a range of neutron star properties such as cooling rates, the thickness of the crust, the mass-radius relation ship, and the moment of inertia. The better we can constrain the symmetry energy in laboratory measurements and using theoretical approaches, the more we can learn from neutron star observations, and the more meaningful will the constraints be that neutron star observations impose on the remaining aspects of the nuclear matter equation of state that are not accessible in laboratories.

Laboratory measurements that can constrain compressibility and symmetry energy are studies of masses, giant resonances, dipole polarizabilities, and neutron skin thicknesses of neutron rich nuclei. Extending such measurements to more neutron rich nuclei, and increasing the precision, especially of neutron skin thickness measurements, at existing and next generation radioactive beam facilities will be important (see section 4.2). Experimental constraints on the symmetry energy at supra-saturation densities can only be achieved in laboratory-controlled experiments by colliding and compressing nuclei in central collisions. Calculations predict that comparisons of the emission and flows of different members of isospin multiplets such as $(\mathrm{K}^0, \mathrm{K}^-)$, (π^+, π^-), (p, n), and $(^3\mathrm{He}, \mathrm{t})$ in collisions between neutron-rich nuclei can allow such constraints to be extrapolated to neutron rich matter in astrophysical environments such as neutron stars and core collapse supernovae. Constraints on the isospin splitting between the neutron and proton effective masses, which is key to understanding the thermal properties of dense neutron rich matter, will be obtained at FRIB.

In general experiments do not provide direct data on the symmetry energy or the equation of state. An increased and comprehensive theory effort therefore has to accompany experimental programs to extract the relevant quantities with greater precision and to understand systematic uncertainties (see section 4.6). There are significant challenges for nuclear theory. Nuclear interactions and many-body approximations remain uncertain. Advances that combine computational methods, Density Functional Theory and Effective Field Theory ideas can prove useful if experiments can be used to validate them.

We do have available a comprehensive strong-force theory for cold matter: QCD. For example, at supra-nuclear density hyperon-nucleon and hyperon-hyperon interactions can potentially be constrained by lattice QCD. Further developments for the application of QCD to cold matter are beginning to emerge. For these developments to be “useful” will require advances both in ideas (the sign problem) and computational efforts. In the mean time, plausible guesses for the phases of dense matter and calculations of their properties with improved techniques are continuing.

3.6.7 Neutron Star Thrust Area 4: Comprehensive models of accreting neutron stars

The surface and crust of accreting neutron stars exhibit a wide range of observable phenomena of current interest. Timescales are relatively short on astronomical scales, ranging from ms oscillations over burst phenomena to crust cooling timescales of years, making these systems unique laboratories to study astrophysical explosions and the properties of dense matter. To address the open questions, progress in astronomy and nuclear physics has to go hand in hand with progress in theoretical modeling. Current models are not adequate. The puzzling transition from unstable to stable burning at relatively low accretion rates, the appearance of burst oscillations, very short burst intervals indicating incomplete burning of fuel in X-ray bursts indicate that multi-dimensional models that can follow the accretion flow, hot spots, and the spreading of the burning front during X-ray bursts are needed to understand observations even on a qualitative level. This requires low Mach number modeling codes that are currently under development (see section 4.8 and 4.7).

The problems with explaining superbursts - neither can the correct amount of carbon fuel be produced, nor can ignition depth we understood - strongly indicate that effects such as rotation, gravitational settling of heavy elements, diffusion and phase separation at the liquid to solid transition at the bottom of the surface ocean have to be taken into account. While progress has been made in identifying the nuclear reaction sequences in the crust of accreting neutron stars, the interplay between the nuclear physics and magnetic field, lattice, plasma, and superfluidity has not been included systematically.

An additional complication is the interconnectedness of the different processes that require treatment with vastly different physics. Superbursts in the ocean depend sensitively on the composition created by the shallower X-ray bursts, and the ashes of the superbursts defines the possible nuclear reactions that can occur in the crust. Similarly, heat generated in the crust affects superburst ignition, and superbursts strongly affect the behavior of normal bursts triggering normal burst precursors, and quenching normal bursts for some time after a superburst. It is therefore important to treat all surface and crust processes in accreting neutron stars self consistently in a comprehensive way.

3.6.8 Impact on other areas in nuclear astrophysics

Neutron stars play a central role in nuclear astrophysics as the engines of core collapse supernovae, and as the likely providers of neutron rich matter for the r-process. In particular the r-process in core collapse supernovae depends sensitively on neutron star properties. The role of the nuclear equation of state and neutrino interactions in supernova and neutron star mergers remains to be systematically explored. In supernovae they affect neutrino luminosity, collapse dynamics, and and the lower limit of the neutron star mass distribution constrains fall back, which is an important aspect of the explosion mechanism and supernova nucleosynthesis. With future gravitational wave observations of neutron star mergers even stronger synergistic overlaps can be exploited. The goal will be to arrive at a consistent picture of neutron stars and the nuclear physics that governs them, informed by X-ray observations, gravitational wave observations, and laboratory experiments.

There are also connections between the physics of neutron stars and condensed matter physics. An interesting question is, for example, whether condensed matter physicists could study glitches and pinning in superfluid helium with geometries appropriate to neutron stars (spheres, not cylinders). Such experiments could be extremely useful.

3.7 Big Bang Nucleosynthesis

3.7.1 Introduction for non experts

Standard Big Bang nucleosynthesis (SBBN) is one of the most successful theories in nuclear astrophysics. As the relevant nuclear reactions are relatively well known, the amount of hydrogen, helium, and lithium produced about 3 minutes into the Big Bang can be predicted with just one free parameter, the cosmic baryonic matter density. WIth this parameter now fixed from observations of directional variations in the cosmic microwave background, the electromagnetic echo of the Big Bang, SBBN becomes essentially a parameter free theory. At the same time, the amount of hydrogen, helium, and lithium produced in the Big Bang can be inferred from observations, for example from observations of relatively unmodified gas clouds at large distances, or from observations of the composition of very old stars. Comparing the observationally inferred composition with the parameter free SBBN predictions provides stringent constraints on any Beyond the Standard Model scenarios, including non standard Big Bang models, or Beyond the Standard Model particle physics such as dark matter decays and/or annihilations, non standard neutrino physics, the existence of new particles, and supersymmetry. SBBN light-element constraints on Supersymmetry are powerful and are complementary to accelerator probes, extending to parameter regimes inaccessible to the LHC. Overall the agreement between SBBN and the observed Big Bang element composition is good within observational uncertainties, with the exception of a puzzling discrepancy for lithium, the so called lithium problem.

3.7.2 Current open questions

- Does the discrepancy between predicted Big Bang lithium production and the primordial lithium abundance inferred from observations point to new physics?
- Will the combination Big Bang nucleosynthesis studies with new precision measurements of anisotropies in the cosmic microwave background and improved nuclear reaction rates reveal new particle physics?

3.7.3 Context

Since the 1999 White Paper, cosmology and particle physics have seen major progress and revealed profound surprises. Big-bang nucleosynthesis (BBN) has been cast in a new light in the era of precision cosmology: BBN has become a much sharper probe of physics beyond the Standard Model of particle physics and of cosmology. For example, measurements of the cosmic microwave background (CMB) will soon open the way to powerful and clean tests of neutrino physics using BBN. Moreover, the primordial 'lithium problem' increasingly seems to point to new physics at play in the early universe.

The simplest, 'standard' version of BBN (Standard BBN or SBBN) has only one free parameter: the cosmic baryon density $\Omega_{\rm b}h^2$, or equivalently the baryon-to-photon ratio $\eta = n_{\rm b}/n_\gamma$. SBBN produces only the lightest nuclides, and consequently requires a far smaller and thus simpler nuclear reaction network than typically found in stellar nucleosynthesis calculations; indeed, the light-element abundances are sensitive to only 11 reactions as well as the neutron lifetime. Moreover, the cross sections for these reactions are all measured in the laboratory at the relevant energies. Consequently, SBBN makes tight predictions for light element abundances, and it is feasible to do rigorous error analysis of the predictions and to express the results in terms of likelihood distribution functions.

BBN has a strong interplay with the precision determination of cosmological parameters via measurement of CMB anisotropies. Since the first WMAP data release in 2003, the CMB has provided the best cosmic "baryometer," independently of BBN. The SBBN and CMB determinations of the cosmic baryon density are in broad agreement; this rough concordance represents a great success of the basic hot big-bang model and a triumph for nuclear astrophysics. Furthermore, the CMB holds the promise (through measures of anisotropies at high multipoles) of also determining the cosmic helium abundance and the number of relativistic degrees of freedom (e.g., neutrinos). Indeed, the South Pole Telescope has presented determinations of these parameters, but with large uncertainties; with the upcoming *Planck* data release, these measurements will become competitive.

Using the precise CMB-determined cosmic baryon density, SBBN becomes a zero-parameter theory, and makes tight predictions for the light-element abundances. How do these compare with observations? High-redshift deuterium observations agree quite well, and low-redshift helium observations are also consistent. But the predicted abundance of ^{7}Li is *higher* than that observed in Galactic halo stars by a factor 3–4, or $4 - 5\sigma$. This discrepancy marks the primordial 'lithium problem.' Yet this 'problem' is in fact a success story for nuclear astrophysics: we have only become aware of this discrepancy due to the close interplay among theory, observation, and experiment.

Taken at face value, the lithium problem suggests new physics at play in the early universe, making a large perturbation to the lithium abundance but not to the abundances of deuterium or helium. Such perturbations can arise due to dark matter decays or annihilations; minimal Supersymmetry models can provide such perturbations as well. Changes in the fundamental constants can also solve the lithium problem.

3.7.4 Big Bang Thrust area 1: Improving BBN models

The precision of BBN predictions–both within and beyond the standard picture–directly depends on the nuclear inputs. While these are quite well-studied, a few important reactions remain outstanding and merit experimental study to further increase the reliability and precision of predictions to make BBN a more powerful probe for physics beyond the Standard Model. (1) The neutron lifetime remains an important component of the error budget for all light elements. (2) Some otherwise subdominant reactions could become important if their rates were enhanced due to resonances: $^7\text{Be} + d \rightarrow {}^9\text{B}^*$, $^7\text{Be} + t \rightarrow {}^{10}\text{B}^*$, and $^7\text{Be} + {}^3\text{He} \rightarrow {}^{10}\text{C}^*$. For these light species, direct calculation of nuclear structure is now possible using quantum monte carlo techniques, which can give important guidance in the reaction rates and possible resonant behaviors (see section 4.6). (3) Calculations for nonstandard BBN require accurate determinations of spallation and photodisintegration reaction cross sections and their uncertainties, spanning energies up to 1 GeV (see section 4.1). (4) For some key reactions such as d+p improved cross section measurements would further tighten SBBN particle physics constraints (see section 4.1).

As extragalactic and CMB determinations of the cosmic helium abundance improve, there is a need for improved precise calculations of the primordial ^{4}He abundance and its uncertainties; this involves numerous subtle effects that are challenging to compute accurately and completely. The effects of neutrino oscillations and their interplay with effects of nonstandard neutrino properties (e.g., CP violation, nonzero chemical potential) must similarly be characterized accurately and completely.

A systematic comparison of BBN codes and their uncertainties would be a great service to the field.

3.7.5 Big Bang Thrust area 2: Astronomical observations.

The constraints that Big Bang nucleosynthesis provides are only as good as the primordial element abundances inferred from astronomical observations.

The possibility remains that the lithium problem could reflect systematic errors in the inference of the primordial lithium abundances from observations of Milky Way metal-poor stars. Indeed, the

"Spite plateau" in lithium abundances recently has been shown to "melt down" at very low metallicity ($[\mathrm{Fe/H}] < -3$), indicating that destruction of lithium occurs in at least some of these stars. On the other hand, no lithium abundances are found above the plateau. An understanding of these trends is critical. Fortunately, an independent method has very recently been found to testing lithium observational systematics. Lithium has been detected in the interstellar medium of the Small Magellanic Cloud. The SMC measurement marks the first extragalactic lithium measurement and gives an abundance comparable to that of Milky Way stars with similar metallicity, suggesting that large depletion and/or systematic errors are not plaguing the stellar observations. Future observations of interstellar lithium in low-metallicity galaxies hold great promise of independently determining the primordial ^{7}Li abundance, and possibly separately determining the lithium isotopes and thus providing unique and robust new information on the ^{6}Li abundances.

Deuterium observations in high-redshift quasar absorption line system provide a strong probe of the cosmic baryon density and test of BBN. Unfortunately, suitable systems are rare: after nearly two decades of effort, ~ 10 systems give solid D/H abundances. Clearly there is a need for more. Furthermore, the dispersion among the observations suggests either that unknown systematics are present, or that there are real and unexpected sources of astration. Indeed, there is similarly anomalous dispersion in D/H abundances measured in the local ISM.

Helium-4 observations in extragalactic HII regions are also dominated by systematic uncertainty. Fortunately, *Planck* CMB measurements should give a competitive new measurement of primordial helium. In addition *Planck* data will reveal the cosmic baryon density, and number of relativistic degrees of freedom (expressed, e.g., as the effective number $N_{\nu,\mathrm{eff}}$ of light neutrino species), based solely on the clean determination of CMB anisotropies. BBN predicts light-element abundances as a function of the baryon density and–going beyond the standard model–of $N_{\nu,\mathrm{eff}}$. Thus the *CMB data alone* will provide a zero-parameter test of the consistency of the BBN prediction, and will thus probe new neutrino physics and/or new physics of any other "dark radiation."

3.7.6 Impact on other areas in nuclear astrophysics

The lithium problem currently hinges on the evolution of lithium in halo stars, and its spectral signature. Better theoretical and observational signatures of lithium depletion and diffusion, and therefore improved understanding of the processes in stellar interiors are critical to determine a stellar modeling contribution to the lithium problem.

3.8 Galactic Chemical Evolution

3.8.1 Introduction for non experts

One of the goals of nuclear astrophysics is to explain the relative abundances of elements and isotopes in the cosmos. Observations of the composition of the solar system or other stars provide a snapshot of the composition of the interstellar medium at the time and location the respective stellar system formed. In general, observations don't provide insights on individual nucleosynthesis events, but instead inform us about the cumulative effects of many, in the case of the solar system perhaps 100s, of nucleosynthesis events that occurred in our Galaxy at earlier times (an exception are the compositions of rare, extremely old stars that formed out of the debris of very few nucleosynthesis events). In order to confront nucleosynthesis models with observations it is therefore of critical importance to model the gradual enrichment of the galaxies through various nucleosynthesis events over time. The results do not only depend on the nuclear physics and astrophysics of the individual events that affect their contribution to the galactic inventory of nuclei, but also on how our Galaxy formed, how gas and dust are transported, and how stars form. While this greatly complicates the modeling of Galactic Chemical Evolution, it also offers a new opportunity to in the end investigate fundamental questions on star and galaxy formation through nucleosynthesis. With an explosion of observational data on the evolution of the chemical composition of the Galaxy, and with a new generation of chemical evolution model frameworks that rely on high performance computing, the field is now at the verge of a major advance.

3.8.2 Current open Questions

- **IMF:** Is the stellar initial mass function invariant over time, with metallicity, and galaxy type?
- **ISM mixing:** How effective is the mixing of the interstellar medium? In other words, how much of the observed variation in nucleosynthesis at low metallicity is due to distinct progenitor populations vs. inhomogeneous mixing? Similarly, at later times, what is the role of radial mixing in the Milky Way disk?
- **Pop III stars:** What is the initial mass function of Population III stars, and does it evolve over time? What is the typical multiplicity and distribution of rotation rates for primordial stars? Is there a truly unique nucleosynthetic signature of Population III stars, and can we infer Pop III stellar properties from low-metallicity stellar abundances?
- **Galaxy formation:** To what extent can the Milky Way be regarded as a template for galaxies of its type? How did the components of the Milky Way stellar halo form? What are the signatures of galaxies merging into the Milky Way, and what do they tell us? Is there a fundamental explanation for the differences in enrichment of the Milky Way vs., e.g., the Magellanic clouds? Can hydrodynamic GCE models reproduce the mean trends and the range of variability seen in the solar neighborhood and in star clusters?
- **Stellar populations:** What are the progenitors of the carbon-enhanced metal poor (CEMP) stars, particularly those at the lowest metallicities, and why are there more CEMP stars as one goes to lower [Fe/H]? What are Type Ia supernovae, and how do their populations evolve? How varied can supernova explosions be in their nucleosynthetic outputs? What is the site or sites of the r-process? What are the limits of chemical variability for stars hosting exoplanets?
- **Nucleosynthesis calculations:** What are the key ingredients for modeling the evolution of Population III stars, and for the most massive stars? What is the contribution of intermediate-mass (1-8 Msun) stars to the galactic/extragalactic neutron-capture elements? What are the effects of binary stars and cosmic rays on nucleosynthesis? What is responsible for the behavior of neutron-capture elements at low metallicities?
- **Cosmic Rays:** What is the impact of spallation and cosmic ray propagation on the composition of the interstellar medium.

3.8.3 Context

There have been several important observational advances. Perhaps most profoundly, the Sloan Digital Sky Survey, its follow-on programs, and high-resolution spectroscopic surveys have enabled incredible observational advances with regards to Galactic stellar populations. SDSS has enabled the discovery of two kinematically and chemically distinct components of the Milky Way stellar halo, a population of ultra-faint dwarf galaxies that have extremely low-metallicity stellar populations whose formation was truncated very early in the age of the Universe, and clear signatures of galaxies merging into the Milky Way (including stellar streams and "ringing" of the Galactic disk). Furthermore, these surveys have produced tremendous insights with regards to the early evolution of the Milky Way's progenitors: several interesting low-metallicity populations have been discovered, including carbon-enhanced metal poor stars, and other chemically peculiar stellar populations that have distinct neutron-capture signatures. Nebular spectroscopy has enabled the study of the nucleosynthesis of neutron-capture elements in both galactic and extragalactic planetary nebulae and HII regions. And, finally, low-metallicity, high-redshift Damped Lyman-Alpha systems that are metal-poor, but contain both enhanced carbon and r-process elements have been discovered. All of these observations provide crucial clues to galactic chemical evolution.

Theoretically, ever-growing computational capabilities have resulted in tremendous insights. This includes high-resolution simulations of Population III star formation demonstrating that Population III stars can form in binary or higher-multiple systems. A critical step forward has been made by using semi-analytical models that couple N-body simulations stellar evolution models, as well as full chemodynamic simulations that include both the hydrodynamical and stellar history of a galaxy and its progenitors. These models incorporate chemical evolution models with detailed yields, and enable the comparison of both kinematic and chemical behavior of stellar populations.

3.8.4 Chemical Evolution Thrust Area 1: Observations

Photometric and medium-resolution spectroscopic surveys of large numbers of stars are well underway with the prospect of dramatically increasing the number of old stars with known composition into the millions (see section 4.9.4). The most crucial need is for high resolution spectroscopic follow-ups of metal-poor field stars, dwarf galaxies (particularly ultra-faint dwarf galaxies), open clusters, and globular clusters. This will help to establish in detail the star formation history of these objects, as well as the frequencies of various nucleosynthetic phenomena (e.g., carbon-enhanced metal poor stars, r-process enhanced stars, etc.), and their orbital and binary properties. A critical (and related) theoretical advance that is required is for more careful modeling of stellar model atmospheres, particularly in 3D, to study the effect that this has on hard-to-measure elemental and isotopic abundances.

3.8.5 Chemical Evolution Thrust Area 2: Theoretical Advances

The most critical theoretical advance needed is for libraries of stellar models for GCE evolution using consistent (and possibly open-source) modeling tools and nuclear reactions, densely covering mass and metallicity space. In particular, the field needs improved nucleosynthetic yields for metal-poor and metal-free stars and for intermediate-mass (i.e., asymptotic giant branch) stars. Related to this, there is a critical need for a better understanding of mixing physics in stars and of stellar mass loss, and for an r-process nucleosynthetic models that can explain both the actinide boost phenomenon and the r-process observations in metal-poor stars. On a larger scale, there is a clear need for detailed models of the formation and star formation history of the fundamental building blocks of the Milky Way, including dwarf-like galaxies, and particularly the ultra-faint dwarf population. A related need is for the development of chemodynamical predictions for large spiral galaxies such as the Milky Way and M31, and for techniques to make detailed comparisons between such models and upcoming large astronomical surveys such as LSST, GAIA, HERMES, etc.

Modern chemical evolution studies require aggregating, analyzing, and curating massive amounts of data from observations, experiment, and simulations. The planned introduction of 100Gb internet nationwide will be critical to collaboration and to making progress in the era of Big Data (see section 4.8).

3.8.6 Chemical Evolution Thrust Area 3: Nuclear physics advances

At the heart of chemical evolution are the nuclear processes that create new elements. The advances in nuclear physics (and other areas such as supernova models or the sites of s-, r-, and p-processes) described in section 3.1 are therefore essential for progress in understanding chemical evolution. Of particular importance are key nuclear reactions, where relatively small changes in the rates affect nucleosynthesis broadly, such as the triple alpha and ^{12}C(α, γ rates.

3.8.7 Impact on other areas in nuclear astrophysics

The strong dependence of chemical evolution on galaxy formation and star formation history opens the door to probing these processes once advances in modeling, nuclear physics and observations have been achieved.

4 Experimental, Observational, and Theoretical Tools for Nuclear Astrophysics

4.1 Stable and γ-beam facilities

Stable and photon beam experiments address scientific questions of paramount importance for stellar evolution and nucleosynthesis (see section 3.1): Where are the elements produced that life depends on (carbon, nitrogen, oxygen)? Where are 50% of the elements beyond iron produced? How do stars evolve? Are there nuclear signatures to probe the core of stars, e.g., CNO neutrinos for probing the solar core metallicity? Some of the poorly known nuclear reactions impacting these issues are capture reactions (e.g., ^{3}He(α, γ)^{7}Be, ^{14}N(p,γ)^{15}O, ^{17}O+p), ^{12}C(α,γ)^{16}O, heavy-ion reactions (e.g., ^{12}C+^{12}C, ^{12}C+^{16}O, ^{16}O+^{16}O), neutron sources and neutron poisons (e.g., ^{13}C(α,n)^{16}O, ^{22}Ne+α, ^{17}O+α). These and other reactions involving stable targets (e.g. ^{14}N(p,γ)^{15}O, ^{12}C(α,γ)^{16}O, and ^{22}Ne+α) have a tremendous impact on stellar explosions, since they determine the seed abundance distribution for shockfron induced nucleosynthesis in core collapse supernovae such as the p-process and for the nucleosynthesis patterns in thermonuclear runaways, such as the αp- and rp-process. Without new dedicated and more sensitive measurements, there will be no progress on these fundamental questions in science. Future measurements of key reactions are being planned both at existing university laboratories (e.g., the NSL at the University of Notre Dame, TUNL at Duke University and the University of North Carolina, and the Edwards laboratory at Ohio University) and at proposed national facilities (e.g., the

Compact Accelerator System for Performing Astrophysical Research, CASPAR, and the future Dual Ion Accelerator for Nuclear Astrophysics, DIANA). Complementary studies using indirect methods to probe the reaction mechanisms are being performed at the accelerator laboratories of Florida State University and Texas A&M University.

4.1.1 Experimental Methods and Techniques

Direct measurements of crucial astrophysical reaction cross sections are being planned using a variety of complementary experimental techniques at stable beam facilities: (a) in normal kinematics, i.e., protons or α-particles bombarding a heavier target. In this case, high-current ion beams in excess of 100 μA are mandatory. In addition, efforts must be invested in studying solid targets that can withstand the intense ion bombardment. Beam-induced and room background must be reduced by orders of magnitude, by a combination of ultra-pure targets, passive shielding, and coincidence detection techniques. An existing example for such a facility is the Laboratory for Experimental Nuclear Astrophysics (LENA) at the Triangle Universities Nuclear Laboratory (TUNL); (b) in inverse kinematics, i.e., heavy ions bombarding a hydrogen or helium gas jet target. In this case, the heavy reaction products are detected using sophisticated recoil mass separators with very high detection efficiency. Such a facility (St. GEORGE) was completed recently at the Nuclear Science Laboratory (NSL) at the University of Notre Dame.

When direct measurements are not feasible, for example, if the signal is below current detection sensitivities, experimental methods using transfer reactions have to be employed. Some of these techniques can also be used to indirectly study reactions involving radioactive targets, provided they are close to the line of stability. These measurements, which are termed "indirect" since the experiments are performed at much higher bombarding energy compared to the energies of astrophysical interest, allow for measurements of the energy and quantum numbers of excited nuclear levels that correspond to astrophysical important resonances. An example is provided by indirect studies of the ^{25}Al(p,γ)^{26}Si reaction using stable beams, which include heavy-ion fusion γ-ray spectroscopy, charged-particle spectroscopy, and neutron time-of-flight spectroscopy via the (^{3}He,n) reaction at Ohio University's Edwards Accelerator Laboratory. In addition, the strengths of important resonant and non-resonant cross section contributions can be extracted using the Asymptotic Normalization Coefficient (ANC) method or the Trojan Horse Method (THM). In this case, the data analysis requires application of nuclear reaction models. These methods provide crucial complementary information for estimating reaction rates. However, the measurements require careful validation in order to obtain defensible reaction rate uncertainties. Such experiments are performed, for example, at the Cyclotron Institute at Texas A&M University and the John Fox Laboratory at Florida State University.

Apart from "direct" and "indirect" measurements using hadron beams, photon beams become increasingly important for nuclear astrophysics. The world's premier laboratory in terms of photon beam intensity and resolution is the High-Intensity γ-ray Source (HIγS) at the Triangle Universities Nuclear Laboratory. Measurements can be performed by directing a quasi-monoenergetic γ-ray beam on a suitable sample. The cross section for a reaction of interest can be obtained by measuring the reverse reaction and by applying the reciprocity theorem. A particularly important example is the ongoing measurement of the ^{16}O(γ,α)^{12}C reaction in order to estimate the ^{12}C(α,γ)^{16}O rate, which is crucial for the evolution of stars, at low energies. Near threshold levels that are important as sub-threshold state or resonant contributions to the reaction cross section can also be studied via nuclear resonance fluorescence, i.e., (γ,γ'), in order to measure precise compound level energies and quantum numbers.

4.1.2 Opportunities and Experimental Needs

The past decade featured the construction and commissioning of dedicated stable and photon beam facilities for nuclear astrophysics in the U.S. All of these facilities are university-operated accelerator laboratories: Duke University (mono-energetic photon beam), Ohio University (neutron time-of-flight), Texas A&M University (indirect transfer studies), University of North Carolina (normal kinematics), and University of Notre Dame (normal kinematics and inverse kinematics with recoil separator). The unique and diverse training of graduate students at university facilities cannot be overemphasized: by the time of graduation, the students have become experts in radiation detectors, high-voltage and vacuum systems, electronics, computer programming, nuclear and astrophysics. Consequently, they are highly attractive for academic, federal and corporate employers in an increasingly competitive job market.

Certainly, some important stable-beam and γ-ray-induced reactions will be measured at these facilities over the next decade. To take advantage of the full capabilities of these laboratories, future equipment upgrades are mandatory for measuring astrophysical key reactions, e.g. ^{14}N(p,γ)^{15}O, ^{12}C(α,γ)^{16}O, ^{22}Ne+α, and ^{12}C+^{12}C fusion at lower energies as so far obtained. Future equipment needs include: (a) development of higher ion beam intensities and implementation of pulsed low-energy beams; (b) next-generation γ-ray detector arrays with an increased detection efficiency; (c) construction of ultra-pure low-background neutron detectors, based on the extensive expertise of the neutrino and dark matter community; (d) increase of photon-beam intensity at HIγS.

We expect that these experiments will approach the astrophysical important energy region and, thereby, significantly improve knowledge of crucial thermonuclear reaction rates. However, stable-beam measurements at stellar energies ultimately require a dedicated underground laboratory, where the cosmic-ray muon background is reduced by orders of magnitude. The only underground accelerator facility at the moment is the Laboratory for Underground Nuclear Astrophysics (LUNA), operated for the past 20 years by a European collaboration in the Laboratori Nazionali del Gran Sasso, Italy. A particular highlight among LUNA achievements is the first measurement of a reaction, ^{3}He(^{3}He,2p)^{4}He, at energies occurring in the Sun, which greatly improved our interpretation of the ^{8}B solar neutrino flux. Nevertheless, LUNA has limitations in terms of beam intensity, ion beam type, and detection versatility for measuring the key reactions discussed above. In response to the urgent scientific need, a next-generation underground accelerator facility in the U.S., the design of a Dual Ion Accelerator for Nuclear Astrophysics (DIANA), has been developed by a conglomerate of groups (University of Notre Dame, University of North Carolina, Western Michigan University, and Lawrence Berkeley National Laboratory). DIANA is planned to be located 5000 ft below ground at the Sanford Underground Research Facility (SURF) in South Dakota and would represent a unique combination of background reduction achieved by several orders of magnitude, ion beam intensities up to 100 mA at low energies, and available ion beams ranging from protons to oxygen. A pilot facility, the Compact Accelerator System for Performing Astrophysical Research (CASPAR) is presently under construction at the SURF, to initially focus on the measurement of stellar neutron sources using intense helium beams that are not available at LUNA.

While such underground work is crucial to push the measurements as close as possible to the stellar Gamow range, in most cases the cross sections are just too small to be measurable with sufficient statistical accuracy. It is therefore crucial to understand the reaction physics and the various reaction contributions to the stellar reaction rate. It has been demonstrated that the cross section measurements need to be performed over a much wider energy range than previously thought to map all the components with sufficient accuracy. Also indirect methods such as the Trojan Horse approach or the studies of ANC provide substantial complementary information towards that goal.

We therefore emphasize the utmost importance of upgrading the university-based laboratories for: (a) pursuing complementary experiments at higher energies in order to reduce uncertainties in existing data; (b) developing new experimental techniques and radiation detectors; and (c) attracting and training the future workforce in cutting-edge nuclear technology.

In addition we propose the development of a deep high intensity underground accelerator laboratory such as DIANA to ensure a broad range study and analysis of critical reactions in stellar helium, carbon and oxygen burning, that dictate stellar evolution and provide the seed to all subsequent nucleosynthesis processes.

4.2 Radioactive beam facilities

4.2.1 Existing RIB facilities in North America

The highest nuclear physics priority of the nuclear astrophysics community is the expiditious completion of the planned FRIB facility which is scheduled to be operational by the end of the decade. Until then it is crucial to pursue an active nuclear astrophysics program at existing radioactive beam facilities which will allow us to develop and test new equipment as well as to train the young researchers that will do the experiments at the next generation radioactive beam facility. All existing RIB facilities in North America are presently involved in a vibrant experimental program and at the same time undergo important upgrades that will increase the available beam intensities or give access to new nuclei that are critical to nuclear astrophysics. These facilities are briefly summarized below.

ANL: The CARIBU project has recently been completed providing access to new nuclei on the n-rich side of the mass valley. First experiments with a 400 mCi Cf source have started measuring masses with the Canadian Penning Trap. Transfer reaction studies using the HELIOS spectrometer and measurements of β-delayed n-branching ratios will start soon. The In-Flight radioactive beam program is planning to install a dedicated separator which together with liquid production targets will increase the beam intensities of experiments with radioactive isotopes by factors of 10^2-10^3. With this upgrade (α,p) and (^{3}He,d) reactions (surrogates for (p,γ)) which are critical for novae and X-ray bursts will be measured.

FSU: The RESOLUT facility has started a new program with radioactive beams produced with the In-Flight technique. With the planned installation of additional resonators from KSU the range of radioactive beams will be extended towards heavier nuclei. An active target detector system (ANASEN) has been developed and plans for a neutron detector (ResoNeut) are being pursued. This will allow for (d,n) measurements as surrogate reactions of important (p,γ) processes.

Notre Dame: The TWINSOL facility has been one of the earliest designs to produce and separate light radioactive ions by the In-Flight technique using two superconducting solenoids. TWINSOL has been used for the study of critical reactions for understanding Big Bang nucleosynthesis and is presently focused on reactions associated with the hot CNO cycles. Besides studies in nuclear astrophysics TWINSOL has been instrumental in studying low energy fusion reactions with proton and neutron skin and halo nuclei to study the impact on low energy cross section behavior. The facility focuses on light radioactive beams because of energy limitations of the FN tandem as driver machine. Presently TWINSOL is being modified to operate also as helicital spectrometer for transfer studies using the first solenoid as collecting element and the second as helicital separator.

NSCL: Nuclear astrophysics is presently being pursued with fast, stopped and soon also with reaccelerated beams. The experiments include mass measurements, direct reaction and structure studies, weak interaction studies as well as half-live and decay experiments with astrophysically important isotopes. Of particular importance to nuclear astrophysics are radioactive beams from the ReA3 project which, together with a dedicated recoil separator (SECAR) and a gas target (JENSA), will allow us to measure the resonance parameters of some of the critical (p,γ) reactions that play a role in explosive nucleosynthesis. Initially, the lower energy limit of beams available at ReA3 will be about 300 keV/u. It is foreseen that lower beam energies will be made accessible at a later stage, for example by placing the target at a high-voltage platform. The experience obtained in these experiments will be particularly important for similar studies with this device at the future FRIB facility, as discussed below.

TAMU: The radioactive beam program, which in the past has used the In-Flight technique at the Mars recoil separator, is presently going through an upgrade. Light stable beams from the K150 cyclotron will produce secondary particles which are stopped in a gas stopper and then transported to the K500 superconducting cyclotron for acceleration. Planned experiments will investigate ground state properties and carry out decay spectroscopy of astrophysically important isotopes and will measure nuclear reactions.

TRIUMF: With the closing of the HRIBF facility ISAC is now the only operational ISOL facility in North America. In addition to the low-energy beams from ISAC-I which have been used to measure the rates for several astrophysically important reactions a new accelerator ISAC-II will provide higher energy beams. The Advanced Rare Isotope Laboratory (ARIEL) will open many new opportunities for nuclear astrophysics with neutron rich beams produced through proton or photon induced fission of actinides. These facilities cover a large range of radioactive ion beams from low to high energies and are to a large extent complementary in their capabilities. This variety is an essential feature in order to identify the optimum conditions for future nuclear astrophysics experiments at FRIB.

4.2.2 Facility for Rare Isotope Beams (FRIB)

FRIB will produce a wide variety of short-lived isotopes with sufficient intensity to unlock the fundamental nuclear physics for understanding stellar explosions and the origin of the elements. At FRIB, the number of isotope species that can be produced is roughly double of what is known at present and approximately 80% of the isotopes that are are estimated to exist (see figure **??**). These species include a very large fraction of those needed to accurately model the r-process path in the very neutron-rich regions of the table of isotopes, and all of those needed to extract detailed information on the rp-process and p-process paths in the very proton-rich regions (see figure **??**). It will be possible to demarcate the neutron drip line up to sufficiently heavy masses to model the crusts of accreting neutron stars. And it will be possible to measure the masses and determine the decay and reaction rates of most of the isotopes that play significant roles in a wide variety of astrophysical phenomena. Given the unparalleled discovery potential of FRIB, it is no surprise that expeditious construction of FRIB is the highest nuclear physics priority for the nuclear astrophysics community.

At FRIB, unstable isotopes of interest for astrophysics will be available in the form of fast, stopped and reaccelerated beams. In addition, longer-lived unstable isotopes can be harvested and used in offline experiments, either at FRIB, or at other facilities. The experimental tools to most efficiently and accurately determine the nuclear physics properties of the unstable nuclei of interest for astrophysics have been developed, or will have been developed when FRIB comes online, at a wide variety of institutions by a wide range of collaborations, as briefly summarized in the section on existing facilities.

The availability of reaccelerated beams of unstable isotopes at astrophysical energies is of critical importance for the study of the rp-process in X-ray burts, novae and supernovae, as well as explosive Silicon burning in supernovae. Direct measurement of (p,γ) and (α,γ) reaction rates will be possible using the SECAR recoil separator, in combination with the JENSA gas-jet target. The construction of these devices is of acute importance for advancing the goals of the nuclear astrophysics community. Active targets, such as the AT-TPC and ANASEN will be available for measurements of astrophysical reaction rates with charged-particle final exit channels, such as (α,p) reactions. A HELIOS-type spectrometer will also play an important role in the study of transfer and other direct reaction studies. And a variety of γ-ray spectrometers such as GRETINA (and the future full 4π array GRETA), SeGA, HAGRID, CAESAR and SuN will be used for studying reactions involving γ-ray emission.

Reaccelerated beams of slightly higher energy (up to 15 MeV/u) also play an important role for extracting nuclear physics information for astrophysical purposes, mainly by using transfer reactions, e.g. (d, n) and (d, p), that serve as surrogates for proton and neu- tron transfer studies. Information about charged-particle direct-capture reactions can be obtained by measuring asymptotic normalization coefficients with unstable beams in inverse kinematics. A recoil separator for analyzing the forward-going recoils (at $\sim$6$-$15 MeV/u) is required, in combination with charged-particle, and neutron detectors such as VANDLE and LENDA.

Longer lived harvested nuclei could be used for the determination of (n,γ) rates on unstable nuclei and provide data for branching points in the s-process by creating samples that can be irradiated at neutron beam facilities. Plans for the implementation of isotope harvesting are being developed, both for primary user experiments as well as for secondary harvesting from the primary beam dump, which enables true multi-user capability at FRIB. The availability of such long-lived isotopes for secondary experiments is critical—in neutron capture, for instance, existing neutron facilities have reached a point where measurements on many s-process branch points are possible, but samples are not available. The accurate determination of masses of neutron-rich isotopes is of critical importance for understanding the r-process. High-precision mass measurements can be performed at the LEBIT facility using stopped beams. Further developments, such as the single-ion Penning trap, will be of tremendous value to push further the limit of which neutron-rich masses can be measured.

The highest yields of the most exotic unstable isotopes at FRIB will be achieved for fast beams. Experiments utilizing fast beams will, therefore, be critical in providing nuclear structure and decay information for isotopes furthest from the valley of stability. Decay spectroscopy (β,γ,n and p) of implanted fast beams will be critical to measure half-lives and decay properties of astrophysically important nuclei. Ongoing improvements to the efficiency and accuracy of the detectors (such as the Beta Counting System, 3HeN, NERO for thermal neutrons, and MTAS and a community-supported Clover Array for γ-rays emitted by stopped isotopes) used to characterize the various decay products will be important to optimize decay experiments performed at FRIB. In-flight decay spectroscopy using knock-out, Coulomb excitation, pickup and transfer reactions provides high-precision information on the structure of unstable isotopes. This information is required to improve theoretical models used in astrophysical calculations. More central heavy-ion collision studies provide information on the equation of state of nuclear matter, which is important for understanding dense environments such as neutron stars. Charge-exchange reactions with fast beams provide the only way to effectively constrain theoretical models used for estimating weak interaction rates, which are critical for understanding core-collapse and thermonuclear supernovae. Time-of-flight mass measurements with fast beams will be used for mass regions where the life-time is too short for high-precision trap measurements. The measurement of fission excitation functions of importance for astrophysics can be performed with both fast and reaccelerated beams.

A wide variety of detection systems for particle and gamma detection for experiments with fast-beams are, or will become available for early experiments at FRIB. At present, a large fraction of such experiments are performed with the S800 spectrometer at NSCL. However, in order to reach and perform experiments with nuclei furthest from stability, many of which play important roles in astrophysical phenomena, a spectrometer with a higher bending capability (up to 8 Tm, compared to the existing 4 Tm of the S800) is required. Such a High Rigidity Spectrometer will be very important to reach the long-term objectives of the nuclear astrophysics community.

4.3 High density plasma facilities

4.3.1 Existing high density plasma facilities in North America

A critical aspect of reaction rate calculations is the impact of the plasma environment in stars. Effects like electron screening in particular affect not only the decay and production rates through electron capture processes but also charge particle cross sections, which can be significantly enhanced by the reduction in Coulomb repulsion. These effects so far have only been computed using the Debye Hückel theory, an approach that has not been tested experimentally for stellar plasma conditions. High-energy-density facilities provide unique opportunities to access dense, hot plasmas, and environments with extraordinary high neutron fluxes. The short-lived high density and temperature plasma conditions resemble conditions in the interior of stars. This opens for the first time the opportunity to directly study these effects and test the theoretical predictions that affect all reactions associated with processes in high density conditions from stars to thermonuclear explosions.

At OMEGA and NIF, inertial confinement fusion experiments have been used to observe charged particle reactions produced in plasmas at temperatures ranging between 2-20 keV and densities from 10 mg/cc to 100 g/cc.

OMEGA: Condiderable efforts have been successful in the measurement of a number of light ion, deuteron and tritium induced fusion reactions at low temperatures collecting the reaction products by an external magnetic separator device. The results can be directly compared to accelerator based data to determine the low temperature rates study the impact of plasma screening. This program is scheduled to be expanded to ^{3}He induced processes that are critical for the solar pp-chain reactions.

NIF: Besides efforts to utilize the strong neutron flux for nuclear astrophysics related studies, a major goal is also the study of light isotope fusion reactions. Because of the higher temperature and density conditions achievable (compared to OMEGA) it is planned to study screening processes through selected high cross section reactions such as ^{10}B(p,α)^{7}Be through the collection and measurement of the characteristic ^{7}Be activity.

4.4 Neutron Beam Facilities

The production of the elements beyond iron proceed primarily through neutron-capture reactions, either in explosive environments (via an r process) or in stellar atmospheres (via s-process nucleosynthesis). Further neutron-induced reactions, including (n,γ) and (n,α), are critical for modeling p-process environments as well providing needed nuclear physics underpinnings for γ-ray astronomy and solar system formation. While measurements are still needed in select cases on stable isotopes, the most critical present needs are measurements on light isotope that can act as neutron poisons and on unstable isotopes. The latter serve as potential branching points in the s-process and define the characteristic isotopic abundance features in meteoritic inclusions or produce long-lived radioactive elements observed by gamma ray observatories.

Because of the lack of a Coulomb barrier for these reactions, the energies of interest are significantly lower than for competing charged particle reactions—in fact, the energies reflect directly the thermal particle distributions. This provides additional challenges for theoretical efforts to calculate neutron-induced reaction rates. While the reactions sample regions of relatively high excitation, the details of the nuclear structure at these energies strongly impact the cross sections.

As a result, the measurements of these cross sections have focused strongly on direct reaction measurements with neutron beams. The last 15 years have seen significant changes in the experimental facilities for these measurements. The two major facilities, Forschungszentrum Karlsruhe (FZK) and the Oak Ridge Electron Linear Accelerator (ORELA), have both closed. Taken together, these two facilities represented roughly 80% of the world activity for neutron capture measurements for nuclear astrophysics. While the closing of these facilities is an obvious loss, the measurement techniques they developed and pioneered have been incorporated in the new facilities which have begun operation in the last 15 years.

4.4.1 Present Neutron Facilities

There are a number of neutron beam facilities of importance for nuclear astrophysics currently operating, where the US nuclear astrophysics community is presently being involved:

n TOF: The neutron time-of-flight facility at CERN (Switzerland) couples both C6D6 and BaF2 detector arrays at the end of a $\sim$200 m flightpath to a neutron source driven by 20 GeV proton-induced spallation on a Pb spallation target. This combination of long flight-path with intense production mechanism provides a combination of high neutron energy resolution, intense peak neutron flux, and moderate average neutron flux.

LANSCE: The Los Alamos Neutron Science Center at Los Alamos (USA) is a facility with multiple neutron flightpaths driven by 800 MeV proton-induced spallation on tungsten. The primary capability for nuclear astrophysics comes from the Detector for Neutron Capture Experiments (DANCE), an 160 element, BaF2 calorimeter located 20 m from the spallation target. DANCE was designed specifically with the goal of performing neutron capture cross- section measurements on short-lived (>100 d) isotopes. The combination of short flight-path with high-intensity neutron source offers a high neutron flux with moderate neutron energy resolution. In addition to DANCE, LANSCE offers several other neutron flightpaths for the measurement of (n, n'), (n, p), and (n, α) reactions.

GELINA The Geel Electron Linear Accelerator in Belgium offers multiple flightpaths rang- ing from 10-400 m from the spallation target. Neutrons are produced via photo-neutron production from Bremsstrahlung from the 150 MeV electron beam. Detection capabilities include C6D6 detectors, ionization detectors for neutron-induced charged particle reactions, and 6Li-glass detectors for total cross section measurements. GELINA offers modest flux, but very high energy resolution, which is needed far total cross-section measurements.

JPARC The Japan Proton Accelerator Research Complex includes a HPGe arrays and NaI(Tl) spectrometer for measurements of neutron induced reactions, however, the neutron energy resolution is limited by the quite broad($\sim$800 ns) proton spallation pulse.

In addition to existing neutron facilities, multiple new facilities are either in the planning or construction phases, all designed to push farther from stability and to more exotic astrophysical scenarios.

4.4.2 New and Proposed Neutron Beam Facilities

There are a number of new neutron beam facilities at various stages of development, and there are also upgrades planned at existing neutron beam facilities:

FRANZ: The FRANZ facility at the University of Frankfurt is under construction and is expected to be completed in 2014. It will focus on the production of intense neutron beams specifically for nuclear astrophysics with keV time-of-flight beams of $> 10^7$ n/cm2/s and activation beams of 10^{12} n/s. Detection systems will include a 4π BaF2 array.

n TOF EAR-2: This approved second experimental area located at 20 m for n TOF will provide capabilities for more intense neutron fluxes at a cost of neutron energy resolution.

SARAF: The Soreq Applied Research Accelerator Facility (Israel) will provide high intensity Maxwellian-averaged neutron fluxes for activation measurements.

LANSCE Pulse-Stacking: This is a upgrade path for the LANSCE neutron beam facilities that is still in the proposal stage with NNSA. It would offer significantly enhanced (factors of 50-1000) neutron fluxes in the 1<En <500 keV regime relative to DANCE while simultaneously improving the neutron energy resolution. It would include the construction of a new gamma-ray calorimeter for neutron capture measurements. Further, this redesigned neutron source would be ideal for (n, p) and (n, γ) measurements.

NIF: The National Ignition Facility (USA) is a plasma facility for light isotope fusion (d+d, d+t, t+t) reactions that produce as by-product intense nano-second bursts of neutrons in a 1-20 keV plasma environment. While the neutron spectrum is not not matched to a stellar energy distribution, the combination of extreme peak flux with a plasma environment offers a new method of measuring nuclear reactions. The environment is challenging and present a new set of systematic limitations. Development is underway to determine how to best exploit this new resource for nuclear astrophysics.

Taken together, the future capabilities for neutron facilities is quite bright. As an additional benefit to the nuclear astrophysics community, the operation and construction of many of these facilities has been funded by agencies that are not traditional funding sources for nuclear astrophysics.

4.5 Neutrino Facilities

To be added

4.6 Nuclear Theory

Nuclear theory plays a critical role in nuclear astrophysics (1) to predict nuclear quantities (such as nuclear properties, reaction rates, nuclear matter properties, or transport properties) (2) to calculate corrections to nuclear quantities due to the extreme astrophysical environments and (3) to extract astrophysically relevant nuclear quantities from indirect experimental approaches.

Nuclear theorists already work on a wide range of topics that are important for astrophysics. In this section we summarize the most important areas.

It is worth noting that for processes that involve largely nuclei out of reach of experiments (such as the r-process) the uncertainties in nuclear theory predictions strongly hamper constraints on astrophysical models that can be obtained from observations. Progress therefore requires a reduction in these uncertainties. A first step, significant in its own right, is accurately quantifying the uncertainty in existing calculations. In the next few years, the effort to quantify the error in nuclear theory predictions should allow us to make more meaningful statements about processes like the r-process.

4.6.1 Nuclear Theory for Neutron Stars

Neutron stars are complex objects in which nuclear physics plays a critical role. Bulk properties can be summarized by an empirical equation of state (EOS); density and isospin dependence of the energy are particularly important. Nuclear theory has reached the point, however, at which it can aim for an ab-initio calculation of nuclear-matter properties. These include neutrino propagation and transport properties, viscosity, and heat conductivity.

More basic properties that enter the EOS — the magnitude and derivative of the symmetry energy with respect to density (S and L) — still need to be nailed down. At present the only way to learn about the EOS at supranormal densities in the laboratory is through central collisions. But the extraction of S and L from collisions is still model dependent. Different transport models provide different results and so we need to understand their ingredients better. Which of them has the best numerical approximations? How do we most effectively treat the production of light bound nuclei? Personpower shortages are slowing the resolution of these problems. The shortages were clearly identified by the theory community in the users meeting in 2011.

With increasing computational power, researchers are supplementing and/or replacing phenomenological model with nuclear-matter results rooted in QCD and implemented through effective field theory (EFT). Consistent EFT implies three-body (and more) interactions, which pose a practical challenge. Most theoretical methods are now able to tackle this challenge and the inclusion of three-body interactions in nuclear matter computations is on the verge of becoming routine.

When moving from stellar evolution to phenomena in neutron stars, astrophysics simulations require transition strengths, including GT strengths and others, up to high excitation energies (10 MeV). This poses particular challenges. Unfortunately many nuclear predictions restrict themselves to low energies.

4.6.2 Nuclear Theory for Nucleosynthesis

To explore any hypothesis about a nucleosynthesis site or mechanism, one needs to know nuclear reaction rates (for neutron capture, proton capture, alpha capture and some transfer reactions) and nuclear masses as well as the astrophysical site. Nuclear theory plays an important role in this context.

The nuclear reactions rates that are presently being used still carry large uncertainties since the stellar reaction cross sections rely on the extrapolation of data taken at laboratory energies towards the stellar energy range. A reliable extrapolation requires a full understanding of the reaction mechanism and the various reaction contributions to the reaction channel of interest to be modeled in the framework of nuclear reaction theory. This requires a detailed knowledge of the structure near the particle entrance threshold and reliable modeling of the strengths of all possible reaction channels. Experimental evidence points of the large impact of single particle and cluster resonance structures to the low energy reaction cross sections in hydrogen burning and helium of carbon burning, respectively. A detailed understanding of the nuclear structure phenomena near the thresholds need to be addressed by improved shell- model or cluster model theory, complemented by improved reaction models that will improve upon traditional phenomenological approaches such as R-matrix and Hauser Feshbach theory.

Light nuclei have been a major focus of theoretical research. The field has seen a clear shift from so-called realistic or old effective forces to soft interactions derived from Effective Field Theory, which provide control on the precision of a calculation through power counting. The improvements are being felt in astrophysics. One example is the RIA-Theory road map (see `http://fribusers.org/8_THEORY/3_DOCUMENTS/Blue_Book_FINAL.pdf`) that identifies an accurate description of the ^{12}C Hoyle state as one of the most important problems in nuclear astrophysics. We are now close to seeing this problem solved. We also expect that modern methods will solve another longstanding problem: a theoretical description of the ^{16}O(α,γ) reaction. The no-core-shell model, Greens-function-Monte-Carlo and coupled-cluster methods have all made tremendous progress in the last five years. Most recently they have managed to include the one-particle continuum and, as mentioned above, three-body forces, both of which are key to correctly describing reactions. And a new method — lattice effective field theory method — promises a unified description of bound and resonant states and an accurate treatment of clustering.

For nuclear reactions in the low mass range (A=4-24) the reaction rates rely on phenomenological models such as R-matrix theory. The R-matrix approach has been substantially improved over the last decade by expanding the traditional single channel approach to a multi-channel approach which allows a much more reliable fit of the contributions in the different reaction channels feeding the critical energy range of the compound nucleus. Other improvements have been made by directly including important nuclear structure parameters such as ANC values that have been determined by indirect transfer reaction means. This approach is been systematically tested and significantly reduces the uncertainties in a broad range of proton and alpha capture reactions important for hydrogen and helium burning. Nevertheless, these techniques rely sensitively on a broad range of data for further improvement.

In medium mass nuclei (A=16-100), the large-basis shell model is the best method for predicting nuclear energies, level densities, spectroscopic factors, gamma-decay widths, Gamow-Teller strength functions, and other properties important in nucleosynthesis. Here research is focused on improving effective Hamiltonians and pushing the computational boundaries. Effective Field Theory has made its presence felt here as well, serving as a starting point for derivations of effective shell-model interactions that include three-body pieces.

In still heavier systems, density functional theory is the method of choice. The functional itself is the most critical ingredient and the recently concluded UNEDF/SciDAC project improved our functionals substantially, in particular by systematizing their uncertainties. It also began a long-term effort to derive a functional from the underlying fundamental forces without phenomenology. The resulting functionals will improve calculations of masses and beta-decays required for the r-process simulations.

One limitation of traditional nuclear DFT, which looks formally like mean-field theory, is in the kind of observables it can predict: usually bulk and/or ground-state properties. New methods that include beyond-mean-field effects explicitly promise to predict spectroscopy and strength functions — important, for example, in radiative capture and beta decay — with the same level of accuracy as the shell model. The beyond-mean-field methods are technically challenging and have seen slow progress recently as we learned important lessons (e.g. that neutron and proton channels must be treated in a unified way), but are poised to move into the mainstream in the next five years. That move will have great benefits for astrophysics as properties of excited states (e.g. half lives) in heavy nuclei become increasingly easy to compute.

Reaction theory clearly plays an important role in understanding nucleosynthesis Optical potentials are a necessary ingredient whenever the number of nucleons involved in the problem is too large for a fully ab-initio approach. The enormous progress in the last decade in many-body methods has led, finally, to microscopically derived overlap functions with the correct long distance behavior. We expect in the near future to see efforts on microscopically derived effective interactions between incoming nucleons and the heavy target. Better astrophysical reaction predictions will result.

In addition to all these developments involving structure, some researchers are focused explicitly on reaction theory. One of the most promising indirect methods for determining (n,γ) capture involves measuring (d,p) reactions instead. The idea is particularly useful for the r-process, where the important (n,γ) reactions cannot be measured directly because the nuclei are very short lived. The topical collaboration TORUS is advancing reaction theory for (d,p) with the aim of connecting the rates to those of (n,γ) reactions. This represents a challenge since high energy s-wave resonance contributions and their interference with low energy resonance states are difficult to model in a reliable way without mapping the subsequent particle and gamma decay channels.

For many astrophysical reaction rates, the statistical Hauser Feshbach model is still the only practical method for calculating compound contributions. In order to perform a reliable Hauser Feshbach calculation however, it is crucial to have sound models for nuclear level density descriptions, nuclear potential and gamma strength functions. Recent efforts exploring the impact of pygmies occurring at the low-energy tail of the gamma strength function, have shown that sub-neutron threshold enhancements can lead to globally increased radiative capture cross sections. New shell model calculations have suggested that a significant M1 strength function enhancement may be anticipated for nuclei near to magic numbers. Research into the origins and impact of the enhancement is still in the early stages, but initial results indicate that radiative capture cross sections for these nuclei could be greatly underestimated, a result that could be of particular significance for the path of the r-process. Because the Hauser Feshbach approach is so widely used, there are a number of codes in the literature dedicated to statistical model calculations, however each code has its own set of nuclear models and implementation details associated with it. Recently a systematic study comparing the results of the various codes, and identifying the main reasons for the discrepancies, has been initiated. The study has highlighted the often overlooked effects on calculations arising from code structure and model approximations. As useful as the Hauser Feshbach model is for obtaining cross sections, the method will fail, however, when the level density is low, as in the case of unstable nuclei. An alternative approach for low level densities is therefore needed, but progress has been slow due to limited activity. Work performed under an NNSA center of excellence will accelerate progress in this area.

When the r-process reaches mass $A = 200 - 250$, fission can become important. While models used in astrophysics for heavy-ion fission still are often very simple, some nuclear theorists are working to solve the fission fusion problem within modern DFT. The problem is difficult, though, and will require a concerted effort, beginning as soon a possible, to tie astrophysical fission to FRIB results when the facility comes online.

4.6.3 Nuclear Theory for Neutrinos

The nuclear physics community has played a leading role in neutrino astrophysics. We are at the point now where we can use solar neutrinos to test the assumptions of the standard solar model with great precision, and can better understand neutrino oscillations inside supernovae, where neutrino-neutrino scattering has recently been shown to induce flavor oscillations. Neutrino propagation in such environments has been identified as a topic of critical importance and a DOE topical collaboration on neutrinos and nucleosynthesis in hot and dense matter is addressing the problem. The topical collaboration has focused the research effort and speeded progress.

4.6.4 Nuclear theory needs

FRIB opens many new and exciting opportunities but it also presents great challenges for nuclear theory. In order for FRIB to realize its full scientific potential, the nuclear theory effort needs to strengthen in a structured manner and the connection of nuclear theory and astrophysics needs to become pervasive.

One problem in nuclear theory is that personwpower is subcritical, a fact that was discussed at length in the FRIB theory users meeting [1]. The key solution is to increase the number of faculty. To do that effectively, an FRIB theory institute following the RIKEN/BNL model is essential.

Another problem is communication between groups. In times where funding is competitive and the work-force is limited, it is hard to leave one's priorities within the discipline and invest in bridges with other disciplines. But doing so is essential. Many astrophysics simulations are still performed with "old" nuclear theory. Astrophysics is therefore not fully benefiting from the advances made in nuclear theory over the last decade. Close ties between the astrophysics and nuclear-theory communities would allow information to flow naturally, and having a group of researchers working on the borders between fields would be of immeasurable use. JINA has been helpful, making nuclear data easily accessible, but these data do not always include the latest advances in nuclear theory.

In this context we propose to create a nuclear theory tool box. We would like to convert recent theory developments into user-friendly software to be made available to astrophysicists. A connection with the Brookhaven database resource may be helpful.

The working groups emphasized communication between the astrophysics theory community and the nuclear theory community. The effort to bring the two communities together needs to go beyond common workshops at the INT. Some kind of larger structure that can drive, coordinate and support interactions, through common projects and shared students is important. Students at the interface would acquire a unique interdisciplinary training, of great value to the country. JINA has achieved this to some extent and in certain areas, but these efforts must be strengthened and broadened (see section 4.11).

Equally important is more communication between the nuclear structure and nuclear reaction communities. The traditional separation between these sub-areas is fading but needs to disappear completely so that reaction theories can incorporate advances from the structure side.

Nuclear theory has and will continue to contribute to the solution of astrophysical problems. Theory is advancing quickly in ways that can benefit astrophysics. FRIB brings the prospect of greater integration between nuclear theory and astrophysics, but theorists have much to do before the facility comes on line. The challenge requires a vigorous nuclear theory effort together with a strengthened connection to astrophysics theory.

4.7 Astrophysics Theory

Astrophysics theory is essential in nuclear astrophysics as it connects nuclear physics with related observables. There are a number of theoretical challenges that have been mentioned in the science section. A major thrust in the next 10 years will be multi-dimensional models of a range of astrophysical sites of interest to nuclear astrophysics: X-ray bursts, novae, fast rotating stars, core collapse supernovae, type Ia supernovae, neutron star mergers, and low metallicity stars. In many cases full 3D models of the entire evolution of the stellar object will not be possible. What will be possible is the modeling of key aspects of all these scenarios in 3D. This is important to get a handle on scenarios were 3D effects have a drastic impact on observables and nucleosynthesis. Examples include the supernova explosion mechanism, the rise time of X-ray bursts, mixing of white dwarf matter in classical novae, or hydrogen entrainment in low metallicity stars. Such 3D studies can then be used to inform and adapt 1D models that are still needed as workhorses to predict nucleosynthesis for a wide range of elements and for a wide range of stellar parameters. Another important theoretical challenge are atmosphere models of neutron stars and predictions of mass loss through stellar winds.

While it is important to develop further the broad suite of astrophysical models needed to address the open questions in nuclear astrophysics, it is equally important to carry out the work needed to make the connection between nuclear physics and astrophysics. This is essential if one wants to apply astrophysical models to nuclear astrophysics problems such as nucleosynthesis. Such connections require major efforts in implementing large nuclear reaction networks, in finding ways to overcome the computational challenges that come with a full treatment of the nuclear physics, and thorough analysis of the resulting nuclear processes, in particular related to the sensitivity of observables to nuclear physics uncertainties. In the past, it has often been difficult to carry out such interdisciplinary activities - they may not fall into traditional funding categories, or traditional areas of work in the respective subfield (and neither in nuclear physics nor in astrophysics is the full expertise for such work available). Some individual collaborations and, at a larger scale, JINA has helped to overcome this issue to some extent (see section 4.11). However, cultural differences between nuclear physics and astrophysics remain a significant hurdle that must be overcome in the future to ensure nuclear astrophysics programs at nuclear facilities and observatories are properly guided and results are used to address the open questions in the field.

4.8 Computational Astrophysics

The dramatic impact of computation on astronomy and astrophysics is manifested in many ways. Modern numerical codes are now being used to simulate and understand the evolution, explosion, and nucleosynthesis of stars, how the elements are injected into the interstellar medium, molecular clouds, and extant planetary systems, and the cosmic evolution of the abundances. They are also essential to processing astronomical spectral databases whose sizes now exceed one terabyte into abundance data that are usable by the nuclear astrophysics community. The largest codes may have in excess of a million lines and run on supercomputers that have more than 100,000 cores, generating datasets that occupy one to a hundred terabytes of storage. The most widespread codes may be driven by comunities with hundreds of users and run on desktop class machines that generate a significant fraction of the published literature. Such codes are now an indispensable part of the nuclear astrophysics enterprise. They often deploy teams – astronomers, astrophysicists, computer scientists, visualization professionals, applied mathematicians, and algorithm specialists – to create, maintain, and constantly develop them.

NSF, NASA, and DOE have made substantial investments in the advanced computing and networking ecosystem over the last few decades, from national to regional to university to individual facilities. Sustained peta-scale, and soon exa-scale, computing capabilities will be available to the nuclear astrophysics community. Such capabilities will enable cutting-edge theoretical calculations and analyses that push the nuclear astrophysics frontier. One example is 3D core-collapse simulations run to 500 s to better quantify the neutron star winds, the r-process signatures, and evolution of the proto-neutron star. Another example is routinely deploying reactions networks with 1000's of isotopes in all 2D or 3D models. Future progress in advanced computing for nuclear astrophysics will come from further parallelization, ubiquitous deployment of next-generation 100 GB/s internet connectivity in tandem with Globus Online, distributed cloud storage systems, extracting actionable knowledge from big data, and, potentially, social computing.

Similarly, Spectroscopic stellar surveys that are scheduled over the next 5-10 years, or are recently completed (SEGUE, LAMOST, APOGEE, HERMES, GAIA, a variety of LSST followups, and the proposed 10 meter spectrographic survey telescopes), as well as all-sky surveys that will provide signifcant new information on supernovae and other transient events (LSST, SkyMapper). Nuclear astrophysics will have terabytes of spectroscopic data and petabytes of photometric all-sky data that need to be analyzed and compared to simulations.

These new technological capabilities and data driven science will enable qualitatively new physical modeling in topics relevant to nuclear astrophsyics. Exploiting these new capabilities for nuclear astrophysics will require new software instruments (e.g., run-time visualization for 100TB of 1PB data sets) and sustained funding support for focused multi-institutional research collaborations.

4.8.1 Reccomendations to address needs

1) Make long-term investments in appropriately focused research collaborations and codes that can make be uniquely effective in tackling some of the most difficult problems in modern nuclear astrophysics. The collaborations would be devoted to a specific nuclear astrophysics problem or topic that is believed to be ripe for a breakthrough within five years. One example, would be deploying 2D or 3D hydrodynamic simulations of the ^{13}C pocket in low- and intermediate mass stars to produce a breakthrough in quantifying the main s-process.

2) Encourage the astro computation community to maintain common and clearly-documented data formats and standards. This will facilitate direct collaborations as well as encouraging the data to be publicly available, and will allow analysis codes to accomodate multiple data sources. For example, current challenges exist in reaction rate databases, nucleosynthetic yield data from stellar evolution calculations, and supernova simulations as input into interstellar or molecular cloud mixing calculations or large-scale chemical evolution simulations.

3) Motivate the creation of "data libraries" for simulation inputs and outputs. This maximizes the reach and impact of the simulations, since the data can be useful for more science than the authors originally intended, thus increasing the science-per-dollar (or cpu-hour) of the simulations.

4) Inspire multiple collaborations to maintain their simulation and analsyis codes as open source projects. Having open source access to a variety of codes that do the same type of simulation or analysis is a necessary part of the scientific process. This improves transparency, cross-portability, and trust in the simulation results. For example, in a few subfields of astrophysics some results from non-open-source codes are starting to be dismissed as unreliable, and this early trend may propagate to other sub-fields of astrophysics. In addition, open source instruments lowers the barrier to entry for the next-generation of researchers and can significantly increases the amount of science produced by a community (e.g., the MESA or GR1D projects).

5) Encourage the development of an open source, community driven and supported radiation transfer code. This is a critical, but missing, piece of insfrstructure that connects stellar models with the light curves and spectra obtained from observations.

6) Persuade collaborations to engage in vigorous code comparisons and verifications as a mechanism to improve the fidelity of the codes and build trust in the results. Comparison to observations requires trustworthy simulation results. For example, the puzzeling variation in the nucleosynthetic yields from AGB stars hampers galactic chemical evolution studies. This can often be traced back to assumptions

about the treatment of convection and mixing, but in some cases can be attributed to a discovered numerical instability.
7) Encourage policies that balancing capacity computing with cabability computing on the largest supercomputers. Capability computing uses all or a large fraction of the supercomouter to solve a few large problems (i.e., hero calculations). In contrast, capacity computing uses the supercomputer to solve a large number of smaller problems (e.g., surveying a parameter space). Many, but not all, members of the working group th ebalance was scewed too much towards capability computing.
8) Develop and implement an annual Summer School on numerical algorithms, parallel techniques, Big Data, and advanced computing in nuclear astrophysics.

4.8.2 Big Data

The phrase “Big Data” refers to large, diverse, complex, longitudinal, and/or distributed data sets generated from instruments, sensors, computational models, images and/or all other digital sources.

Big Data in nuclear astrophyiscs aims to advance the core scientific and technological means of managing, analyzing, visualizing, and extracting useful information from large, diverse, distributed and heterogeneous data sets so as to:

- accelerate the progress of scientific discovery and innovation in fields of broad interest to nuclear astrophysics;
- lead to new fields of inquiry via intellectual fusion of fields of interst to nuclear astrophysics that would not otherwise be possible;
- encourage the development of new data analytic tools and algorithms;
- facilitate scalable, accessible, and sustainable data infrastructure across the nuclear astrophysics community’s efforts;

Today, the federal funding agencies and private enterpise recognize that the scientific and engineering research communities are undergoing a profound transformation with the use of large-scale, diverse, and high-resolution data sets that allow for data-intensive decision-making, at a level never before imagined. New statistical and mathematical algorithms, prediction techniques, and modeling methods, as well as transdisciplinary approaches to data collection, data analysis and new technologies for sharing data and information are enabling a paradigm shift in scientific investigations. Advances in machine learning, data mining, and visualization are enabling new ways of extracting useful information in a timely fashion from massive data sets (e.g., 3D simulations and spectroscopic surveys), which complement and extend existing methods of hypothesis testing and statistical inference. As a result, a number of federal funding agencies are developing big data strategies to align with their missions.

Embracing a Big Data initiative will help to accelerate discovery and innovation in nuclear astrophysics. The pipeline of data to knowledge to action has tremendous potential for transforming all areas of scientific interest to nuclear astrophysics. This initiative will lay the foundations for engaging enterprise level Big Data infrastructure projects, workforce development, and progress in addressing the complex, transdisciplinary grand challenge problems in nuclear astrophysics. The field’s state-of-the-art research is increasingly data-intensive and adequate sustained support for a Big Data initiative is imperative if the field is to realize its research aspirations.

4.9 Astronomical Observations

Nuclear astrophysics is reflected in (and often dominating) a broad range of astronomical windows and messengers. The following lists the major wavebands of interest and some of the primary science goals, measurements and sources of interest to nuclear astrophysics:

- Electromagnetic Radiation: Specific Elemental Abundances; others
- Radio: Molecular Isotopes in ISM; Pulsar masses
- Sub-mm: Cold-gas Cooling Lines (CI etc.)
- Infrared: PAH and Dust Emission; Atomic Lines (eg. Ag)
- Optical: Metal Elemental Abundances; timing for pulsation studies
- Ultraviolet: Element Abundances (eg. Ag); Transient LCs
- X-rays: Hot-Plasma Abundances; X-ray bursts; transients; compact star structure (EOS)
- MeV Gamma-Rays: Radioactive Isotopes o GeV Gamma-Rays: Cosmic Rays Interactions (spallation)
- TeV Gamma-Rays: Cosmic Ray Accelerators
- Meteorites and Presolar Grains: Specific Isotopic Abundances & Ratio
- Asteroseismology, Stellar Interiors (Core Size; convection, rotation)
- Cosmic Rays: Specific Isotopes; ISM Spallation
- Neutrinos: ccSNe; solar Nucleosynthesis
- Gravitational Waves: Binary Source and ccSN Dynamics

Comparing nucleosynthesis source model predictions to observational data is a major challenge, often beyond the capabilities of single scientists or groups. Progress therefore depends on interactions and discussions among observers across different fields and modelers/theoreticians of different sources/processes (including chemical evolution modelers). A dedicated effort to further stimulate such cross-field interaction appears to be a most-promising first step to advance nuclear astrophysics in general (see section 4.11). We need to learn which questions can be pursued, and how. We also need to learn how to best exploit the vast observational diversity in terms of validating key astrophysical models and addressing specific nuclear astrophysics questions.

Multi-messenger studies of nuclear astrophysics sites will gain in importance in the future and require coordination among different astronomy communities, astrophysicists and nuclear physicists. An example are neutron stars where merger observations with LIGO, gamma-ray telescopes, and X-ray telescopes will have to be combined with X-ray observations of isolated and accreting neutron stars and, possibly, neutrino signals from supernovae.

A lack or loss of observational facilities may incur significant setbacks in the above prospects. The nuclear-astrophysics community should speak up as appropriate in critical cases. Primary concerns at present appear to be the potential Green Bank Telescope shutdown, which could adversely impact future NS (pulsar) mass measurements using radio pulsar timing, as well as a potential reduction in Kitt Peak National Observatory availability for optical astronomy. Also, major telescope survey programs are often driven by the science issues of dark energy, dark matter, and cosmology. This incurs the risk that the also-interesting and unsolved issues of nuclear astrophysics are not addressed adequately. In particular, in the case of expensive space programs, opportunities may be thinned-out below a minimum threshold that keeps expertise for nuclear-astrophysics observations sustained.

4.9.1 Radio Astronomy

Current instrumentation includes the eVLA, Arecibo, GBT, and LOFAR on the ground, and the Planck space mission. Capabilities in this field include, spectroscopy resolving isotopes in molecular lines, and an imaging resolution milli-arcsec.

The relevance for nuclear astrophysics lies in determinations of abundances of molecules and isotopic ratios (^{12}C/^{13}C, ^{16}O/^{17}O, etc.) in the ISM. Furthermore, radio pulsar observations can provide precise NS masses, and pulsar timing glitches can provide constraints on NS interior physics. Also, measurements of global supernova explosion energy and nova ejected masses can be made. Additionally, radio transients may be powered by nuclear processes.

The future instrumental perspectives are the SKA, MeerKAT, ASKAP, and ATA . Recent pulsar mass measurements have found heavy 2 solar mass neutron stars. Such high mass measurements are quite constraining on EOS models, and given the complimentary focus of nuclear laboratory measurements to constrain the EOS and symmetry energy, it would be a set-back to lose such a capability. Moreover, continued measurements of the double pulsar system (PSR J0737-3039) over the next 5-10 years could provide a direct measurement of the moment of inertia of pulsar A in this system.

4.9.2 Sub-mm Astronomy

Current Instruments are JCMT, CSO, SCUBA, IRAM, APEX, Mopra, and the space instruments on Herschel (single-dish instruments), and the BIMA, SMA, IRAM, CARMA, ATCA, and ALMA (Interferometers).

Relevant capabilities are in the mapping of dust emission (tracing star formation), and the spectroscopy of molecular lines , with imaging resolution few arcsec. Their relevance for nuclear astrophysics is through the provision of star formation tracers, and isotopic ratios in different molecular species also related to star formation sites. Rotation-band lines of molecules probe abundances and the gas kinematics. Moreover, mass loss around evolved objects, and the chemistry around new stars can be studied. The future instrumental perspectives are the LMT, SCUBA-2, and ALMA.

4.9.3 Infrared Astronomy

Current missions and telescopes include; Spitzer, Herschel, Sofia, IRAS, and instrumentation at the VLT. Capabilities include spectroscopy adequate for resolving PAH lines. Studies relevant to dust emission, and arcsec imaging.

The relevance for nuclear astrophysics includes abundances of PAHs, ISM chemistry. Moreover for Galactic stars photospheric abundances can be acquired in detail (due to low absorption in the IR).

The future instrumental perspectives are the space missions Euclid and NASAs JWST.

4.9.4 Optical Astronomy

Current missions and instruments are HST, and on the ground the variety of large-aperture telescopes such as the VLT, Keck, Subaru, Gemini (N and S), and the Magellan telescopes. Capabilities include spectroscopy with resolution adequate for resolving lines of elemental species, and imaging resolution of arcsec.

The relevance for nuclear astrophysics is in abundance measurements and isotopic ratios in stellar atmospheres in the Galaxy, the halo system, and nearby galaxies. Current observations are beginning to probe the abundance patterns, and in some cases, the isotopic patterns, that are thought to be produced by the very first generations of stars. Large spectroscopic surveys (SDSS/APOGEE, AEGIS, LAMOST) will be further exploited in the near future. Astrometry (and limited photometry and spectroscopy) with the Gaia mission will enable radial velocity measurements, proper motions and geometric distances for 1 billion stars, and precise luminosities for all classes of stars. Massive ground-based spectroscopic follow-up efforts to obtain radial velocities (and stellar parameters) for stars that are too faint for Gaia need to be supported vigorously. Future instrumental perspectives include the LSST, ELT, and E-ELT.

A particularly important thrust for the future are advanced capabilities in the time domain. By observing significant parts of the sky with unprecedented repetition rates new transient phenomena can be discovered and studied. This development has begun at a broad range of observatories where robotics are used to automate observations. Examples include the Las Cumbres observatory network, or the Palomar Transient Factory. Major new facility for the future of this area will be PAN-STARRS and LSST. Automated high repetition wide field observations will pose new challenges for processing, storing, and analyzing the large amounts of data generated (see section 4.8.2).

4.9.5 UV Astronomy

Past missions were IUE, and FUSE. Currently, HST provides limited UV capabilities, and the GALEX mission provides 4-5 arcsec imaging and spectral resolving power of 200 and 90 in far- and near-UV bands, respectively.

The relevance for nuclear astrophysics includes measurements of abundances of light elements, and low-abundance heavy elements (for example, Ag), as well as the measurement of nova ejecta abundances. Moreover, photometry for studying the time domain behavior of transients is important.

A concern here is limited future instrumental perspectives. The group did not identify a future space capability beyond HST, for example.

4.9.6 X-ray Astronomy

Current missions include Chandra, XMM-Newton, Swift, Suzaku, MAXI and the recently launched NuStar.

Capabilities include spectroscopy with a range of resolving powers; as high as 1000 with the Chandra and XMM gratings, resolving power < 100 with X-ray CCDs, adequate for identifying some ion species and constraining abundances. Imaging resolution ranges from < 1 arcsec with Chandra to arcmin with Suzaku and MAXI. The recently launched NuStar mission adds ^{44}Ti low-energy line imaging. Sensitive X-ray timing and broad-band spectroscopy provides essential constraints to understand the explosive phenomena such as Type-I X-ray bursts and superbursts. These capabilities also provide direct probes of the neutron star, its environs and the nuclear physics driving the explosions, as for example, by observing the thermal surface emission during X-ray bursts. Long term monitoring (as for example, with MAXI) can provide burst recurrence times as well as capture rare events such as superbursts.

The relevance for nuclear astrophysics includes abundance measurements in hot astrophysical plasmas, SNR, and WHIM abundances. In addition, X-ray light curves and spectra provide detailed probes of the NS surface and nuclear physics processes relevant to thermonuclear X-ray bursts. Such measurements can, in principle, also be used to estimate global NS structure parameters such as the mass and radius, both crucial for EOS constraints.

Future instrumental perspectives include high spectral resolution with micro-calorimeters on Astro-H (2014); wide field surveys with eRosita (2014+); very large collecting area and fast timing (excellent for X-ray burst studies) with ESA's Large Observatory For X-ray Timing (LOFT, 2020+); fast timing and wide field monitoring with India's Astrosat (2013+); precision soft X-ray timing and medium resolution spectroscopy with NASA's Neutron Star Interior Composition EexploreR (NICER) International Space Station (ISS) payload, and possibly high throughput and high resolution spectroscopy with IXO/Athena (2024+).

There is presently a substantial effort to probe the nuclear symmetry energy with laboratory nuclear experiments. These efforts are strongly complemented by astrophysical observations of neutron stars, which probe fundamental physics to higher densities. Recent measurements of 2 Msun neutron stars, and the opportunity that could be provided by missions presently in development, such as LOFT and NICER, which can enable direct NS radius measurements (that directly probe the symmetry energy), suggests a strong potential for important breakthroughs in this area within the next decade.

4.9.7 MeV Gamma-ray Astronomy

Current Missions are INTEGRAL with SPI, Fermi-GBM, and RHESSI. The Fermi-GBM provides low energy and imaging resolution but is an efficient all-sky monitor for 0.1-40 MeV. The other instruments provide high energy resolution of 3 keV, adequate for resolving isotopes, with modest imaging resolution of 3 degrees, and with sensitivities few 10^{-6} photons cm^{-2} s^{-1}, they can reach Galactic sources, and supernovae to 5 Mpc.

The relevance for nuclear astrophysics lies in direct measurements of radioactive isotopes from cosmic sources of nucleosynthesis. Surveys can find/measure new sources before their appearance otherwise (511 keV; ^{7}Be, ^{22}Na), or when they are embedded in dense clouds (supernovae, ^{44}Ti), ^{56}Ni decay is a diagnostic of supernova interiors both in type Ia supernovae and core collapse supernovae. ^{26}Al from stellar groups constrains stellar-group yields (stellar and supernova), and allows the study of ISM dynamics around those. ^{60}Fe probably originates from the same stellar groups that produce ^{26}Al, and their isotopic ratio is an important diagnostic of multi-shell-burning structures in late evolutionary stages of massive stars. Positron annihilation relates nuclear astrophysics to the properties of cosmic rays and their propagation near sources of nucleosynthesis as well as pulsars and binaries. Much can be learned from observations of solar flares on nuclear processes in the Sun's outer layers.

In terms of instrumental perspectives there are none presently identified in the major space agencies for the time after INTEGRAL (>2016), although Compton Telescope missions have been proposed, and technology & balloon projects are underway.

4.9.8 GeV Gamma-ray Astronomy

Past and current space missions include CGRO/EGRET, Agile, and Fermi.

Capabilities include spectroscopy with a resolution of 0.1 GeV, adequate for resolving nucleonic lines, and imaging with resolution of a degree.

The relevance for nuclear astrophysics is less direct than in most other fields, yet is given through the tracing of Cosmic-Rays in the Galaxy, and how this relates to nucleosynthesis sources.

Instrumental perspectives include Fermi (expected to continue for at least several years), but none identified after that in the major space agencies.

4.9.9 TeV Gamma-ray Astronomy

This is ground-based gamma-ray astronomy. Current experiments are H.E.S.S., MAGIC, and Veritas. Instrumental capabilities relevant for nuclear astrophysics lie in its imaging resolution of 10 arcsec. The relevance is less direct than in most other fields, but is given through constraints on CR accelerators in supernova remnants, and pulsar wind nebulae. Future instrumental perspectives are focused in HAWC and the CTA project (2014+).

4.9.10 Meteorites and Pre-solar Grain Studies

The Stardust mission provided samples of interplanetary particles, caught from the current medium within the solar system. Then, a rich body of meteoritic samples is available, where condensation occurred a long time ago under poorly-known conditions, but mineralogical studies help to identify origins. Of particular value are pre-solar grains identified herein, where identification is chemically through extreme resistance to acidic solvents, and observationally through extremely deviant isotopic ratios from solar-system material.

Laboratory instruments are Nano-SIMS, RIMS, Ion Microprobe. They provide capabilities of mass spectroscopy, adequate for resolving ion species., and imaging at few nm scales, i.e. down to resolving individual pre-solar grains.

The relevance for nuclear astrophysics includes measurement of abundances of specific ions in dust-producing nucleosynthesis sources; mixing in stellar atmospheres (esp. in AGB stars); solar system formation history.

Instrumental perspectives include future Nano-scale probe analysis (single grain study of isotope ratios).

4.9.11 Asteroseismology

Past and current missions and instruments include Kepler, Corot, MOST, and the Whole Earth Telescope. The primary relevant capability is to measure stellar oscillation modes with high precision. The relevance for nuclear astrophysics is in direct constraints on stellar interiors. Study of oscillations can determine the size of convection zones, explore mixing and measure differential rotation within stars. Oscillation frequencies can also depend on the nuclear reaction rates themselves.

No new missions are in advanced planning at present, but exo-planet search missions will likely provide such useful data. The Kepler mission is providing a wealth of new oscillation data on stars in its field of view. These observations have the capability to provide direct constraints on the stellar properties relevant to nucleosynthesis calculations. A deeper exploitation of these observations for nuclear astrophysics, however, will require further development of diagnostics to relate oscillation frequencies to nuclear reaction rates. This is worthy of future efforts and support.

4.9.12 Cosmic-Ray Astronomy

Direct Cosmic Ray collectors and experiments are ACE, Pamela, ATIC, AMS-II, and indirectly AUGER. Capabilities include measurement of near-earth Cosmic Ray abundances, and Cosmic-Ray composition at VHE/UHE.

Relevance for nuclear astrophysics is in measuring abundances in CRs at different energies. Future instrumental perspectives include AUGER (ground-based), Jem-EUSO (space).

4.9.13 Neutrino Astronomy

Current Experiments include IceCube, Amanda for GeV neutrinos, Borexino for MeV neutrinos, and SK-IV. Neutrino detections (time tagged) can provide direct diagnostics of core collapse Supernovae (SN) as well a probe of the solar nuclear energy generation process. Excitingly, future detection of SN neutrinos could provide a resolution of the neutrino mass hierarchy. A further goal for future studies is to directly detect the p-p chain solar neutrinos and directly measure the solar luminosity in neutrinos. This can also provide constraints on the solar core metalicity.

Future instrumental perspectives include KM3Net; Laguna, SNO+, CLEAN.

4.9.14 Gravitational-Wave Astronomy

Current experiments include Virgo, LIGO, Geo600. The goal of these ground-based experiments is the detection of gravitational radiation in the frequency band from about 50-2000 Hz. Current detectors have not yet achieved source detections, and several facilities (LIGO, VIRGO) are in the process of upgrading their sensitivities. Primary source types include SNe in the Galaxy, and compact object mergers (neutron stars with neutron stars, neutron stars with black holes, or black holes with black holes) in galaxies out to 300 Mpc. Other potential sources include periodic, rotating neutron stars (pulsars), and perhaps accreting neutron stars with significant r-mode amplitudes. Space-based observatories (such as the LISA concept) are sensitive in a lower frequency band and not as directly relevant to nuclear astrophysics questions.

The relevance for nuclear astrophysics includes the potential for direct study of binary mergers. For neutron stars the waveforms encode information about the EOS. Predictions are uncertain but 10 events per year may be seen with the upgraded detectors. Theoretical modeling of mergers has advanced substantially in recent years, and there is some indication from these simulations that such mergers may be an important site for explosive nucleosynthesis (perhaps an r-process site). Another important open question is whether or not such mergers lead to short GRBs?

For nearby (< 50 Mpc) events it may be possible to catch the tidal distortion phase of mergers, and this could provide constraints on the NS radius and EOS. Detections in many cases depend on accurate simulated waveforms so a rigorous theoretical program is important to facilitate and optimize the scientific return.

Future ground-based high frequency detector perspectives include Advanced LIGO 2015+; KAGRA Japan 2015/16+; Advanced Virgo 2015/16+; LIGO India 2020+. A global network of such 2nd generation detectors should enable localization of merger (and other) events and trigger multiwavelength follow-up observations.

4.10 Data and Codes

Nuclear astrophysics research requires rapid and efficient exchange of astronomical, nuclear experimental, and nuclear theoretical data products and codes. There are a number of challenges that are specific to nuclear astrophysics. The field therefore cannot rely on existing data compilation, evaluation, and dissemination efforts in astronomy and nuclear physics alone. These challenges include:

- Data and codes need to be exchanged across the field boundaries of astrophysics and nuclear physics. Data therefore need to be analyzed consistently, processes need to be well documented, and data, together with uncertainties, and codes need to be selected and presented in easy to use formats and interfaces, so that they can be used by researchers in other fields who are not necessarily experts.

- Nuclear data are often obtained for nuclei under terrestrial conditions. Modifications due to the extreme astrophysical temperatures and densities are often needed to make these data applicable for nuclear astrophysics.

- Astrophysical models require specific inputs that are not always directly measured or calculated, but are derived from a variety of quantities and measurements. An example is the stellar reaction rate, which needs to be determined based on individual direct and resonant components, and each of these components may have to be derived from a combination of experimental and theoretically predicted quantities. Measurements or theoretical work related to stellar reaction rates can therefore not be used in astrophysical models unless all ingredients are reevaluated and a new stellar reaction rate is derived. Deriving a stellar reaction rate can be a very elaborate process that has to be carried out by experts in nuclear astrophysics, especially if for example, R-matrix calculations are necessary to combine the various inputs.

- Nuclear data sets for astrophysical applications need to be complete. However, experimental and theoretical data are limited to what can be obtained with current techniques. For example, even basic nuclear properties for nuclei far from stability are missing from experimental data sets, and many theoretical approaches are limited to certain mass regions, to nuclei near closed shells, or, even-even nuclei. New data therefore need to be combined with other data sets that fill in the gaps, or the missing data need to be determined in other ways, such as using simplified approaches, or interpolation or extrapolation before they can be used in astrophysical calculations. This is not straight-forward and transitions from one data set to another can lead to artifacts in the output of astrophysical models.

In addition, there are challenges related to processing large amounts of data as part of nuclear astrophysics research projects (”Big Data”). These are discussed in section 4.8.2.

4.10.1 Existing Data Resources

Since the last Nuclear Astrophysics Town Meeting in 1999 there have been major advances in evaluating and making publicly available astrophysical and nuclear data for nuclear astrophysics. Major efforts that make results publicly available and address specific needs in nuclear astrophysics are summarized below:

- **Big Bang Online:** `http://bigbangonline.org` is a Cloud computing system that provides codes and data related to Big Bang nucleosynthesis.
- **Cococubed:** `http://cococubed.asu.edu/code_pages/codes.shtml` provides a set of useful fortran codes for nuclear astrophysics.
- **JINA:** `http://www.jinaweb.org` The Joint Institute for Nuclear Astrophysics (JINA) provides a frequently updated database of currently recommended stellar reaction rates (JINA reaclib), a public R-matrix code (AZURE), and a virtual journal that identifies literature with new data for nuclear astrophysics.
- **KADoNiS** `http://www.kadonis.org` provides an occasionally updated and well documented data base of evaluated s- and p-process stellar reaction rates.
- **Livermore:** `http://adg.llnl.gov/Research/RRSN/` provides a website with links to a broad range of nuclear and astrophysical data for use in astrophysical models.
- **MINBAR:** `https://burst.sci.monash.edu/wiki/index.php?n=MINBAR.Home` The Mulit-Instrument Burst Archive will provide data for more than 6000 X-ray bursts that are consistently analyzed.
- **MESA:** `http://mesa.sourceforge.net` is a modern 1D stellar evolution code that is open source, modular, takes advantage of modern computational techniques, and is well supported. It includes nuclear reaction networks.
- **NACRE:** `http://pntpm.ulb.ac.be/Nacre/nacre_d.htm` provides a set of evaluated rates for reactions with stable nuclei from 1999.
- **NETGEN and BRUSLIB:** `http://www.astro.ulb.ac.be/pmwiki/IAA/Databases` provides databases for reaction rates and tools to create tailored reaction networks.
- **NNDC** `http://www.nndc.bnl.gov/astro/` The National Nuclear Data Center (NNDC) provides stellar neutron capture rates evaluated based on the NNDC evaluated nuclear data.
- **NuGrid** `http://www.nugridstars.org` makes available a number of tools and data products for nucleosynthesis calculations, including a virtual box based nova model.
- **nucastro.org** `http://nucastro.org` provides various nuclear astrophysics data sets based on theoretical calculations with the Hauser-Feshbach approach.
- **nucastrodata.org** `http://nucastrodata.org` provides a computational infrastructure for nuclear astrophysics, including tools to evaluate and calculate reaction rates and to carry out reaction network calculations.
- **SAGA:** `http://saga.sci.hokudai.ac.jp/wiki/doku.php` provides a database for stellar abundances.
- **STARLIB:** `http://starlib.physics.unc.edu` provides stellar reaction rates derived with a novel Monte Carlo method for estimating experimentally-based reaction rates, and associated uncertainties, in a statistically meaningful manner.

- **Webnucleo:** `http://nucleo.ces.clemson.edu` provides a variety of public codes for nuclear astrophysics, including the reaction network code libnucnet. XML is used as data format, and tools are available for converting and manipulating data.

4.10.2 Future Data Developments

Continuity: Continuous support for existing database efforts in nuclear astrophysics is critical. Without long term continuity databases become quickly outdated, and new data that are often obtained using significant resources cannot be used in astrophysical calculations. Continuous support is therefore essential for rapid progress in the field, for taking advantage of nuclear and observational data, and to ensure researchers are not reaching the wrong conclusions because of the use of outdated nuclear data.

Evaluation: a community-wide effort is needed to identify and evaluate important stellar reactions. Researchers should reach out to the astrophysics modeling community to provide them with needed input as well and to the nuclear data community for their expertise in evaluations. The community must develop a set of best practices for rate evaluations, and communicate these widely together with the necessary data, tools, and codes. This must include the evaluation and proper determination of uncertainties. A series of workshops may be a good approach to achieve this goal.

Transparency: While already a number of open source nuclear astrophysics codes exist, it will be important in the future to expand the number of open source codes. Open source has many advantages, including broader use (advancing the science more rapidly) and community input and contributions on code improvements. On the other hand, concerns about return of investment for funds and efforts by individual institutions and researchers, and concerns about ongoing code support have to be addressed.

Ease of Use: Ease of use could be improved for many public nuclear astrophysics codes. Possibilities include cloud computing or virtual boxes to avoid compatibility, update, version, backup, or cyber security issues. GUIs could customized for different users. No single data format will work for all the diverse phenomena in nuclear astrophysics but robust database storage with custom graphical user interfaces are an excellent solution for many cases. The use of XML as a standardized but flexible format is being explored.

Distribution and Hubs: Multiple distribution sites are currently quite effective in satisfying diverse user needs. However, there are also drawbacks from such an approach. It would therefore be interesting to explore a unifying HUBZero based approach for nuclear astrophysics. Such an approach has been successful for other communities, for example nano technology (nanoHub.org). Such a hub could be created together with the broader nuclear physics community. The HUBZero is an open source system that enables a wide variety of codes to be put online, controlled with a standardized graphical user interface and visualized with a variety of plotting routines. The hub could also serve as a gateway to other resources for the field. Advantages of this approach include the ease of use of a wide variety of codes and the raised visibility of the various database efforts that ensures a user is choosing the best database for the project at hand.

Cloud Computing Opportunities: ”cloud computing” services may also be a transformative vision for the future of the field. This opens up many possibilities including: having a digital assistant who automatically collects relevant masses, level schemes, references; a way for experts to easily upload supplemental information for your evaluations; having all major databases just one mouse click away; having an evaluation template automatically filled out for you; running analysis and application codes without compatibility, updates, backups, or cyber security issues; designing custom views of datasets from a variety of visualization tools; having a ”virtual expert” online 24/7 to consult with questions; sharing your large data sets easily with colleagues; easily uploading your evaluation and visually tracking its progress for reviews, revisions, and acceptance; using a pipeline to process your evaluated data for use in simulations codes; running and visualizing these simulations, then sharing the results with colleagues

4.11 Centers

Nuclear astrophysics requires coherent research efforts and rapid exchange of information and results across the field boundaries of astrophysics and nuclear physics, and between theory, experiment, and observations. There are many centrifugal forces at work that prevent such coherence - including the lack of common language and common training in nuclear physics and astrophysics, growing specialization, boundaries and different priorities between funding agencies, lack of opportunities for exchange, and other cultural differences. The formation of centers that can overcome these divergent forces is therefore essential for nuclear astrophysics. In the early stages of nuclear astrophysics (mid 20th century) such centers formed around the eminent personalities of the field. However, with growing specialization, broadening of the field, the increased complexity of the questions to be addressed, and changes of funding patterns larger scale government or privately supported centers are essential in todays research environment. Such centers serve as intellectual focal points for the field, they stimulate the development of common goals, they provide resources needed to connect research efforts in various subfields, they facilitate the rapid exchange of ideas and data across field boundaries, they provide interdisciplinary education and development opportunities for young researchers in the field, and they stimulate leading edge and innovative research.

In the US the Joint Institute for Nuclear Astrophysics (JINA) serves as the main dedicated center for nuclear astrophysics. JINA has had an enormous impact on the field and brought together nuclear experimental, nuclear theory, theoretical astrophysics, observational astronomy, and computational astrophysics communities. JINA has stimulated the formation of similar centers across the world, as other countries recognized the importance of centers for nuclear astrophysics. Examples include the VISTARS, NAVI, and EMMI centers in Germany, the Munich Universe Cluster also in Germany, an initiative at the Institute for Advanced Studies in Sao Paulo Brazil, and the Shanghai Center for Nuclear Astrophysics in China. It will be important for the US community to continue its leadership in this area, especially in light of new large scale experimental (FRIB) and observational (LSST, LIGO) facilities (together with many new opportunities at smaller university laboratories) that will require interdisciplinary research networks to exploit their potential for addressing the forefront questions in nuclear astrophysics.

Other centers that occasionally offer nuclear astrophysics programs for specific topics are the Institute for Nuclear Theory in Seattle, the KITP in Santa Barbara and the Aspen Center of Physics. These centers focus on theory, and play an important role in connecting nuclear astrophysics with the broader theory community.