4. Nuclear Astrophysics

Nuclear astrophysics addresses the role of nuclear physics in our universe. It is a field at the interface of astrophysics and nuclear physics that is concerned with the impact of nuclear processes on the evolution of the universe, the development of structure, and the build-up of the chemical elements that are the building blocks of life. It is a broad discipline that can identify new observational signatures probing our universe. It studies the constituents, including dark matter and baryonic matter, and elusive particles such as weakly interacting massive particles (WIMPs) and neutrinos. Nuclear astrophysics can identify the conditions at the very core of stars and provide a record of the violent history of the universe.

Large supercomputers facilitate the development of new generations of complex tools and models for interpreting the multiple nuclear processes that drive the evolutionary progress from the early seconds of the Big Bang to the first and many generations of subsequent quiescent and explosive stellar events that led to the formation of the elements on our earth.

Nuclear astrophysics stands on the forefront of scientific developments. New initiatives include the development of experimental tools that open new vistas into the nuclear processes that take place at extremely low energies during the long evolutionary phases of stars and in explosive events, from novae to supernovae and from X-ray bursts to superbursts.

Nuclear physics plays a unique role in astrophysics. A few of the major achievements and accomplishments of the field over the last decade include the following:

- Big Bang nucleosynthesis and simple neutrino physics made the determination of the baryon content in our universe possible on the basis of observational data and cosmic microwave background anisotropy measurements.

- The observation of early stars and their distinctively different abundance patterns from today's stars provide us with important clues on the origin of the elements.

- The observation of the unique r-process patterns in very metal-poor, old stars defines a unique site; the two possible candidates are core-collapse supernovae and merging neutron stars.

- Solving the solar neutrino problem established that neutrino flavor physics is fundamental in astrophysics. This understanding verified that neutrinos are important tools for probing the interior of our sun and that they will provide new opportunities for probing other stellar events.

- A number of successful low-energy reaction experiments were completed using university accelerators and deep underground accelerators for shielding the cosmic-ray background. The results often showed startling differences between predicted and observed results.

- A deeper understanding of the physics of neutron stars was achieved through the observation and interpretation of X-ray bursts and the experimental study of high-density nuclear physics conditions using radioactive beams.

- New experimental tools and methods were developed for the measurement of nuclear masses, decay processes, and reactions far off stability, all with unprecedented accuracy.

- The use of high-performance supercomputers has revolutionized the modeling of stellar evolution, core collapse supernovae, compact object physics, neutrino astrophysics, and the emergence of structure in the universe.

The symbiotic relationship between nuclear physics and astrophysics continues to pose new questions, providing new scientific opportunities for the next decade:

- Where do the chemical elements come from, and how did they evolve?

- How does structure (e.g., stars, galaxies, galaxy clusters, and supermassive black holes) arise in the universe, and how is this related to the emergence of the elements in stars and explosive processes?

- What is the nature of matter at extreme temperatures and densities? How do neutrinos and neutrino masses affect element synthesis and structure creation in the history of the universe?

- What is dark matter, and how does it influence or is it influenced by nuclear burning and explosive stellar phenomena?

All of these questions are interrelated, sometimes tightly coupled, and nuclear physicists are making unique contributions in answering them.

THE ORIGIN OF THE ELEMENTS

The origin of the elements is one of the fundamental questions in science. The solar abundance distribution of the elements is a product of multiple nucleosynthesis events over the history of the universe. The identification of these processes and their astrophysical sites has been one of the main goals of the field (Figure 4.1).

Within the first few minutes of the Big Bang, in a rapidly expanding early universe, the primordial abundance distribution emerged, consisting of hydrogen, helium, and traces of lithium. These abundances provide a key signature for our understanding and interpretation of the early universe.

How did the universe evolve from an environment of only three elements to a world with the incredible chemical diversity of 84 elements that are the building blocks of planets and life? These elements were formed at the high density and high temperature conditions in the interior of stars. The first stars emerged a few hundred million years after the Big Bang. A lack of nuclear fuel caused their fast collapse, forming the first generations of supernovae. Recent observations detected the dust of one of the very early supernova explosions in our galaxy; a spectroscopic analysis of trace elements shows that carbon and oxygen, the elements that provide the basis for biological life many billions of years later on our earth, had been formed. Many star generations followed; as observations show, with each generation the abundance of heavy elements increases. This synthesis of the elements in the interior of stars follows a nuclear fuel cycle that is dictated by the fuel available and by the balance between the gravitational forces of the star and the interior pressure generated by the nuclear energy released. These conditions are reflected in the different burning phases that characterize the evolution of each star during the course of its life.

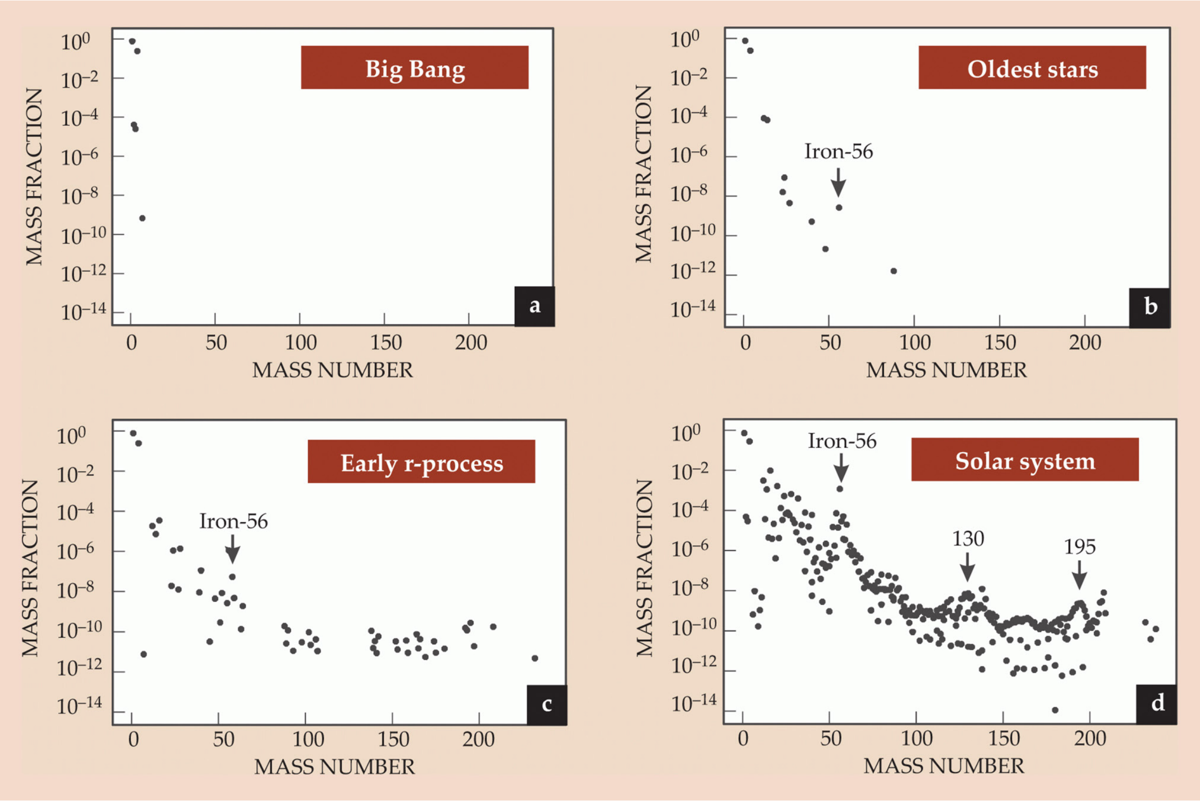


Figure 4.1: *Development of the elemental abundances from the primordial abundances of the Big Bang, the abundances observed for the earliest star generations, the appearance of r-process abundance patterns in very old stars, to the solar abundances observed today. Image credit: H. Schatz, Physics Today.*

THE LIFE OF STARS

The first phase of hydrogen burning characterizes the so-called main sequence stars. Low mass main sequence stars generate energy through the pp-chains, direct fusion reactions between hydrogen isotopes forming helium. Weak interaction processes in the reaction sequence produce neutrinos that have been observed with neutrino detectors such as Sudbury Neutrino Observatory (SNO), SuperKamiokande, and Borexino. These measurements provide a unique view into the interior of stars. For more massive stars the pp-chains are not sufficient in providing the energy necessary for stabilizing the star against collapse. In these cases, a second catalytic reaction sequence—the CNO cycles—dominates the conversion of hydrogen into helium. The CNO cycle stabilizes stars more massive than our sun, such as Sirius, Vega, and Spica to name just a few visible in the Northern Hemisphere. The reaction rates defining the CNO cycle are highly uncertain and require experimental confirmation.

When a star's hydrogen fuel diminishes, the core contracts, and the nuclear burning zone extends outwards. The star evolves into a red giant. The increase in the temperature and density of the stellar core sets the stage for the next burning cycle. Helium is the ash of hydrogen burning; it will undergo fusion to carbon through the triple-alpha-process and to oxygen through a subsequent alpha capture (Sidebar 4.1). The best known example of a red giant star is Betelgeuse in the Orion constellation. When all the helium in the core is converted to carbon and oxygen, further energy production has to come from the fusion reactions involving these heavier nuclear species. These reactions can occur only in massive stars as shown in Figure 4.2. In low mass stars the nuclear burning stops, and they contract under their own gravity into white dwarfs that are stabilized by their internal electron capture. In more massive stars, temperature and density conditions can be reached where nuclear burning of carbon, oxygen, and even heavier species can proceed. This phase is followed by neon burning, oxygen burning, and silicon burning, all proceeding toward nuclei in the iron peak (i.e., species at the peak of nuclear binding energy).

The rates of nuclear reactions that dictate the fuel consumption, and, therefore, determine the energy production and lifetime of the various stellar evolutions phases as well as those that determine the change in chemical composition, still carry large uncertainties. These reactions have extremely low cross sections. Their measurement can only be pursued in deep underground laboratories that provide shielding from cosmic radiation background. Enormous progress has been made over the last decade in developing new techniques for these studies, but many critical questions remain unanswered. **A high-intensity underground accelerator would be essential for addressing the broad range of experimental questions associated with the nucleosynthesis in stars.**

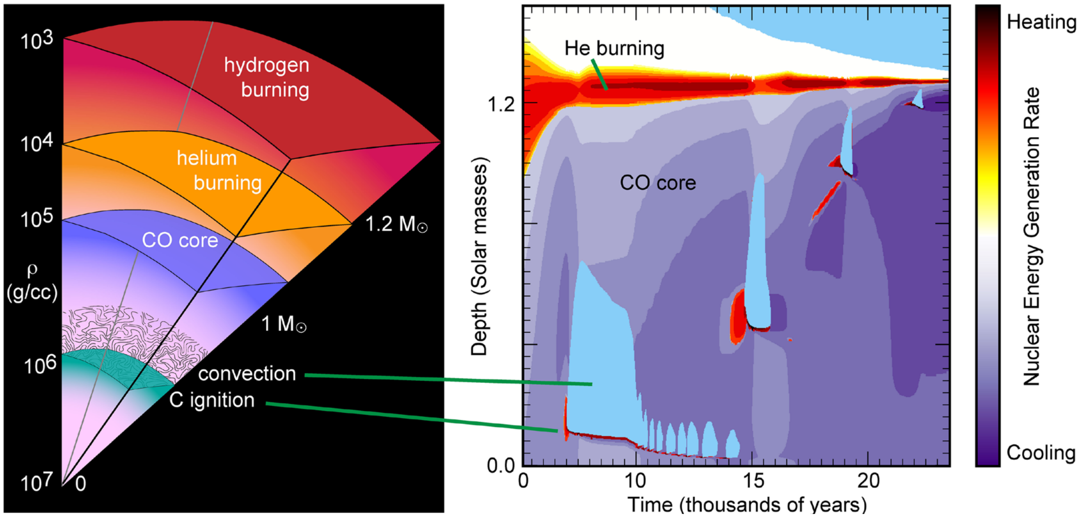
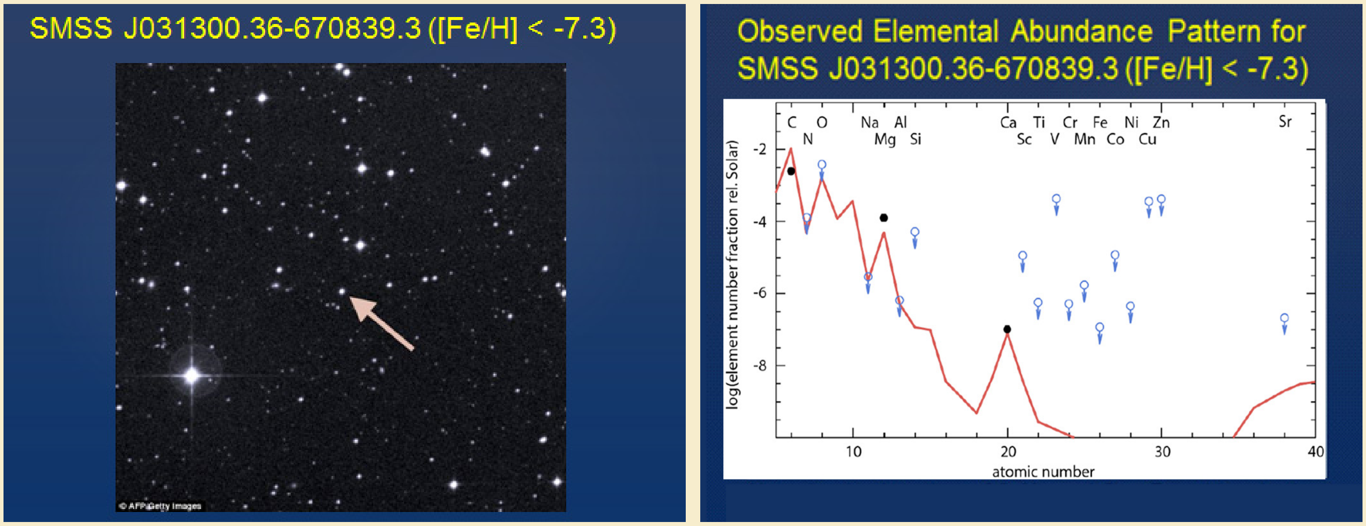


Figure 4.2: *Super asymptotic giant branch stars form the boundary between stars whose final fate is a white dwarf and stars whose final fate is a massive star supernova explosion. Left: Structure of a super asymptotic giant branch star with a carbon/oxygen burning core, surrounded by a layer of helium, which is then surrounded by a hydrogen envelope. The right-hand figure demonstrates the time evolution of several episodes of carbon burning flashes travelling towards the core at that stage. Regions in red are undergoing vigorous burning, purple are regions which are cooling, and light blue are regions of convection. Image credit: Rob Farmer, Carl Fields, Frank Timmes.*

Sidebar 4.1: The Carbon-to-Oxygen Ratio in Our Universe

A fundamental question for nuclear astrophysics is the ratio of ^{12}C to ^{16}O that emerges in the very first generations of stars. This ratio is not only important for the development of the chemical building blocks of life but also for the entire scheme and sequence of nucleosynthesis events as we imagine them now. The carbon-to-oxygen ratio determines the sequence of late stellar evolution phases for the massive stars that give rise to core collapse supernovae. It determines the ignition and burning conditions in Type Ia (thermonuclear) supernovae, and it dictates conditions for the ignition of so-called superbursts observed in accreting neutron stars. Carbon induced reactions are, therefore, of extreme importance for our entire understanding or interpretation of nucleosynthesis patterns and the identification of nucleosynthesis sites.

Present extrapolation of the reaction rates associated with the ^{12}C/^{16}O ratio from the presently existing data depends very much on the reliability of nuclear structure and reaction models, which introduce orders of magnitude uncertainty into the predictions. This problem has been well known for decades, and its solution requires new experimental efforts in a cosmic-ray-background-free (deep underground) environment to provide the necessary experimental conditions for putting to rest the question associated with low-energy carbon capture and fusion reactions.



SMSS J031300.36-670839.3 ([Fe/H] < -7.3)

Observed Elemental Abundance Pattern for SMSS J031300.36-670839.3 ([Fe/H] < -7.3)

The oldest known star (arrow in left picture), with an age of about 13.6 billion years, is located in our Milky Way at a distance of 6000 light years from the sun. Its abundance pattern (right picture) proves early stellar nucleosynthesis of light elements like carbon and oxygen. Image credit: Timothy Beers.

THE DEATH OF STARS

Another frontier in nuclear astrophysics is the study of nuclear processes that drive stellar explosions. There are two kinds of explosions, the core collapse of massive stars at the end of their lives and thermonuclear explosions as a consequence of stellar accretion. The core collapse of a massive star is caused by neutrino energy losses exceeding the energy generation rate from nuclear burning. The cores of these stars are refrigerated, their entropy is lowered, and the internal pressure support is entirely defined by relativistically degenerate electrons. According to W. A. Fowler and F. Hoyle, the cores of these stars are “trembling on the verge of instability.” The core will collapse, either through that instability or by destabilization through electron capture on heavy nuclei.

The core density will reach nuclear densities in about one second, producing a hot proto-neutron star generating a high flux of neutrinos. While the core remains as a neutron star, the neutrino flux, in total comprising about 10^{58} neutrinos, drives energy deposition in the surrounding material and produces a supernova explosion. Detection with the large detectors of today and the future of such a neutrino burst from a nearby supernova could provide critical insights into the explosion mechanism and valuable information about the properties of neutrinos. The core bounce conditions for the in-falling material in this collapse scenario depend on the equation of state, particularly on the incompressibility of neutron star matter. The bounce-initiated and neutrino-revived shockwave traverses the outer layers of the star, generating conditions that lead to multiple nucleosynthetic pathways behind the shock (see Sidebar 4.2).

Thermonuclear explosions are driven by accretion of light element fuel in binary star systems onto a compact star, either a white dwarf or neutron star whose abundance pattern is defined by its nucleosynthesis history. Such events are observed as novae and X-ray bursts, respectively. Within a few seconds the light fuel material ignites and is converted by rapid alpha and proton capture reactions to a heavy element isotope distribution. The timescale of the burst, the endpoint, and the final abundance distribution depend upon the nuclear reaction and decay rates along the reaction path. Measurements of the key reaction cross sections are crucial for interpreting the burst characteristics, but successful measurements require the high beam intensities anticipated for FRIB.

The Type Ia supernova is interpreted as a thermonuclear-energy-driven explosion. In this case, carbon/oxygen burning ignition takes place near the center of a white dwarf star. Ignition and propagation of the burning front in this explosion depend on the abundance composition of post-helium burning stars. The rates for the fusion reactions between carbon and oxygen nuclei that are important for igniting and driving the burning front are uncertain for the temperature range anticipated for such an event. The flame front propagation speed depends on additional reactions, namely alpha capture reactions that require further experimental studies.

Merging neutron stars can be considered an extreme case of accretion. Two neutron stars in a double star system spiral into each other under the influence of their gravitational potential. The merging of the two stars generates extreme density conditions, prodigious neutrino emission as in core collapse supernovae, and, likely, very high neutron flux conditions suitable for a rapid neutron capture process, or r-process, with the reaction products being dynamically ejected by tidal and pressure forces during the merger. Detecting these events and the event rate with new instruments such as the Advanced Laser Interferometer Gravitational-Wave Observatory (LIGO) will provide us with important information on the possibility of identifying these events as r-process sites (see Sidebar 4.3).

All these explosive events occur rapidly on a timescale of a few seconds. This prevents radioactive nuclei formed in the explosion from decaying within this short period. They become part of the sequence of nuclear reactions that develop far beyond the limits of nuclear stability. A study of these reactions, and of the decay and structure characteristics of the nuclei along the reaction path, provides fundamental insight into the nature of these processes, the rapid timescale of the explosion, the associated energy release, and, of course, nucleosynthesis. **FRIB will provide the beam intensities for a direct study of key reactions and key nuclei necessary for understanding the specific nature of the nuclear pathway during an explosive event and, through comparison with the emerging abundance distribution, the nature of the astronomical site and the conditions during the explosion.**

THE MATTER OF NEUTRON STARS

The physics of neutron stars is of particular interest to the nuclear physics community. Indeed, the structure and composition of neutron stars in hydrostatic equilibrium are uniquely determined by the equation of state (EOS) of neutron-rich matter, namely, the relation between the pressure and energy density. Measurements of neutron-star masses and radii place significant constraints on the EOS (Figure 4.3). Conversely, future measurement of both masses and the neutron-rich skin of exotic nuclei at FRIB will provide critical insights into the composition of the neutron star crust.

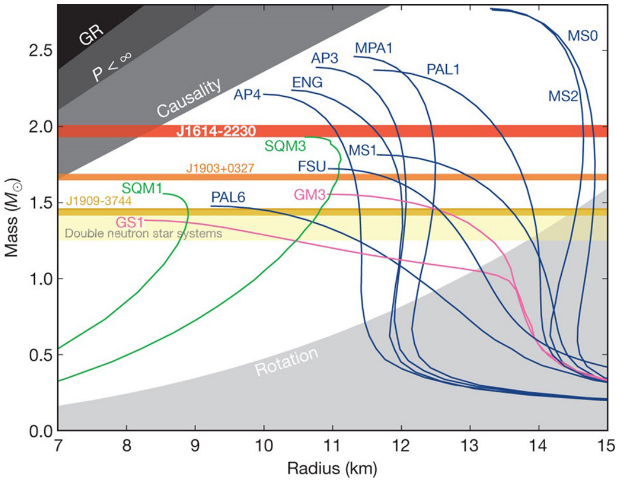
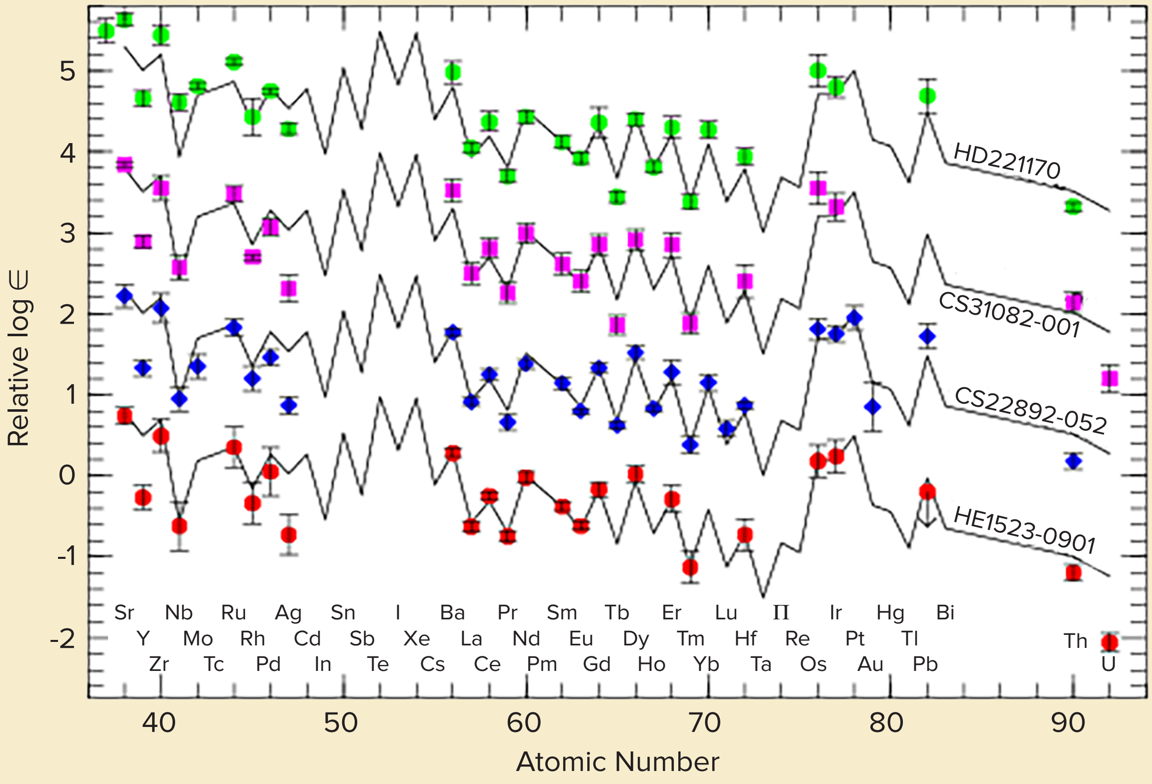


Figure 4.3: *Astrophysical measurements of masses and radii of neutron stars can provide key insights into the equation of ultra-dense neutron star matter. Image credit: P.B. Demorest et al. Nature 467, 1081 (2010).*

Sidebar 4.2: The Origin of Heavy Elements

A fundamental question for nuclear astrophysics is the origin of the neutron-rich elements heavier than iron. These heavy elements are mostly produced either by a slow neutron capture process (the s-process) that takes place during helium and carbon burning phases of stellar evolution or by a rapid neutron capture process (the r-process) that requires a much higher temperature and density environment. The latter can only be associated with violent events generating high neutron excess. The masses (binding energies) and the lifetimes of nuclei along the r-process path are the most important microscopic parameters for theoretical simulations. These inputs are currently taken from extrapolations based on theoretical models. Experiments at existing facilities on isotopes near the r-process path show us that these extrapolations are highly uncertain and may lead to faulty conclusions about the r-process conditions.

New constraints are coming from large aperture observatories such as the Hubble Telescope, the Very Large Telescope, Keck, Subaru, and Magellan observatories. Observations of early-generation stars (see figure) indicate a heavy-element abundance distribution that matches the patterns in the higher mass range, albeit not the absolute abundances of the r-process element abundance distribution in our sun. This suggests that there may be a unique site for the r-process. The nature of the actual astrophysical site of the r-process has been a matter of fierce scientific debate for many decades. Both the neutrino wind driven ejecta from a core collapse supernova and the violent collision of merging neutron stars could conceivably provide conditions for an r-process to occur—depending on many uncertain issues in nuclear and neutrino physics. Improved nuclear physics data from FRIB are crucial to make detailed predictions and to determine potential features for identifying the actual site. The r-process site is a critical issue in which observational, modeling, and experimental data are essential to reach a solution to an important and long-standing astronomical problem. The nuclear physics studies, in combination with signals from Advanced LIGO, will determine whether neutron star mergers can be a significant source of r-process elements.



Abundance pattern of heavy elements in old, metal-poor stars compared to the relative solar r-process distribution (solid lines). The absolute scales have been chosen arbitrarily for better presentation. Image credit: Anna Frebel.

The cooling behavior of neutron star transients from X-ray bursts are determined by the energy budget of the nuclear processes in the neutron star crust. Electron capture reactions, driven by the ever-increasing density conditions, drive the abundance distribution to the neutron-rich side. Such electron-capture reactions change the internal energy budget and affect the cooling behavior of matter in the neutron star crust. These electron-capture processes can be studied by means of charge-exchange reactions on neutron-rich isotopes. At extreme densities, density-driven or pycnonuclear fusion between very neutron-rich nuclei from carbon to magnesium can occur in the deeper layers of the neutron star crust. This should be associated with another release of energy that should be reflected in the thermal, neutrino, or gravitational-wave-related energy release in the neutron star transient.

For the foreseeable future, neutron star crust models will have to rely on a combination of experimental and theoretical data, especially modifications to masses and effects such as superfluidity, pasta phases, and neutrino emissivity that will have to be calculated using nuclear theory. Important developments 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 beta decay strength, but the effective interactions used need to be tested with data on neutron-rich nuclei, especially in the electron capture direction.

The nuclear matter EOS is a fundamental aspect of matter but is not well known. Neutron star properties depend sensitively on the EOS of cold nuclear matter in a density range of the nuclear saturation density. 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 relationship, and the moment of inertia. The characterization of symmetry energy through experiment is, therefore, a crucial step towards our capability of interpreting neutron star matter and its characteristics.

Laboratory measurements are necessary to constrain nuclear matter compressibility and the symmetry energy. Likewise, studies of masses, giant resonances, dipole polarizabilities, and neutron skin thicknesses of neutron-rich nuclei will provide key insights for astrophysics. **Extending such measurements to more neutron-rich nuclei and increasing the precision, especially of neutron skin thickness measurements, will be an important component of FRIB studies.**

CONNECTIONS: DARK MATTER, QCD PHASE DIAGRAM, WEAK INTERACTIONS, AND NEUTRINOS

Nuclear structure and nuclear response issues can be important in efforts aimed at direct and indirect detection of dark matter. Laboratory direct detection schemes rely on detecting the energy deposition caused by dark matter WIMPs scattering via the neutral current weak interaction on silicon or germanium atoms or on argon or xenon atoms in liquid noble gas experiments as summarized in Chapter 5, Fundamental Symmetries and Neutrinos. Nuclear response calculations indicate that there may be significant differences in expected scattering cross sections and interaction rates, depending on the target nuclei involved, especially in the spin-dependent channels. This effort is being complemented by low-energy studies at nuclear accelerator facilities using neutron beams or other probes to test the predicted detector responses and achieve a better sensitivity for the signal analysis. These nuclear physics aspects will need to be addressed before any signals from the direct detection experiments can be reconciled with astrophysical models for the local dark matter composition and distribution.

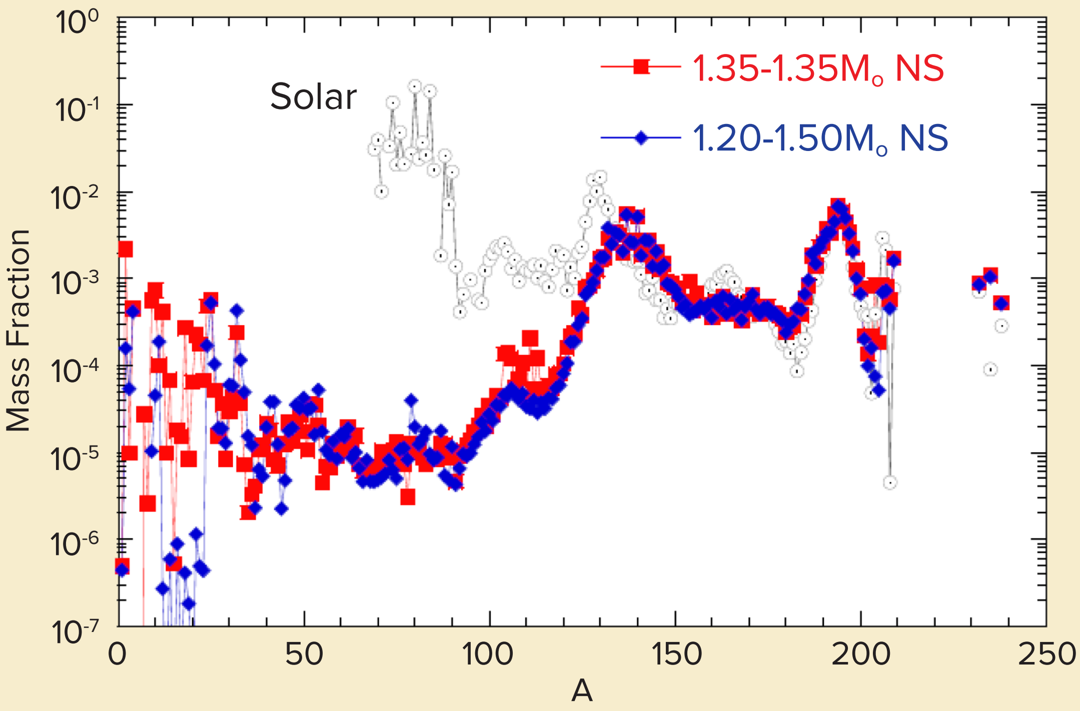
Likewise, indirect detection of WIMP annihilation from gamma-ray fluxes in the galactic center and in the galaxy's bulge and dark matter halo is complicated by cosmic-ray-generated background. Gamma-ray emission from millisecond pulsars (neutron stars) matches closely the spectrum expected from WIMP annihilation. Millisecond pulsars are old as they are the endpoints of the evolution of neutron stars. Understanding this source of background for indirect detection of dark matter, therefore, couples into many of the issues of neutron star production, space motion, and associated galactic chemical evolution described above.

Astrophysical observations can probe environments with extreme conditions of temperature and density. These conditions are sometimes difficult or even impossible

Sidebar 4.3: Advanced LIGO and Nuclear Physics

The detection of gravitational radiation from the violent merging of neutron stars in binary systems could have profound implications for nuclear astrophysics. We expect such mergers to be rare events in a galaxy like ours, perhaps happening once per 10 thousand to 1 million years. Fortuitously, the Advanced Laser Interferometer Gravitational-Wave Observatory (Advanced LIGO) will very soon be able to detect gravitational waves from these events out to a distance of 200 megaparsecs, a volume encompassing some millions of galaxies. In fact, the first observable from this observatory will be the *rate* of neutron star mergers, a key parameter in differentiating between sites proposed for the origin of the heaviest nuclei, like uranium. We have known for more than 50 years that roughly half the nuclei with mass numbers greater than 100 originate in the r-process. It is a vexing problem that we know the r-process happens, but we do not know *where* it happens. Proposed production sites have centered on astrophysical environments either having abundant free neutrons or where neutrino or nuclear reactions can *mine* neutrons from lighter nuclei. Core collapse supernovae, which happen about once per century in our galaxy, and the much less frequent neutron star mergers are the leading candidate sites. Whatever site or sites contribute, 10 thousand solar masses of r-process nuclei must be synthesized in our galaxy in 10 billion years. That datum, combined with an Advanced LIGO-inferred observed merger rate, could tell us whether mergers are a significant r-process source. If the r-process nuclei originate in neutron star mergers, the observed local rate of these events, combined with abundance observations at high redshift from the next generation of ground-based telescopes, may suggest a higher rate of compact object mergers in the past.

The gravitational waves that Advanced LIGO will observe come from violent motions of matter at nuclear density. As a result, the details of the observed neutron star in-spiral gravitational-wave signal may provide insights into the nature and behavior of ultradense neutron matter and the general conditions in the merger environment. In both mergers and core collapse supernovae, weak interactions, neutrino flavor physics, and neutrino-nucleus processes are key ingredients in understanding r-process nucleosynthesis. Knowing more about the merger environment can help guide this research.



Nuclear abundance distributions as a function of atomic mass of the ejecta for two different combinations of neutron star mergers. The distributions are normalized to the solar r-process abundance distribution. Image credit: Stephane Goriely.

to reproduce in a terrestrial laboratory. Therefore, astrophysical studies of the properties of nuclear matter may be uniquely complementary to laboratory probes at JLab, RHIC, and FRIB. On the other hand, for example, our understanding of the early quark-gluon phase of the universe and in the core of neutron stars may profit substantially from relativistic heavy-ion experiments at RHIC, probing the phase diagram for strongly interacting matter.

The QCD transition in the early universe, where chiral symmetry is broken and quarks and gluons are annihilated/incorporated into color singlets, is predicted by LQCD calculations to be a crossover transition and to occur when the universe is tenths of microseconds old. At this point, the causal horizon scale (sometimes referred to as the “size of the universe”) is about 20 km and contains a total mass-energy of ~1 solar mass, all made up of relativistic particles, mesons, and nucleon-antinucleon pairs which are all touching and overlapping. A causal horizon volume at this epoch is in essence an ultra-high entropy neutron star.

The significant change in the numbers of relativistic degrees of freedom at this epoch (roughly a factor of three) has important implications for the histories of fluctuations and potential beyond-Standard-Model particle relic densities.

As described above, weak interaction processes involving nuclei are at the heart of core collapse supernova and neutron star merger physics. Neutrinos produced in these environments more than make up for the *weakness* of the weak interaction with their huge numbers. In fact, neutrinos can carry and transport the bulk of the energy and entropy (disorder) in these environments. In turn, this makes unknown weak interaction physics in the nuclear physics realm and in the neutrino sector potentially important players. For example, collective neutrino flavor oscillations may take place in these environments, and this phenomenon is sensitive to the neutrino mass hierarchy.

There are aspects of nuclear structure physics at extreme temperatures and densities that impact the role of weak interactions in astrophysical environments. For example, the heavy, neutron-rich nuclei, which are the principal targets for electron capture in the pre-collapse and collapsing core of a supernova, reside in very highly excited states. Weak interaction strength functions in these exotic nuclear species and the associated high temperature nuclear partition functions remain key unknowns in our models for core collapse supernova explosions and associated nucleosynthesis. **Charge exchange reactions performed at FRIB can be an important guide to theorists tackling these issues.**