Nuclear Astrophysics

“The aim of nuclear astrophysics is to understand those nuclear reactions that shape much of the nature of the visible universe. Nuclear fusion is the engine of stars; it produces the energy that stabilizes them against gravitational collapse and makes them shine. Spectacular stellar explosions such as novae, X-ray bursts, and type Ia supernovae are powered by nuclear reactions. While the main energy source of core collapse supernovae and long gamma-ray bursts is gravity, nuclear physics triggers the explosion. Neutron stars are giant nuclei in space, and short gamma-ray bursts are likely created when such gigantic nuclei collide. And last but not least, the planets of the solar system, their moons, asteroids, and life on Earth—all owe their existence to the heavy nuclei produced by nuclear reactions throughout the history of our galaxy and dispersed by stellar winds and explosions.”

• How did the elements come into existence?
• What makes stars explode as supernovae, novae, or X-ray bursts?
• What is the nature of neutron stars?
• What can neutrinos tell us about stars?
deficit of solar neutrinos combined with the results of advanced neutrino detectors led scientists to the discovery that neutrinos have mass (as discussed in more detail late in this chapter under “Fundamental Symmetries”) and confirmed the accuracy of solar models. Laboratory precision measurements also revealed that the nuclear reactions that burn hydrogen in massive stars via the carbon-nitrogen-oxygen (CNO) cycle proceed much more slowly than had been anticipated, changing the predictions for the lifetimes of stars. A few key isotopes in the reaction sequence of the rapid neutron capture process (r-process) responsible for the origin of heavy elements in nature have now been produced by rare isotope facilities. Advanced experimental techniques also enabled measurements of the nuclear properties that characterize their role in the r-process, despite short lifetimes and small production quantities. The same sensitive techniques enabled precision mass and decay measurements of the majority of the extremely neutron-deficient rare isotopes.

**Figure 2.11** Schematic outline of the nuclear reactions sequences that generate energy and create new elements in stars and stellar explosions. Stable nuclei are marked as black squares, nuclei that have been observed in the laboratory as light gray squares. The horizontal and vertical lines mark the magic numbers for protons and neutrons, respectively. A very wide range of stable, neutron-deficient, and neutron-rich nuclei are created in nature. Many nuclear processes involve unstable nuclei, often beyond the current experimental limits. SOURCE: Adapted from a figure by Frank Timmes, Arizona State University.
The Eve of Chemical Evolution: How Did the First Stars Burn?

How were the first heavy elements created by the potentially extremely massive stars formed after the big bang? The pattern of the elements ejected in their deaths might still be observable today in the most iron-poor stars of the galaxy, survivors of an early second generation of stars. Candidate stars with iron content a few 100,000 times lower than that of the sun have been found (see Figure 2.13). Comparing the signatures of these elements with predictions from theoretical models of first stars requires a quantitative knowledge of the nuclear reaction sequences generating these elements. This opens up an observational window into the properties of first stars that is complementary to the planned, very difficult direct observations with future infrared telescopes. The reward might be not only a deeper understanding of the beginnings of chemical evolution in our galaxy but also clues about the nature of the early universe and the formation of structure in the cosmos.

FIGURE 2.12 The ongoing cycle of the creation of the elements in the cosmos. Stars form out of interstellar gas and dust and evolve only to eject freshly synthesized elements into space at the end of their lives. The ejected elements enrich the interstellar medium to begin the cycle anew in a continuous process of chemical enrichment and compositional evolution. SOURCES: (Background image) NASA, ESA, and the Hubble Heritage Team (AURA/STScI); (red giant) A. Dupree (Harvard-Smithsonian Center for Astrophysics), R. Gilliland (STScI), Hubble Space Telescope (HST), NASA; (x-ray) NASA, Swift, and S. Immler (NASA Goddard Space Flight Center); (planetary nebula) NASA, Jet Propulsion Laboratory (JPL)-California Institute of Technology (Caltech), Kate Su (Steward Observatory, University of Arizona) et al.; (thermonuclear supernova) NASA/Chandra X-ray Center (CXC)/North Carolina State University/S. Reynolds et al.; (nova) NASA, ESA, HST, F. Paresce, R. Jedrzejewski (STScI).
The fusion probability of helium-3 (3He) and helium-4 (4He), an important reaction in stars affecting neutrino production in the sun, measured directly at various laboratories. The challenge is to measure the extremely small fusion rates at the low relative energies that the particles have inside stars. The reduced background in underground accelerator laboratories (LUNA data shown above in green) compared to aboveground laboratories (all other data) enables the measurement of fusion rates that are smaller by a factor of approximately 1,000. This reduces the error when extrapolating the fusion rate to the still lower stellar energies. SOURCE: Courtesy of Richard Cyburt, Michigan State University.
slow neutron capture process (s-process) in red giant stars is thought to produce about half of these elements, ending with the production of lead and bismuth. The other half, including the heaviest elements found on Earth, such as uranium and thorium, require an astrophysical environment with an extraordinary density of neutrons. While such an environment has not been identified with certainty, theory predicts that under such conditions, captures of neutrons are very fast, enabling the synthesis of heavy elements beyond bismuth. During the brief duration of this rapid neutron capture process (r-process), exotic short-lived nuclei with extreme excesses of neutrons come into existence as part of the ensuing chain of nuclear reactions. Most of these exotic nuclei have never been made in the laboratory. This will change with the advent of next-generation rare isotope beam facilities like FRIB, which will allow experimental nuclear physicists to produce such nuclei and to determine their properties. The goal is to finally understand how and where nature produces precious metals like gold and platinum and heavy elements like thorium and uranium. Physics questions concerning the neutron-induced processes that constitute the r-process are closely related to neutron-driven applications such as nuclear reactors.

FIGURE 2.15 Very neutron-rich r-process nuclei observed in a rare isotope laboratory. Each dot represents an isotope that has arrived at the experiment, and the dot’s location on the map identifies mass number and element. The production and identification of the r-process waiting point nucleus nickel-78 was a challenge, though a sufficient number of isotopes were identified to determine a first measurement of its half-life. Because most r-process isotopes are out of reach of current rare isotope facilities, their study must await a new generation of accelerators such as FRIB. SOURCE: P.T. Hosmer, H. Schatz, A. Aprahamian, et al. 2005. Half-life of the doubly magic r-process nucleus $^{78}\text{Ni}$, Physical Review Letters 94: 112501 Figure 1. Copyright 2005, American Physics Society.
observed during these flares are interpreted as starquakes. Much as earthquakes are being used to probe the composition of the crust of the Earth, attempts have been made to use these starquakes to probe neutron star crusts. Similarly, pulsar glitches—sudden changes in the rotation of the neutron star crust, which can be detected with radio telescopes that observe the radio beam emitted by the rapidly spinning neutron star—provide insights into the structure of the crust and evidence for the superfluidity of neutrons. Together these studies have opened up the field of neutron star seismology.

Another example of an external influence is a neutron star that collects a steady flow of gas from an orbiting companion star. This process, together with the various types of thermonuclear bursts that occur in the accumulated gas layer, heats the crust over years or decades. Occasionally this flow of matter gets disrupted. In some cases, modern X-ray observatories have then been able to observe the cooling of the freshly heated crust over many years. Since over time the released heat comes from deeper and deeper layers, the cooling rate contains information about

FIGURE 2.19 (Left) The neutron star KS1731-260, a giant nucleus in space, observed with the Chandra X-ray Observatory. The observed brightness is heat emitted by the crust, which is a surface layer made of rare isotopes that has been heated by nuclear reactions in an earlier phase of rapid accretion. Accretion stopped in February 2001, and the cooling of the crust has been observed repeatedly since then. (Right) Schematic view of a neutron star. The thin crust is mostly made of neutron-rich rare isotopes, while the interior consists chiefly of neutrons with small admixtures of protons, electrons, muons, hyperons, and other particles. At the extreme densities in the core, other forms of nuclear matter, such as a quark gluon plasma, might exist. SOURCES: (left) NASA/CXC/Wijnands et al.; (right) NASA/GSFC.