feature article

Rare isotopes in the cosmos

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Such stellar processes as heavy-element formation and x-ray bursts are governed by unstable nuclear isotopes that challenge theorists and experimentalists alike.

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Radioactive nuclei with extreme neutron-to-proton ratios—rare isotopes—often decay within fractions of a second. Typically, they are not found on Earth unless produced at an accelerator. Yet nature produces copious amounts of them in supernovae and other stellar explosions in which the rare isotopes, despite their fleeting existence and small scale, imprint their properties. Large amounts of them also exist as stable layers in the crusts of neutron stars.

Rare isotopes are therefore intimately linked to fundamental questions in astrophysics. An example is the origin of the 50-odd naturally occurring elements between the iron region and uranium in the periodic table. As figure 1 shows, with recent progress in stellar spectroscopy and the continuing discovery of very old and chemically primitive stars, a "fossil record" of chemical evolution is now emerging. Nuclear science needs to make its own progress to match specific events to the observed elemental abundance patterns produced in stellar explosions. That has turned out to be a tremendous challenge. Nuclear theory is still far from being able to predict the properties of rare isotopes. On the contrary, the limited experimental data obtained so far have produced many surprises that have forced theorists to adjust or to rethink nuclear theory (see the article by David Dean, PHYSICS TODAY, November 2007, page 48). In some cases, such as certain nuclear masses or the excitation energies of resonant states in nuclear reactions, theory is not likely in the foreseeable future to reach the precision needed for reliable astrophysical models.

If scientists are to make further inroads, they must produce and study in the laboratory the rare isotopes that exist in astrophysical environments. That task, too, has proved to be enormously difficult. To date, the vast majority of the astrophysically important rare isotopes are still out of reach of even the most advanced rare-isotope production facilities, and, more often than not, the isotopes that can be made cannot be produced in the quantities needed to extract the necessary information.

Nevertheless, impressive progress has been achieved. A number of rare-isotope facilities now operate worldwide, and nuclear astrophysics has been an important motivation for many of them. In recent years, centers and networks for nuclear astrophysics have emerged that facilitate interdisciplinary connections and integrate experiments at rare-isotope and other experimental facilities with astronomical observations and astrophysical and nuclear theory to address open questions in nuclear astrophysics. The Joint Institute for Nuclear Astrophysics in the US exemplifies such a center. Across the Atlantic, Europe is witnessing such initiatives as the Extreme Matter Institute and the Munich Cluster of Excellence on the Origin and Structure of the Universe, both in Germany, and the international Challenges and Advanced Research in Nuclear Astrophysics network.

Origin of the elements

Nuclear processes in stars and stellar explosions have forged nature's chemical elements out of the hydrogen and helium left over from the Big Bang. Fusion reactions in stars drive the formation of elements with atomic numbers up to about that of iron. But fusion does not produce heavier elements; the nuclear binding energy per nucleon is maximal for nuclei around iron and nickel, so continued fusion would be endothermic.

Heavier elements are thought to be built up by a neutron-capture process that iterates a two-step sequence. First, neutrons bombard a seed nucleus until a number have been captured and an unstable isotope forms. Then beta decay increases the number of nuclear protons by one and creates a new element. The resulting nucleus is heavier than the seed and has less binding energy per nucleon, but the additional binding of the free neutrons makes the process exothermic. A slow neutron-capture process (the s-process) that has been found to operate in red giant stars explains the origin of about 60% of the heavier elements. The remaining 40% are usually attributed to a rapid neutron-capture process, the r-process (see the article by John Cowan and Friedrich-Karl Thielemann, PHYSICS TODAY, October 2004, page 47). But we still do not know where that r-process takes place and what exactly the reaction sequence is that builds up the heavy elements.

The pattern of elemental and isotopic abundances produced by the r-process can be directly related to properties of rare isotopes such as their shell structure. Those abundances can be extracted from solar-system data by subtracting the predicted contributions from the s-process. Though the procedure has its uncertainties, the residual r-process abundances clearly show pronounced peaks at nuclear mass numbers $A = 130$ and $A = 195$ (see figure 1d) that correspond to enhancements of the stable isotopes of elements near tellurium and platinum. Such peaks reflect a neutron-capture process in which the neutron number N crosses that of a closed neutron shell; for the peaks shown in figure 1d, the neutron magic numbers are $N = 82$ and $N = 126$. Now, a rare isotope's beta decay toward stability does not change the

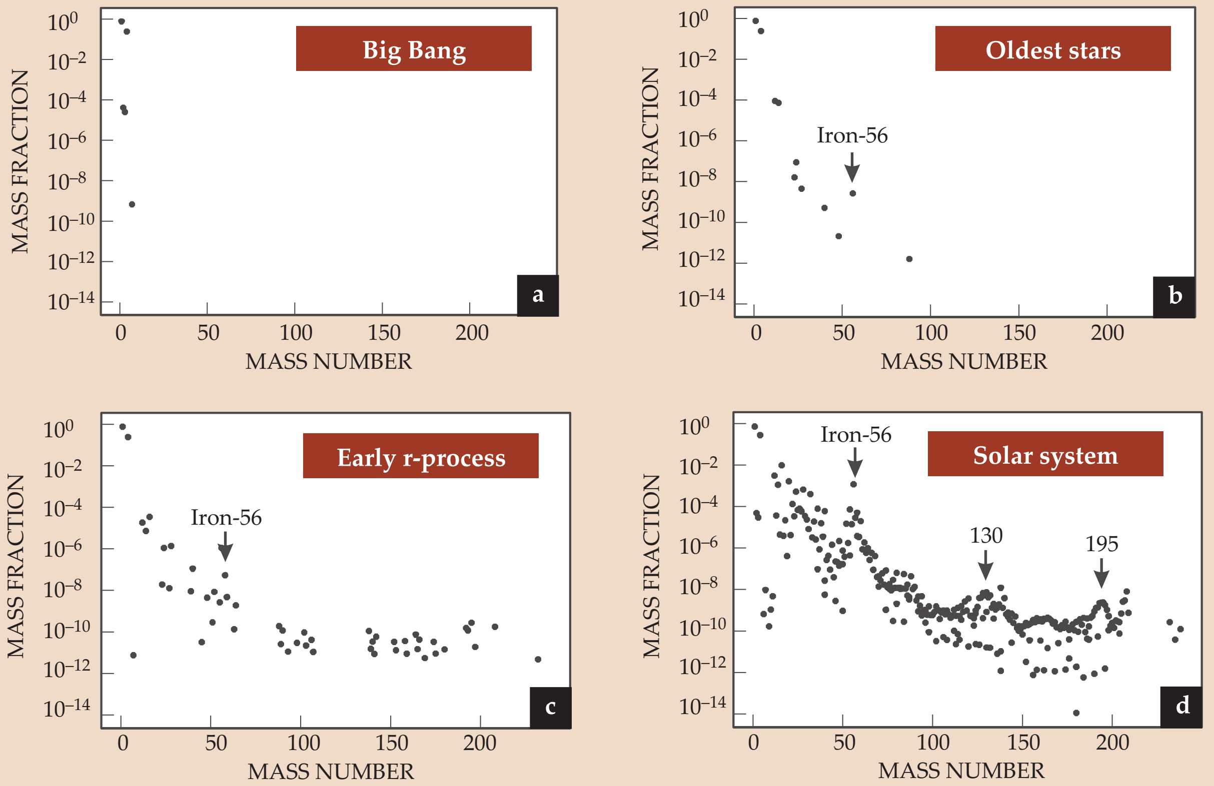

Figure 1. Chemical evolution in the Milky Way, from the Big Bang to the present. The iron abundance allows for rough dating so that one can establish a record of chemical evolution. **(a)** Element abundances attributed to the Big Bang. (Adapted from ref. 13.) **(b)** The composition of HE 1327-2326, which represents that of the oldest, most Fe-poor stars known. This panel indicates elements contributed by the first supernovae in the galaxy. (Adapted from ref. 14.) **(c)** The composition of CS 22892-052, a star much older and poorer in Fe than the Sun. The spectrum here is dominated by the decay products of the rare isotopes produced early in the so-called r-process discussed in the text. (Data courtesy of John Cowan; see also ref. 15.) **(d)** The composition of the solar system, as inferred from solar spectra and the analysis of pristine meteoritic material. The peaks at mass numbers 130 and 195 are signatures of the r-process. (Adapted from ref. 16.) The stellar observations reflected in panels b and c directly provide only an element's atomic number. Atomic masses are assigned based on assumptions about the nucleosynthesis process.

mass number of the nucleus by much, since only a small number of neutrons are emitted along the decay chain. Thus the r-process evidenced by the figure 1d peaks proceeds through or near cadmium-130 ($N = 82$, $A = 130$) and thulium-195 ($N = 126$, $A = 195$), as shown in figure 2. The lighter ^{130}Cd is a rare isotope with a half-life of 160 ms, and ^{195}Tm is an extremely neutron-rich rare isotope of thulium that has never been observed in a laboratory.

How can such short-lived rare isotopes be produced by neutron capture, given that first the r-process has to produce isotopes that have fewer neutrons and that decay within a fraction of a second? Evidently, neutron densities are extremely large and make neutron-capture rates even faster than beta-decay rates. In some r-process models, the neutron-capture rate is always greater than the beta-decay rate. In those cases, it is photon bombardment in the hot stellar plasma that removes neutrons and eventually halts the chain of neutron captures. The r-process then has to pause until a beta decay occurs; it is stuck at a so-called waiting point.

With some assumptions about the nuclear physics of rare isotopes—including that $N = 82$ and $N = 126$ remain magic numbers for neutron shell closures—it follows[1] that the production of exotic nuclei like ^{195}Tm requires mind-boggling free-neutron densities of up to 10 kg/cm^3. Accounting for those extraordinary densities is a considerable challenge for theoretical astrophysics. Most current models involve neutron stars in some form—for example, the neutron-rich outflow from a proto-neutron star that forms in a core-collapse supernova or from the merging of two neutron stars into a black hole. All the proposed scenarios have issues that need to be addressed. Astronomical observations and experimental nuclear data are needed to guide and ultimately verify or falsify the theoretical possibilities.

What needs to be measured?

The beta-decay half-lives of the nuclei along the r-process path determine the time it takes to build up heavy elements. After all, a beta decay occurs for each step up the element chain. Even more important, as the r-process attempts to approach a local steady flow, beta-decay half-lives set the abundances of the nuclides produced at the various locations in the path. A long half-life will slow the process and lead to a high local abundance. Conversely, a short half-life will accelerate the process and lead to a low local abundance.

Nuclear masses play an extremely important role as well. In the interplay of neutron capture and the reverse process of photodisintegration, the mass differences between neighboring isotopes determine the path of the r-process for

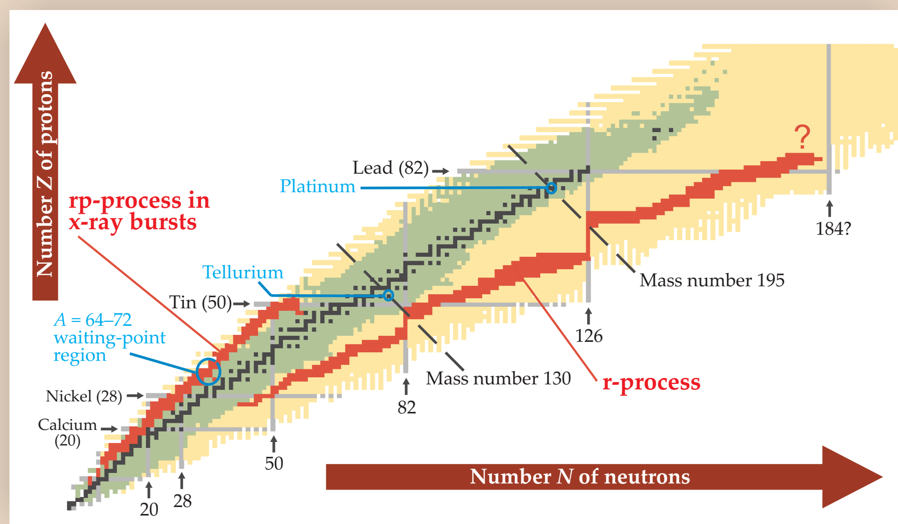

Figure 2. Chart of the nuclides, showing the valley of stability (black), unstable nuclides with known mass (green), and other rare isotopes predicted to exist. Red indicates the isotopes along the path of the r-process on the neutron-rich side and the rp-process on the neutron-deficient side. Gray lines mark shell-closing magic numbers for neutrons and protons. The r-process path crosses the neutron magic number 82 at a mass number of about 130 and crosses magic number 126 at a mass number of about 195. The rp-process slows when the nuclear mass *A* ranges from 64 to 72.

a given set of astrophysical conditions. Model calculations have shown that altering nuclear masses by just 1 part in 100 000 can lead to dramatic changes in the produced r-process abundances.[2] That 1/100 000 figure is comparable to the uncertainties in mass predictions that result from the nuclear physics community's lack of understanding of rare-isotope properties. As a result, r-process model predictions have large uncertainties.

Other important nuclear physics ingredients are neutron-capture rates and the probability of neutron emission during beta decay. The associated processes absorb and produce free neutrons, respectively, and therefore determine the free-neutron abundance near the end of the r-process, when neutrons become rare. Fission and neutrino-induced reactions could also affect the r-process at specific sites.

Progress in understanding the nuclear physics of the r-process has not come easily. The challenge is to produce beams of rare isotopes with sufficient intensity that one can perform measurements. Half-lives of some 20–30 r-process nuclei have been obtained since 1986, when pioneering experiments determined the half-lives of the r-process waiting-point nuclei zinc-80 and cadmium-130. A milestone measurement, shown in figure 3, was achieved three years ago at Michigan State University: the determination of the half-life of nickel-78, the only doubly magic nucleus along the main r-process path.[3] (Tin-132 is close.)

In principle, modern experimental techniques allow for mass measurements with a precision of much better than 1 part in 100 000, but mass determinations typically require more beam intensity than decay studies. Therefore, it was only in the past few years that the masses of ^{80}Zn and ^{130}Cd were experimentally obtained. For ^{80}Zn, the mass was determined at the University of Jyväskylä in Finland and at CERN's ISOLDE facility from observations of the isotope's characteristic motion in the magnetic field of an ion trap. The ^{130}Cd mass was obtained at ISOLDE from a measurement of the maximum energy of the beta spectrum.

Neutron-capture rates on rare isotopes are even more difficult to determine, because both projectile and target are radioactive. Progress has been made by shooting radioactive beams at deuterium targets. The resulting neutron transfer reaction, which leaves a proton in the target and adds the neutron to the incoming beam, resembles the capture of a neutron. From the reaction cross section, one can constrain the stellar neutron-capture rate. Experiments at Oak Ridge National Laboratory (ORNL) are currently under way to perform the first such measurement for an r-process nucleus, ^{130}Sn. That particular isotope is of interest because it affects the balance of free neutrons during late stages of the r-process.[4]

Most of the exciting experimental developments described thus far would have been considered impossible only a few decades ago. They have already helped to refine the constraints on the astrophysical conditions necessary for the r-process. The main limitation to further progress is the low production rate for the extremely neutron-rich nuclei that participate in the r-process. To interpret observational data, the nuclear astrophysics community will need new accelerator facilities such as the Facility for Antiproton and Ion Research in Germany, the Rare Isotope Beam Facility in Japan, and the proposed Facility for Rare Isotope Beams in the US.[5] The US Department of Energy is currently soliciting proposals for FRIB and is expected to choose a site by year's end. Today's facilities can just barely produce some r-process nuclei. Next-generation facilities, especially FRIB, are projected to produce most nuclei along the r-process. With their data, researchers will be able to test various r-process models against precision observations and probe the conditions in the environment of the r-process.

Cosmic hydrogen explosions

X-ray bursts, as far as we know the most common thermonuclear explosions in the universe, are thought to be powered by an rp-process involving the rapid capture of protons by neutron-deficient rare isotopes and subsequent positron decay. The bursts occur in stellar binary systems comprising a neutron star and a normal companion star (see figure 4). A stream of hydrogen-rich matter falls from the companion star onto the surface of the neutron star, where it accumulates in a thin layer. Owing to the extreme surface gravity of the compact neutron star, the accreted material quickly becomes dense and hot; within hours a density of 1000 kg/cm^3 and temperature of half a billion kelvin can be reached. Under those conditions, the system becomes unstable. A continued increase in temperature accelerates nuclear reactions, which in turn generate energy that further heats the layer. Within seconds, thermonuclear runaway leads to an explosion that appears to us as a bright x-ray burst lasting

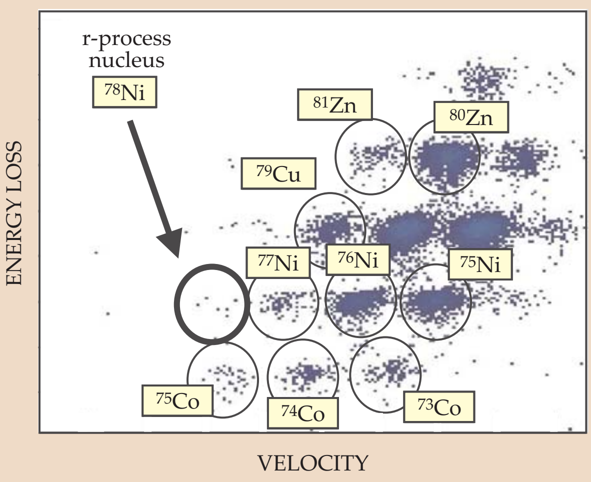

Figure 3. A doubly magic r-process nucleus observed. An accelerator experiment can identify rare isotopes via their charge and unusual mass-to-charge ratio. In the plot shown here, energy loss (a measure of nuclear charge) and velocity (in a fixed magnetic field, a measure of mass to charge) reveal the rare isotope nickel-78 as data points inside the indicated bold circle. (Adapted from ref. 3.)

from 10 to 100 seconds. Mass accretion then resumes, and an hour to several days later, the next burst occurs. The bursts' long duration and their numerous occurrences make them prime targets for currently operating x-ray observatories such as *INTEGRAL*, the *Rossi X-ray Timing Explorer*, and *XMM-Newton*.

Indeed, a large amount of data exhibit a rich set of often poorly understood phenomena. Those include rare superbursts that last thousands of times as long as conventional bursts, multipeaked bursts, millisecond oscillations, and an unexpected paucity of bursts for very high mass-accretion rates. In many cases, speculations about the physics of rare isotopes have been invoked to explain the puzzling observations. What is needed, however, is to pin down the nuclear physics through laboratory measurements and to advance nuclear theory. Once the nuclear physics is on solid ground, one can use the observations to test astrophysical models and their inherent approximations, assess the relevance of additional physics not included in current models, and ultimately extract information about binary systems and neutron stars.

The close interplay of nuclear physics and astrophysics in x-ray bursts can be illustrated by way of often observed, minutes-long burst tails. Figure 5 shows empirical x-ray burst light curves along with several models that give details of tail structure. A major accomplishment of rare-isotope science was to demonstrate that the rp-process slows down considerably in the $A = 64$–72 mass region (see figure 2). That slowdown leads to an extended generation of nuclear energy and provides an explanation for the observed long-lasting tails.

With an improved understanding of the underlying nuclear physics, observers could use burst tails as an indicator of the amount of hydrogen in the accreted layer; after all, many protons need to be captured if the burst is to involve the $A = 64$–72 mass region. The amount of hydrogen, in turn, affects the ability of the x-ray radiation to blow up the atmosphere. If the x rays actually do blow up the atmosphere, the burst is called a radius expansion x-ray burst. Knowing the amount of hydrogen in the accreted layer therefore allows one to use radius expansion bursts to constrain neutron stars' surface gravity and compactness. Or, with assumptions about the surface gravity, one can use radius expansion bursts as standard candles for distance measurements.

Successes and challenges

Experimental and theoretical studies have now established some of the details behind the slowdown of the rp-process in the crucial $A = 64$–72 mass region. As the rp-process moves via proton capture and positron decay along the proton drip line, which delimits the maximum number of protons that can exist in a bound nucleus, it encounters the exceptionally long-lived positron emitters germanium-64, selenium-68, and krypton-72. Pioneering experiments at National Superconducting Cyclotron Laboratory (NSCL) in Michigan, GANIL in France, and ISOLDE failed to find bromine-69 and rubidium-73 and thereby demonstrated that the well-established nuclei ^{68}Se and ^{72}Kr are indeed located at the proton drip line—and therefore that the slow positron decay of those two nuclei is the most efficient way to continue the rp-process.[6]

There is, however, another possibility: a small leakage by a two-proton capture sequence that jumps over the unbound isotope, say from ^{68}Se to ^{70}Kr. This alternative process depends very sensitively on unknown nuclear mass differences.[7] For example, a change in the mass of ^{68}Se by 1 part in 100 000 can change by an order of magnitude the time needed for the rp-process to proceed beyond ^{68}Se. Only within the past few years have rare-isotope facilities at Argonne National Laboratory (ANL), NSCL, and ISOLDE succeeded in using ion traps to make mass measurements at that level of precision. Such results have greatly reduced uncertainties in predicting x-ray burst time scales. Still, the proton-capture rates and masses of a few key isotopes with short lifetimes remain unknown; those measurements might have to await the next generation of rare-isotope facilities.

Despite progress at stable beam and rare-isotope beam facilities, there is still much physics to understand. Topics ripe for investigation include critical reaction sequences, such as the mechanism for breakout of hydrogen burning from the carbon-nitrogen-oxygen cycle; a number of waiting points along the long rp-process reaction path; and the tin-antimony-tellurium cycle that terminates the rp-process in rare, particularly powerful x-ray bursts.

Rates of proton- and alpha-induced reactions with unstable rare isotopes are especially difficult to measure. The short half-lives of the isotopes prohibit manufacturing a target that can be bombarded with intense beams of protons or other light ions. However, unlike for the case of neutron capture, one can bombard a hydrogen target with a heavy rare-isotope beam, essentially reversing the role of target and beam. Such inverse kinematics, applied to the measurement of stellar reaction rates, has been pioneered at the Louvain-la-Neuve facility in Belgium, where experiments were run at hundreds of keV in the center-of-mass frame; those low energies correspond to the kinetic energies of the interacting nuclei in a stellar plasma. Inverse kinematics techniques were further developed at rare-isotope facilities at TRIUMF in Canada, ORNL, ANL, and others.

Several important reaction rates have been measured with inverse kinematics, but the technique is suffering from the limited beam intensities available at current radioactive beam facilities. The field of reaction-rate measurement with rare-isotope beams is still in its infancy, and next-generation facilities will be needed to enable a broad-based advance in nuclear astrophysics. An important development toward

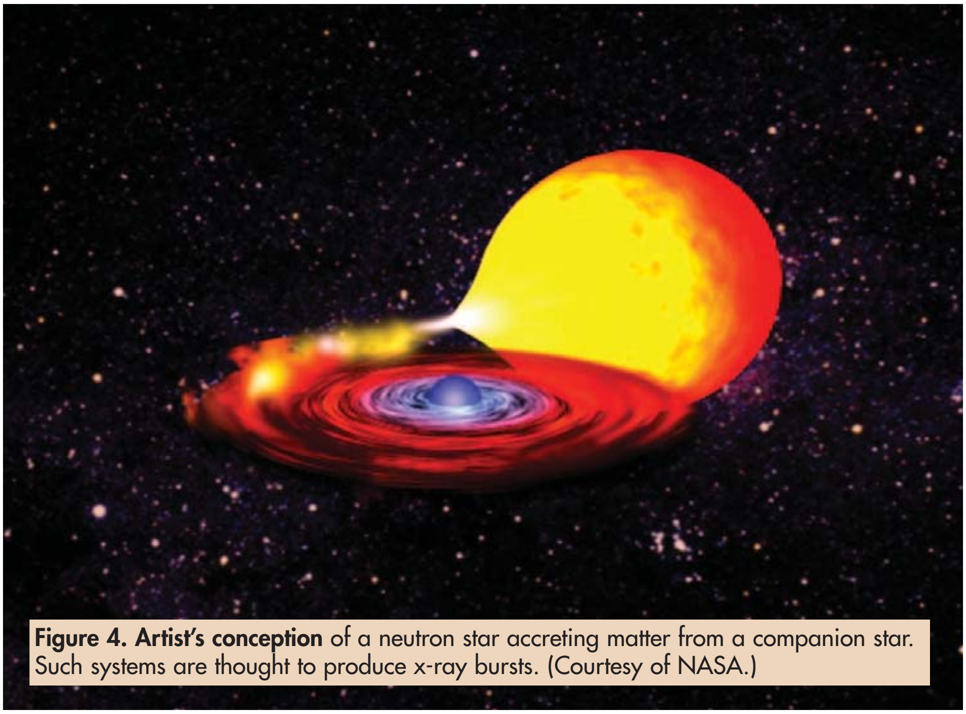

Figure 4. Artist's conception of a neutron star accreting matter from a companion star. Such systems are thought to produce x-ray bursts. (Courtesy of NASA.)

improving rate measurements is the so-called reaccelerated rare-isotope beam: A rare-isotope beam produced by in-flight fragmentation is stopped and then reaccelerated to low astrophysical energies. That technique combines the production and separation advantages of in-flight fragmentation at intermediate energies with the high beam quality of accelerated beams. The first facility based on the concept is under construction at NSCL. Reaccelerated rare-isotope beams will also be an important element at FRIB.

The progress described above and the new facilities on the horizon give hope that a quantitative interpretation of x-ray burst observations is within reach. Models, tested with empirical data, will allow researchers to probe, for example, hydrogen content and burning conditions. Insights into nuclear reactions that help us understand x-ray bursts will also apply to other explosive hydrogen-burning scenarios in astrophysics, such as surface explosions on accreting white dwarfs ("nova explosions") and the recently proposed νp-process in supernovae—an rp-process accelerated by an intense neutrino flux that creates small amounts of neutrons and so opens up additional reaction channels.[8]

Neutron-star crusts

In addition to rapid neutron or proton capture, Nature has devised another way to overcome beta decay and produce copious amounts of rare isotopes. In neutron-star crusts, the density is high enough (10^6–10^{14} kg/cm^3) and the temperature low enough (less than about half a billion kelvin) that degenerate electrons effectively block the electron emission process necessary for the beta decay of neutron-rich nuclei. At the same time, high-energy degenerate electrons can induce electron captures that produce neutron-rich nuclei. With increasing depth, the electron Fermi energy increases, and both effects become stronger; in essence, the valley of stability is shifted toward neutron-rich nuclei. Therefore, in the crusts of neutron stars, ordinary nuclei become highly unstable, and exotic rare isotopes become the "normal" stable nuclei that exist in bulk quantities.

The stability shift is of particular interest for neutron stars that are accreting. Over a span of hundreds of years, the pressure and density at any given location in the crust continuously increase due to the infall of matter onto the surface, and electron captures lead to a continuous change of composition. Eventually, nuclear densities become large enough to induce so-called pycnonuclear fusion reactions. Unlike in thermonuclear fusion, in pycnonuclear fusion the Coulomb barrier is overcome by the zero-point motion of the nuclei in the solid lattice of the crust.

The fusion reactions and nuclear transformations induced by electron capture play an important role as heat sources in the crust[9] and lead to several observable effects. The temperature profile of the neutron-star crust sets the ignition conditions for the x-ray bursts that occur on the surface of the accreting neutron star. X-ray burst ashes, in turn, determine the initial composition for the crust transformations. In the past several years, x-ray astronomers have been able to observe neutron stars that stop accreting and transition into a period of quiescence when the accretion shuts off. The luminosity of the source drops by a factor of more than 100 000, but, as figure 6 shows, x-ray telescopes such as the *Chandra X-ray Observatory* and *XMM-Newton* have observed a residual luminosity and its many-year decline.[10] It is thought that what one sees is the gradual cooling of the neutron-star crust that had been heated by electron capture and fusion processes during the accretion phase.

Knowledge of the heat-source distribution is important if one is to interpret observations in terms of nonstandard core-cooling processes and neutron-star properties such as thermal conductivity. And heat release is sensitive to the structure of excited states and the mass differences, arising from nuclear pairing, between nuclei with even and odd numbers of protons (or neutrons). That sensitivity has led nuclear physicists to realize that accurate nuclear physics is needed in models to realistically predict the thermal structure of the crust of an accreting neutron star.[11] Of particular importance is understanding how the nuclear physics evolves as nuclei with mass numbers of up to about 100 approach the neutron drip line: The maximum mass of interest is determined by the heaviest nuclei that can be produced on the surface via the x-ray burst rp-process. As in the case of the r-process, the existence of closed nuclear shells near exotic rare isotopes is critical, as the shell structure can have a large impact on electron-capture transitions and the associated heating. Many of the experiments performed for r-process studies are also relevant to crustal heating.

The location of the neutron drip line is important because the drip line sets the timing and location of neutron release in the neutron-star crust as the composition transitions with increasing depth to a mix of nuclei and free neutrons. Unfortunately, knowledge of the limit of neutron stability is sketchy beyond oxygen. Rare-isotope experiments, however, keep pushing toward that limit and are obtaining information on the location of the low-mass portion of the neutron drip line. An example is the recently discovered[12] existence of magne-

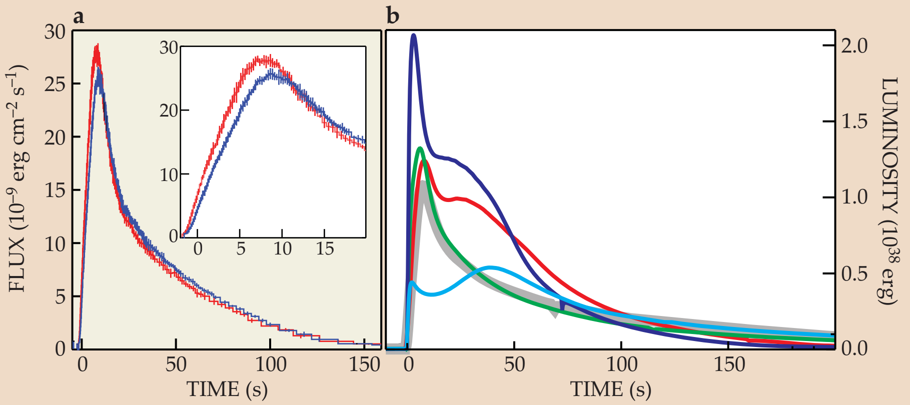

Figure 5. X-ray bursts. (a) The curves show averages over many relatively long bursts for two (red, blue) observational periods. The data include error bars, and the thinness of the curves illustrates the precision that can be achieved. The inset expands the time axis near the peak. (Adapted from ref. 17.) **(b)** These curves are derived from x-ray burst model calculations that include an extended rp-process. The different curves, derived from models with different assumptions about the nuclear physics of rare isotopes, illustrate the interplay of rare-isotope physics and burst-tail structure. (Adapted from ref. 18.)

sium-40 and, surprisingly, aluminium-42. With new rare-isotope facilities on the horizon, it is likely that the drip line will be delineated up to about mass 70, which would include most of the important range for neutron-star crust models. Electron-capture rates on neutron-rich rare isotopes may also be within reach of experiments in the near future. Rare-isotope physicists are currently developing techniques to perform such measurements on unstable nuclei by using charge exchange reactions with relatively fast rare-isotope beams.

From development to application

Nuclear astrophysicists are now at the threshold of understanding the role of rare isotopes in the cosmos. New rare-isotope beam facilities should propel nuclear astrophysics into an "application era," in which the techniques developed over the past decades will be used to address the most pressing rare-isotope physics questions confronting the field. Those facilities should also drive progress in theoretical nuclear physics that will enable reliable predictions of rare-isotope properties that are out of experimental reach—in particular, properties modified by astrophysical environments.

The field will continue to require a wide range of nuclear accelerator facilities and experimental techniques. Low-energy rare-isotope beams are used in experiments that directly measure some key astrophysical reaction rates, but higher-energy beams are needed to clarify the nuclear properties that enter into theoretical predictions of many other important reaction rates. Some reaction measurements are best carried out at beam energies of about 10–20 MeV per nucleon, but others need to take advantage of simplifications in nuclear processes at higher "fast" beam energies. Experiments probing the most exotic rare isotopes will also require fast rare-isotope beams. With the planned FRIB facility, US researchers will have an accelerator laboratory that meets all the requirements for rare-isotope research at the forefront of nuclear astrophysics. But nuclear astrophysics, of course, is about more than just rare isotopes. Together with the rare-isotope facilities, other facilities that provide beams of stable isotopes, neutrons, electrons, or photons will address the broad nuclear physics that drives astrophysical phenomena.

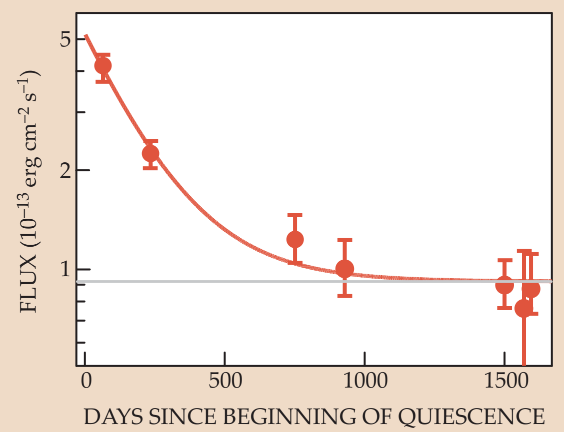

Figure 6. Neutron-star cooling curve. When a neutron star accretes matter from its companion star in a binary system, its crust heats up. The cooling of the crust after accretion shuts off is evident in these measurements made by the *Chandra X-ray Observatory* and *XMM-Newton* of a neutron star in the x-ray binary KS 1731-260. The red curve is an exponential fit to the data; the gray line gives the inferred asymptotic flux. (Adapted from ref. 10.)

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