The Evolution of Elements and Isotopes

The Cat's Eye planetary nebula, the remnant of a star that has expelled freshly synthesized elements via stellar winds. Image captured by the Hubble Space Telescope. COURTESY OF J.P. HARRINGTON AND K.J. BORKOWSKI (UNIVERSITY OF MARYLAND) AND NASA

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The basic building blocks of all minerals are the approximately 290 stable or long-lived isotopes of 84 elements. Yet, when the universe began and nuclear reactions ceased after about 15 minutes, the only elements present were hydrogen, helium, and traces of lithium. After the groundbreaking work by Cameron and Burbidge and coworkers in the 1950s, it is now understood that all the other elements are made in stars in an ongoing cycle of nucleosynthesis. Stars form, create new elements via nuclear reactions, and finally disperse the new elements into space via winds and explosions, forming the seeds for new stars.

KEYWORDS: nucleosynthesis, stellar evolution, r-process, s-process, isotopes

STARS: NATURE'S ISOTOPE FACTORIES

The isotopes found today in our solar system (Lodders et al. 2009) were formed in numerous cycles of nucleosynthesis over the ~10 billion years from the Big Bang to the formation of the solar system. But how did the composition of the universe evolve from the simple mix right after the Big Bang to the complex distribution of isotopes shaping our world today? Our understanding of this process of chemical evolution is still fragmentary.

The origin of the heavy elements beyond iron in the periodic table (about 2/3 of all elements) figures prominently among the many open questions. The existence of these elements in nature is somewhat surprising. Nuclear fusion reactions, the energy source of stars, cease to produce energy once the most tightly bound isotopes in the iron region are formed. At that point the star has squeezed out as much nuclear energy as it can, and the formation of heavier elements, which would consume energy, does not take place. Yet, nature has found a way to produce the heavier elements in stellar environments, albeit in rather low concentrations. These elements are thought to be formed mostly by two classes of neutron-capture processes: the so-called slow neutron-capture process (s-process) and the rapid neutron-capture process (r-process). Each process produces a distinct pattern of elements and together they add up to the observed composition. In both processes, seed nuclei capture neutrons until unstable isotopes form. These isotopes then undergo beta decay, converting a neutron inside the nucleus into a proton, an electron, and an electron antineutrino. The result is a new element with the atomic number increased by one. The new element then captures more neutrons, repeating the process until, step by step, the heavy elements are formed.

Even though the newly formed elements are less tightly bound than their seed nuclei, the additional binding of the free neutrons more than compensates and makes the process exothermic. However, these neutrons are unstable and decay with a half-life of about 10 minutes. The challenge for theorists is to identify stellar sites with sufficiently intense sources of neutrons. The site of the s-process has been identified in a certain class of red giant stars (AGB stars) and in the cores of massive stars, where helium-burning nuclear reactions can produce neutrons that are then captured on iron nuclei from previous stellar generations (Käppeler 1999). On the other hand, the site and exact reaction sequence of the r-process are still not known with certainty (Cowan and Thielemann 2004). Given that this process is responsible for about 40% of the heavy elements and is the sole source of uranium and thorium in the universe, these are some of the most important open questions in nucleosynthesis. The challenge is to find a considerably more intense source of neutrons for the r-process—mind-boggling free-neutron densities of up to 10 kg/cm^3 are likely needed. Not unexpectedly, most proposed models therefore involve neutron stars in one form or another, for example, the neutron-rich outflows from a neutron star forming as a result of a supernova explosion (FIG. 1), or the matter ejected during the merging of two neutron stars to form a black hole.

UNANSWERED QUESTIONS

All proposed nucleosynthesis scenarios for the r-process have major problems. Observations and experiments are needed to provide guidance and to verify or falsify the numerous theoretical possibilities. Major insights come from recent advances in astronomy, which are beginning to revolutionize our understanding of chemical evolution. Large-scale surveys of millions of stars in our Galaxy have led to the discovery of more and more stars that are extremely iron-poor (Yanny et al. 2009). These low-mass stars formed in the early stages of galactic chemical evolution, when stellar winds and explosions had just begun to enrich the Galaxy in the first heavy elements and iron was still scarce. The spectroscopic analysis of the surface compositions of these stars reveals the chemical makeup of the Galaxy at the time and location of their formation (with the caveat that in some stellar binary systems there may have been later pollution via mass transfer from the

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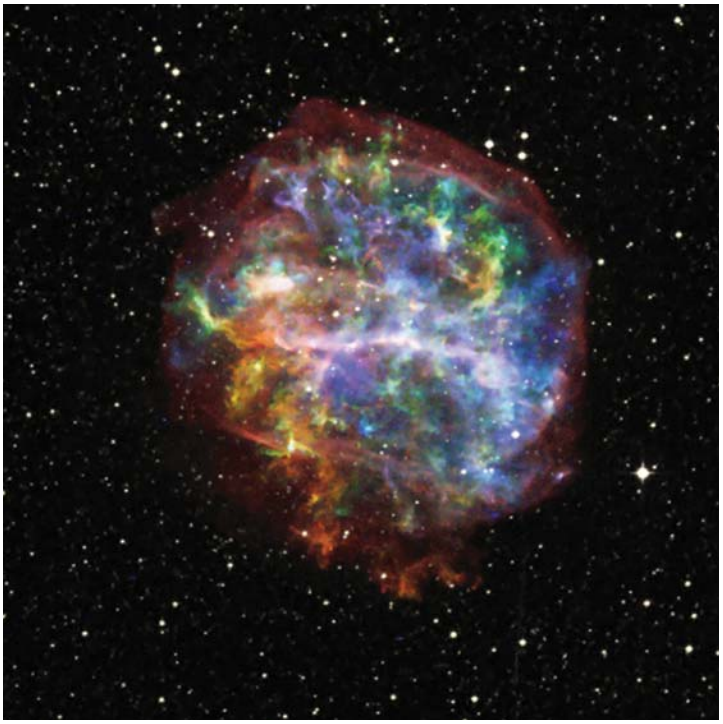

Figure 1 X-ray image of the supernova remnant G292.0+1.8 from the Chandra X-ray observatory (color), overlayed with optical data (white). Various elements synthesized in the supernova explosion can be identified through their characteristic X-ray energies and are color coded in blue (silicon and sulfur), green (magnesium), and yellow and orange (oxygen). Unfortunately, r-process elements are too rare to be detected. Credit: X-ray data from NASA/CXC/Penn State/S. Park et al.; optical data from Palomar Observatory Digitized Sky Survey

companion star). The iron content of the star can serve as a rough "chemical" clock that allows one to date the sample. These stars represent an emerging "fossil record" of chemical evolution, revealing the steps nature took to transform the simple composition just after the Big Bang into the complex distribution of elements found today (Fig. 2).

Of particular interest are the few most iron-poor stars found today—stars that have iron contents of 1:100,000 of that of the Sun and possibly provide a glimpse of nucleosynthesis in the very first generation of stars (Frebel et al. 2009). Slightly less iron-poor stars provide information on another interesting epoch of galactic chemical evolution. During these early times, the r-process dominated the synthesis of the heavy elements, because the iron seed nuclei required by the s-process had not yet been produced in sufficient quantity.

Several stars with a composition completely dominated by the r-process have now been discovered, and they are thought to illustrate the abundance patterns of heavy elements created by individual r-process events in the early Galaxy (Sneden et al. 2008). Among the most intriguing insights into the unknown site of the r-process is the apparent consistency, from event to event, of the abundance pattern for elements from Ba to just below Pb in the periodic table. Moreover, this characteristic pattern is also consistent with the solar r-process contribution. This consistency may thus hint at a particularly narrow range of conditions leading to an r-process. On the other hand, the production of U, Th, and Pb seems to vary from star to star, at least occasionally, making attempts to use the actinides for radioactive dating of the r-process events difficult. Maybe most intriguing are variations for elements below Ba that indicate the existence of a separate process—either a variant of the r-process or something entirely new. A fascinating aspect of this field is that new nucleosynthesis processes are still being discovered. Currently a number of large-scale surveys to search for metal-poor stars are underway, and extensive programs for follow-up high-resolution spectroscopy using the largest telescopes are in place. These efforts promise a drastic increase in the number of iron-poor stars with detailed information on their composition. It is reasonable to expect that within the coming decade a much more complete "fossil" record of chemical evolution will emerge.

Along with such dramatic advances in observations, similar progress is needed in our understanding of the underlying nuclear processes that drive chemical evolution. The structure of nuclei has been referred to as the "DNA" of chemical evolution (Woosley et al. 2003), in the sense that it encodes and defines, together with environmental cosmological conditions, the composition of the universe. Nuclear reactions are the mechanisms by which nature translates this "DNA" into chemical abundance features. New generations of stars begin with an initial composition enriched by new abundance features, and in that sense they inherit a modified "DNA" that, through differences in the resulting nuclear reactions and atomic processes, affects their nature and the further evolution of the elements.

The structure of nuclei and their reactions under astrophysical conditions therefore need to be deciphered to understand chemical evolution. Nuclear physics enables one to predict the abundance signatures of specific astrophysical models, which can then be compared to observations. Many of the nuclear reactions in stars involving stable nuclei have been studied in the laboratory, though many surprises and challenges still remain. For example, most measurements of reactions between charged particles have been performed at higher energies than occur in stars, because the electrostatic repulsion between nuclei can then be overcome more easily, leading to sufficiently large event rates in the experiments. Extrapolating these measurements to lower energies requires theoretical assumptions that are not always correct. For example, recent measurements of the rate of proton capture on ^{14}N have been done with new techniques, such as improved detection systems (Runkle et al. 2005) or the use of the European underground laboratory LUNA (Formicola et al. 2004), to extend experimental conditions to lower energies and lower event rates. As a result, the newly established rate that sets the speed of hydrogen burning via the CNO cycle in stars is a factor of 2 slower than previously assumed. The CNO cycle is a circular sequence of nuclear reactions involving carbon, nitrogen, and oxygen nuclei effectively fusing hydrogen into helium. It plays a small role in the Sun, but is the dominant hydrogen-burning process in more massive stars. Another example is the ^{12}C fusion rate in stars—there is currently a debate about whether the rate at stellar energies is reduced by many orders of magnitude due to a new fusion-hindrance effect discovered at Argonne National Laboratory in other reactions (Jiang et al. 2007), or whether it is increased by many orders of magnitude due to a hitherto unknown resonance (Spillane et al. 2008). Major technical developments are now underway to enhance the sensitivity of such experiments so that they can be performed closer to the stellar energy range. One such development is the planned DIANA facility at the new U.S. underground laboratory DUSEL.

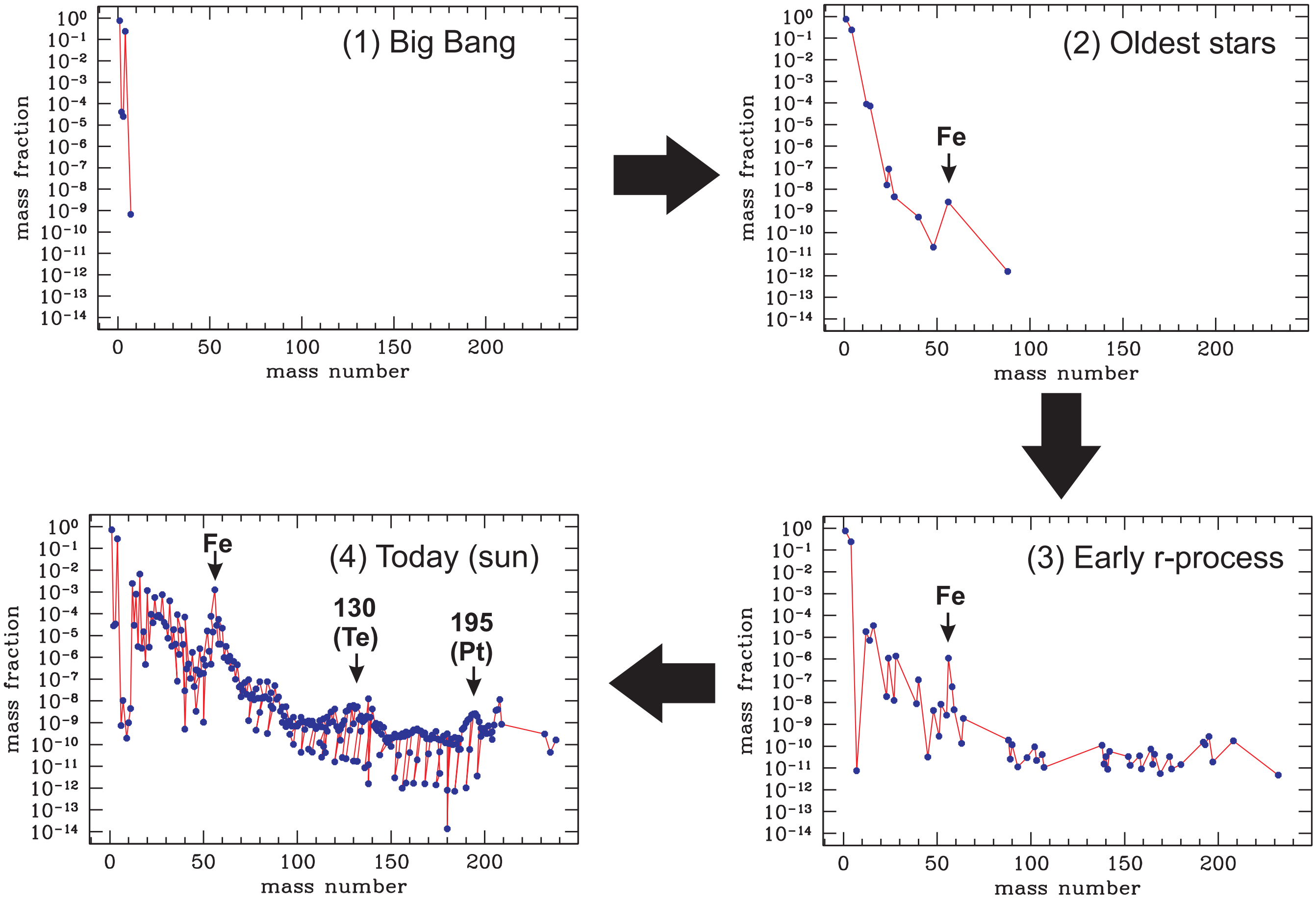

FIGURE 2 Chemical evolution of the universe from the Big Bang (1) to the formation of the solar system (4) (Lodders et al. 2009). Each graph shows the chemical composition of the respective environment. Shown for each isotope is its fraction by mass as a function of the mass number (number of protons and neutrons). For example, hydrogen and helium have mass numbers 1 and 4, respectively. (4) gives some additional examples for elements with various mass numbers. Observations of very metal-poor stars have begun to provide information about the steps nature took to get from the Big Bang to the present composition of the solar system, forming a "fossil" record of chemical evolution. For example, (2) shows one of the most iron-poor stars found to date, HE 1327-2326 (Aoki et al. 2006), and (3) illustrates a star that formed out of the debris of an early r-process event, CS22892-052 (Sneden et al. 2003). In (2) and (3), some assumptions have been made regarding the isotope composition of the elements observed.

RARE ISOTOPES IN THE COSMOS

The study of the many rare, unstable isotopes participating in nucleosynthesis processes has been even more challenging. Rare isotopes are nuclei with extreme neutron to proton ratios that do not exist on Earth unless produced in a nuclear reaction, because they decayed a long time ago. For example, cadmium has 8 naturally occurring isotopes with mass numbers 106, 108, 110–114, and 116. However, unstable, rare Cd isotopes with mass numbers as low as 95 and as high as 132 have been discovered, and many more are thought to exist. For a few rare isotopes with particularly long half-lives of millions of years, there is some geological evidence that they existed at the time of solar system formation but have decayed since (Meyer and Clayton 2000). These isotopes offer exciting possibilities for probing directly the last nucleosynthesis events that contributed to the solar elements. However, most rare isotopes have much shorter half-lives and often decay within fractions of seconds. These isotopes are extremely difficult to produce and study in laboratory experiments. However, at certain extreme conditions in stellar explosions, they are created copiously, and, despite their fleeting existence, they imprint their properties on the composition of the ejected material and therefore on the composition of the universe (Schatz 2008).

Rare isotopes play a particularly important role in the origin of the r-process elements. How do we know this if we haven't even identified the site? It turns out that our current sparse knowledge of the physics of rare isotopes provides, when combined with observations, the first clues. From observations of metal-poor stars and from the composition of the solar system—from which we can subtract the contribution of the better understood s-process (though there are still uncertainties in this procedure)—we have a fairly good picture of the characteristic element and isotope abundance patterns created by the r-process.

The most pronounced features in this pattern are the peaks at mass numbers A = 130 and A = 195, which correspond to particularly large abundances of tellurium/xenon and gold/platinum in nature, respectively. In a neutron-capture process, such peaks are produced naturally when the reaction sequence passes through nuclei with closed neutron shells, the so-called "neutron magic" nuclei. Just like the atomic electrons in chemistry, nuclei exhibit a shell structure for neutrons (and protons). At certain "magic numbers" of neutrons, the nucleus has a completely filled (closed) shell, leading to the analogue of a noble gas electron configuration in atomic physics. For such nuclei, the rates for further neutron capture are drastically reduced and, once a neutron is captured, the rate for removing it via bombardment of photons is drastically increased. As a consequence, the neutron-capture process slows down dramatically, leading to an increased production of such nuclei. However, the stable ^{130}Te (78 neutrons) and ^{195}Pt (117 neutrons) isotopes found with increased abundance do not have closed neutron shells. Those closed shells rather occur at the magic numbers of 82 and 126 neutrons. We therefore have to conclude that the r-process passes through unstable progenitor isotopes with closed neutron shell numbers, and that these isotopes later decay into ^{130}Te and ^{195}Pt. Though some neutron emission can occur during this decay process, the mass number most likely does not change by much. It follows then that the path of the r-process passes through isotopes with mass numbers (A) and neutron numbers (N) of A ~ 130, N = 82 and A ~ 195, N = 126. These are ^{130}Cd, a rare isotope of cadmium with a half-life of 160 ms, and ^{195}Tm, 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, if isotopes with fewer neutrons, which have to be made first, decay within fractions of seconds? The best explanation is an extremely large neutron density at the r-process site, which makes neutron capture rates even faster than some of the beta decay rates.

This rough constraint on the nature of the r-process had already been postulated in the seminal papers by Burbidge et al. (1957) and Cameron (1957) and led to the notion of the existence of an r-process in the first place. However, it hinges on the assumption that the magic numbers for exotic rare isotopes are the same as the well-established magic numbers for stable isotopes. We now know, thanks to pioneering experiments with rare isotopes, that this is not true in general. Classical magic numbers for lighter nuclei have been shown to disappear in unstable isotopes, and new magic numbers can appear (Otsuka et al. 2001). There is now some evidence that N = 82 is still a strong shell closure at ^{130}Cd (Jungclaus et al. 2007), but for ^{195}Tm the jury is still out.

In principle, the r-process abundance pattern contains much more information about the r-process. It contains signatures of the history of the temperature and neutron density conditions during the r-process. Also, the pattern might have been further shaped by, for example, exposure to strong neutrino irradiation. In fact, the many possible models proposed so far for the r-process site, while all producing abundance peaks at A = 130 and A = 195, otherwise exhibit largely different abundance patterns. Unfortunately, the various possibilities for the unknown nuclear physics of most r-process isotopes can lead to similar or larger variations in predicted abundance patterns (Kratz et al. 1993). Because of this lack of knowledge about the nuclear physics of the r-process, to date the observed r-process abundance pattern cannot be exploited to falsify or verify the theoretical possibilities for the site.

The major challenge is to produce and study experimentally the exotic r-process nuclei. Some impressive progress has been made. Among the important nuclear properties are the beta decay lifetimes of the rare isotopes along the r-process, typically in the range of milliseconds to seconds. A slow lifetime will slow down the r-process, and the respective isotope will be produced in larger quantity because its production will tend to be faster than its decay. This net accumulation translates into a signature in the final abundance pattern once the unstable r-process isotopes have decayed into stable ones. Since the pioneering experiments that determined the first half-lives of the r-process nuclei ^{80}Zn and ^{130}Cd in 1986, half-lives of about two dozen r-process nuclei have now been measured (Kratz et al. 2005). A recent milestone was the measurement of the half-life of ^{78}Ni at Michigan State University (Hosmer et al. 2005; FIG. 3), the only doubly magic nucleus along the main r-process path (though ^{132}Sn is close).

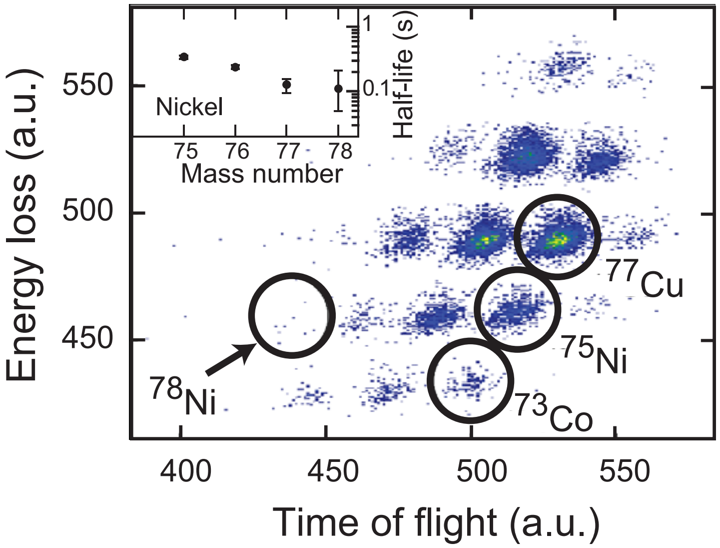

FIGURE 3 R-process isotopes produced at the National Superconducting Cyclotron Laboratory at Michigan State University. Each isotope arriving at the experimental site with about 30% of the speed of light is identified by its characteristic energy loss and time of flight through the accelerator. A given species therefore forms a "blob" in the energy loss versus time-of-flight diagram shown, with the width of the blob determined by the detector resolution. The short half-life of ^{78}Ni, 110 ms, measured for the first time at this facility, accelerates the r-process.

Another critical quantity is the precise mass of an r-process isotope. Model calculations have shown that nuclear mass changes of the order of just 1:100,000 can lead to dramatic changes in the produced r-process abundances. Techniques are now available to measure nuclear masses with this precision, but they require larger production rates for the rare isotopes compared to what is required for the simpler lifetime measurements. Therefore, only very recently were the masses of ^{80}Zn and ^{130}Cd determined experimentally for the first time, in the case of ^{80}Zn through the characteristic motion of the nucleus in the magnetic field of an ion trap at CERN/ISOLDE (Baruah et al. 2008) and the University of Jyvaeskyla (Hakala et al. 2008). A similar technique has been used at Argonne National Laboratory (Van Schelt et al. 2008) to measure masses of nuclei near the r-process path. In the case of ^{130}Cd, a measurement of the maximum energy of the beta spectrum has been used to determine the mass, albeit with somewhat less precision (Dillmann et al. 2003). Neutron-capture rates are even more difficult to determine, as both projectile and target are radioactive. Here progress has been made using reactions resulting from radioactive beams striking deuterium targets. The resulting neutron transfer reaction that leaves a proton in the target and adds the neutron to the incoming radioactive beam resembles the capture of a neutron, and from the rate of the reaction one can in principle constrain the stellar neutron-capture rate. Pioneering experiments at the HRIBF facility at Oak Ridge National Laboratory have recently been performed to explore this possibility for ^{130}Sn. The rate of neutron capture on ^{130}Sn has been shown in model calculations to affect the balance of free neutrons during late stages of the r-process (Jones 2009).

THE FUTURE

Despite this impressive progress, the relevant properties of the vast majority of the r-process nuclei are out of reach of current experimental facilities. At the same time, a comprehensive theory of the rather heavy r-process nuclei grounded in first principles and with a predictive power sufficient for r-process models is lacking, in part due to the absence of experimental information that could reveal the relevant aspects of the nuclear force. However, major advances in our understanding of rare isotopes are expected in coming years from experiment and theory. New accelerator facilities around the world promise to produce most of the important r-process nuclei. The most advanced of this new generation of accelerators is the Facility for Rare Isotope Beams (FRIB), a project of the U.S. Department of Energy now underway at Michigan State University (www.frib.msu.edu). New theory initiatives and advances in computing promise to develop new frameworks for a reliable description of heavy nuclei that, once calibrated with new experimental data, might be able to predict reliably the properties of the few r-process nuclei remaining out of reach. Initiatives such as the Joint Institute for Nuclear Astrophysics (www.jinaweb.org), a Physics Frontiers Center of the U.S. National Science Foundation, are bridging the gaps between nuclear physics and astrophysics to forge a new interdisciplinary approach to the problem of the origin of the elements. We now seem to be at the threshold of finally deciphering the "DNA" of the chemical evolution of the cosmos. In the end, we might gain more than just an understanding of the origin of the elements making up the world around us. The understanding of the chemical evolution of our Galaxy might also provide new insights into its formation history, allowing us to address a broader range of fundamental questions in cosmology.

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