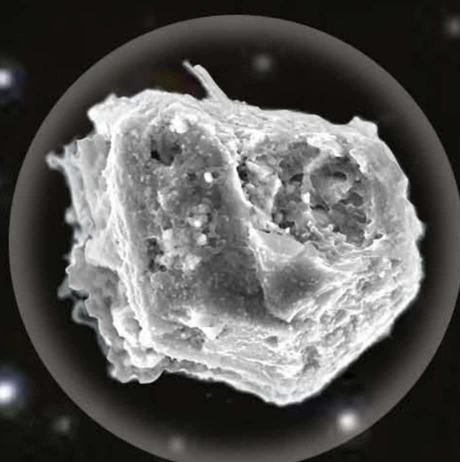
Stardust and the Secrets of Heavy-Element Production

Rene Reifarth

As they come down from the skies, meteorites bring with them stardust—tiny diamond-like grains, each formed from the material in the interior of a single Red Giant star. Those grains contain heavy elements that were synthesized through the slow neutron-capture process, known as the s-process. The relative abundances of the elements hold the secret of how they were made. Just as new neutron-capture measurements of rare and short-lived elements are needed to benchmark weapon simulations against past nuclear test results, similar measurements are needed to infer the stellar conditions that produced the heavy elements in stardust. DANCE, the unique spectrometer at the Los Alamos Neutron Science Center for measuring neutron capture reactions, is now providing the data for both.



Neutron Capture Physics for Nuclear Weapons and Nuclear Astrophysics

Francis X. Timmes

It might seem odd for weapons scientists to be looking to the stars for information and inspiration. However, stars have long been of interest to Los Alamos researchers because there is a tremendous overlap between the physical processes governing stellar systems and those in nuclear-weapon systems. In fact, many of the scientists currently engaged in theoretical modeling of weapon performance and effects have developed the relevant knowledge and skill sets by working on problems in astrophysics.

Today cutting-edge studies at the Los Alamos Neutron Science Center (LANSCE) and the Theoretical Division are exploiting parallels between the two fields. Nuclear astrophysics, which is largely concerned with the origin of the elements, is being paced by LANSCE experiments that delve into the neutron capture physics of nuclear weapons. The reason is that both the production of heavy elements in stars and the transmutation of heavy elements in nuclear explosions occur through neutron capture reactions. Further, just as weapons scientists infer details of weapon performance from the heavy-element abundances found in the debris from past nuclear tests, astrophysicists hope to infer the conditions inside Red Giant stars from the heavy-element abundances in stellar "debris"—micrometer-sized dustlike grains brought to Earth by meteorites. Provided one has measured the neutron capture processes involved in making the heavy elements, the abundances of those elements in the grains lead directly to predictions of the temperatures at which they were made, the neutron densities, and the abundances of the elements that donate neutrons. The temperatures and neutron donor abundances, in turn, reveal the extent of hydrodynamic mixing between the different layers of the Giant stars. For example, the isotope samarium-151, discussed in this article, is a sensitive barometer of the thermodynamics and hydrodynamics in Giant stars.

Neutron capture measurements at the Detector for Advanced Neutron Capture Experiments (DANCE) at LANSCE are the start of a closed-loop effort to provide verified and validated multidimensional hydrodynamic models of convection and other mixing in the presence of thermonuclear reactions. Neutron capture data from DANCE are fed into stellar models created by the Theoretical Division's Astrophysics Group. The models are then checked against measurements of isotopic ratios in the "debris" of a Red Giant by external collaborators. Los Alamos leads work in modeling the slow neutron-capture process of nucleosynthesis (known as the s-process) in Giant stars, which has a direct connection to the work involved in understanding the neutron capture physics required to predict the behavior of nuclear weapons.

Since the middle of the 19th century, the spectral analysis of starlight was used to investigate the elemental composition of stars. Most stars have a very similar composition to our sun and lie along the so-called main sequence in the Hertzsprung-Russel diagram, which shows the stellar luminosity versus surface temperature. There is, however, a small but distinctive group of stars off the main sequence that is characterized by red light (which means relatively cool surface temperature) and enormous brightness (luminosity). The diameter of those Red Giant stars is about 50 times bigger than the diameter of our sun. The 1952 discovery of atomic lines from the heavy element technetium in the spectra of Red Giants was the long-desired smoking gun, revealing the site of heavy-element production. The half-lives of all technetium isotopes are much shorter than the billion-year time scales of stellar evolution, which means that the technetium—and therefore most heavy elements—are produced inside the Red Giants. Shortly after this breakthrough discovery, an overall picture of the synthesis of the elements was developed that took into account all available scientific knowledge at that time. The main aspects of this picture are still valid nowadays.

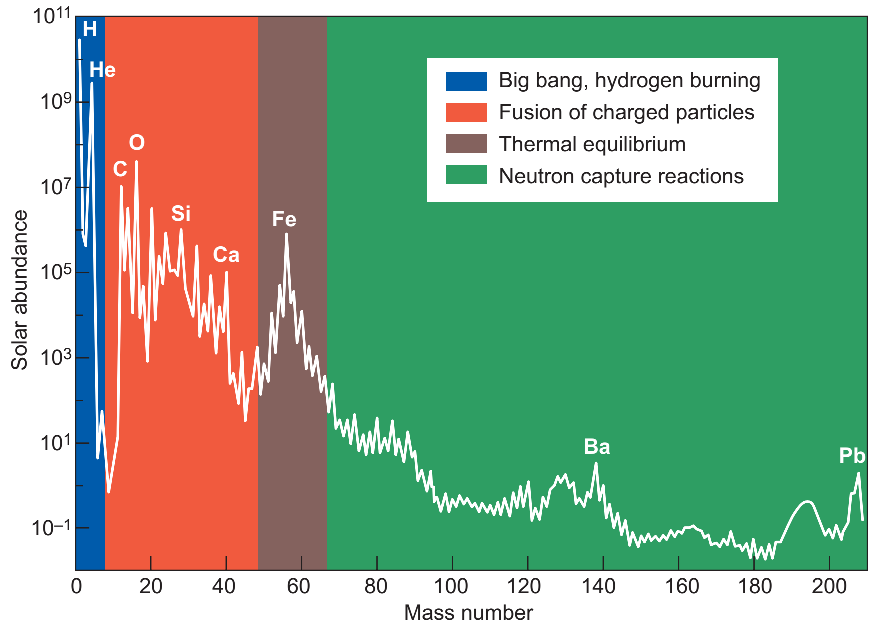


Figure 1. Solar Abundance Distribution and Production Mechanisms
The colored backgrounds in this graph of solar abundances vs mass number indicate the most important mechanisms that produced the elements. Blue and red indicate that most of the elements up to titanium are produced by the fusion of charged particles during the different burning stages of stellar evolution—hydrogen burning (the fusion of hydrogen to helium), helium burning (the fusion of helium to carbon), and so on. At very high temperature and pressure conditions, as during the various stages of compression preceding supernova explosions, production and destruction reactions occur in equilibrium. The very stable iron group is mainly produced in this equilibrium context, hence its high abundance. For elements beyond iron, the enormous Coulomb barrier all but prevents the fusion of charged particles to make heavier elements. Instead, the elements heavier than iron are mainly produced during nuclear processes induced by neutron capture reactions.

According to our current understanding, only the very light elements (hydrogen, helium, and lithium) were produced during the big bang, the initial explosion from which our universe evolved. Those elements condensed into the first generation of stars, and the most massive ones (more than a hundred times the mass of our sun) evolved on a time scale of millions of years through different burning stages, producing heavier and heavier elements up to iron, the most stable element in the periodic table. After forming an iron core, which cannot support further fusion burning of charged particles, these massive stars suddenly collapse under their own weight and then blow off their outer layers in a supernova explosion. During that explosion, heavy elements between iron and uranium were produced in the expanding envelope and blown off into the interstellar medium. The ejected material then served as seed material for new generations of stars, such as, our sun. Only much later did the low-mass stars, which were undergoing very slow hydrogen burning over billions of years, finally evolve to the Red Giant phase and contribute to heavy-element production.

Figure 1 shows a summary of the origin of the elements from the isotopic, or nuclear physics, point of view, which means it focuses on the nuclear processes that produced the elements and does not contain information about the times when those isotopes were produced. Almost all the elements heavier than iron are produced through neutron-induced processes. There are two major processes, the rapid neutron-capture process (r-process), which takes place in explosive scenarios such as a supernova explosion, and the slow neutron-capture process (s-process), which can be found in Red Giants. Solving the secrets of the s-process through new radiochemical measurements of stardust and new nuclear-data measurements at the Los Alamos Neutron Science Center (LANSCE) is the subject of this article.

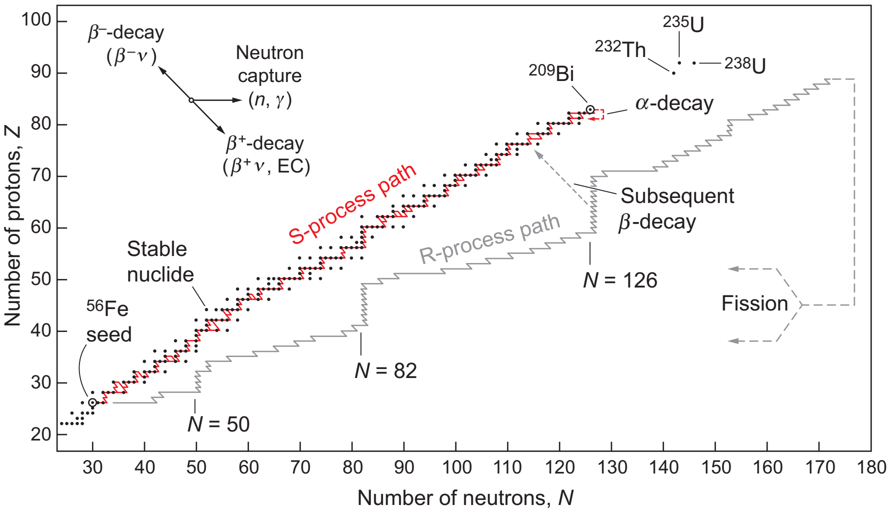


Figure 2. S-Process and R-Process Synthesis of the Heavy Elements
The s- and r-processes start with the iron peak nuclei as seeds. The s-process path follows the nuclear valley of stability until it terminates in the lead-bismuth region. The r-process drives the nuclear matter far to the neutron-rich side of the stability line and upwards until beta-delayed fission and neutron-induced fission occur and recycle the material back to smaller mass numbers. Only a few isotopes on the proton-rich side of the valley of stability get significant contributions from other processes. (This illustration is reproduced from *Cauldrons in the Cosmos*, C. E. Rolfs and W. S. Rodney, 19888, courtesy of The University of Chicago Press.)

Basics of the S-Process

Figure 2 shows the pathways for making the heavy elements through the s- and r-processes. The horizontal axis is the number of neutrons in an isotope, and the vertical axis is the number of protons. About half of the element abundances from iron to the lead-bismuth group are produced by the s-process, and the other half by the r-process. The two most-important reactions occurring during the s-process are neutron capture (right arrow in Figure 2), in which the mass of the nucleus increases by one unit while the charge stays constant, and beta decay (diagonal arrows in Figure 2), in which the charge of the nucleus increases or decreases by one unit and the mass stays constant. Free neutrons must be available for neutron capture to occur, whereas an unstable nucleus undergoes beta decay spontaneously, emitting an electron and an antineutrino as a neutron inside the nucleus changes into a proton (or a positron and neutrino as a proton changes into a neutron).

The s-process starts with an iron seed exposed to free neutrons, and it builds up the elements following the neutron-rich side of the nuclear valley of stability, that is, the region to the right of the stable isotopes in Figure 2. Following neutron capture, the new unstable isotope will almost always beta-decay back to the valley of stability before it can capture another neutron. In contrast, during the r-process, the neutron flux is so high and the neutron capture times so short that a nucleus will almost always capture several neutrons before it undergoes a beta decay. Thus, the r-process follows a path that is shifted farther toward the neutron-rich isotopes. The beta decay half-lives are much shorter for isotopes very rich in neutrons, so that shortly after the neutron source terminates, the products of the r-process will beta-decay back to the valley of stability.

The purely phenomenological, classical approach to describing the s-process was formulated even before a detailed understanding of the development of stars was available (Burbidge et al. 1957, Seeger et al. 1965). It assumes that iron, seeded randomly inside stars, is irradiated by neutrons through an exponential distribution of neutron exposure times. This classical approach also assumes a constant neutron density and temperature.
It turns out that the heavy-element abundances in the solar system can be explained only by assuming two different parameter sets for the s-process—a weak component that explains the s-process abundances between iron and strontium and a main component that accounts for the s-process abundances between strontium and lead. The classical model became a useful tool not only for reproducing the s-process abundances, but also for characterizing in an empirical way the physical conditions during the s-process. Meanwhile, the two components of the classical approach were assigned to different stellar scenarios. The weak component was attributed to helium burning in the core of massive stars (10 to 25 solar masses), whereas the main component was attributed to helium burning in a shell around the carbon-oxygen core of low-mass Red Giants (1 to 5 times the mass of the sun)—refer to Figure 3.

Inferring Stellar Conditions from S-Process Abundances

The exact pathway of the s-process depends on the conditions in the star. Starting at the very abundant iron group, all elements up to bismuth could, in principle, be produced by a sequence of reactions in which each neutron capture produces an unstable isotope that quickly decays to the next higher element through beta decay and then waits for the next neutron capture. If, however, conditions in the star make the rates for neutron capture comparable to the rate of beta decay by a particular isotope, then the s-process path would branch at that isotope with some fraction of that isotope transforming via neutron capture, while another fraction transforms through beta decay. The branching ratio, or relative likelihood, for the different reactions depends on the physical conditions in the interior of the star—temperature, neutron density, and electron density. At higher neutron densities with all other conditions equal, more nuclei of a given isotope would capture a neutron before having the chance to beta-decay than at low neutron densities. Thus, the branching ratios deduced from the isotopic ratios observed in stellar material could provide the tools to effectively constrain modern models of the stars where the nucleosynthesis occurs, provided one knows the fundamental rates, or cross sections, for neutron capture and beta decay.

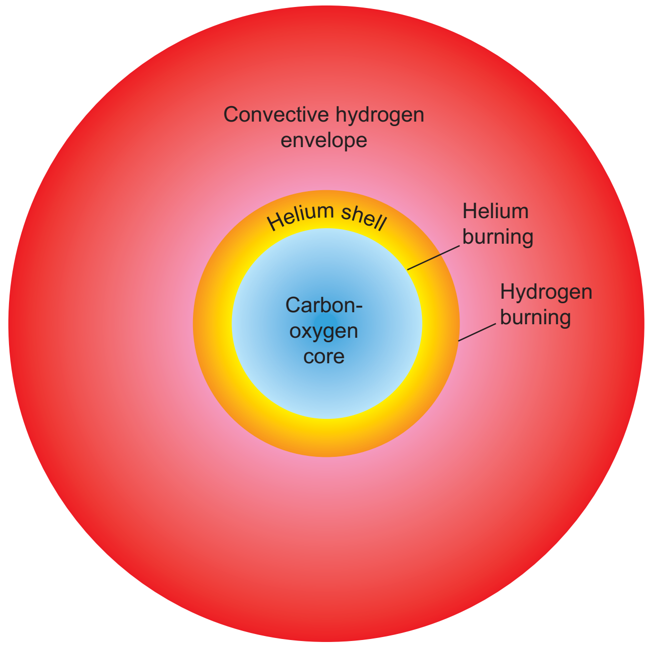


Figure 3. Site of the S-Process in Red Giant Stars
The figure shows a cross section of a Red Giant with its quiescent carbon-oxygen core, a shell of helium surrounding the core in which helium burning creates carbon and oxygen, and an outer envelope in which hydrogen burning creates helium. The helium shell is much thinner than shown in this schematic, and the convective envelope, consisting mainly of hydrogen, is much thicker. In general, the inner shells of stars consist of the burning products of the outer shells.

Evidence of the S-Process in Stardust

At present, the s-process path for the samarium-europium-gadolinium (Sm-Eu-Gd) region shown in Figure 4 is being actively explored. This region is particularly exciting because observational data on the stellar abundances of those isotopes have recently become available from stardust, extremely small diamond-like grains that can be found in meteorites on the earth's surface and are known to be formed in the outer regions of Red Giant stars. Under certain circumstances, such grains survive their long journey through interstellar space and participate in the formation of new stars and their planets. This is the

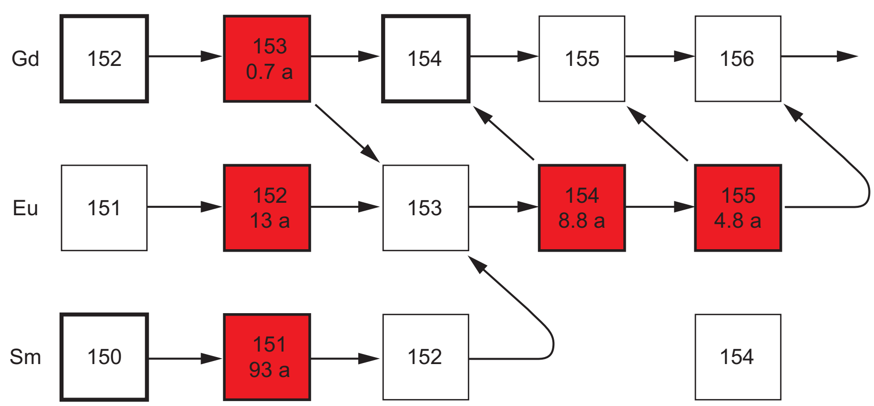


Figure 4. The S-Process Path in the Sm-Eu-Gd Region
The s-process path in the Sm-Eu-Gd region is shown by arrows. This path has branch points at the unstable isotopes (red squares), which have half-lives given in years. All the white squares are stable isotopes. The heavy outlines around samarium-150 and gadolinium-152 and -154 indicate that these stable isotopes are produced only in the s-process. During the r-process, stable neutron-rich isobars (nuclei with the same atomic mass but different atomic number) are made first and halt the beta-decay pathway that would otherwise produce them. Thus, for example, formation of samarium-154 during the r-process prevents formation of gadolinium-154.

reason why we can find them nowadays on earth. Because the grains are extremely small—only a few micrometers in diameter—it was necessary to develop greatly improved experimental equipment to reach the sensitivity needed for isotopic-abundance measurements of several isotopes from a single grain (see Figure 5). Because of these new developments, it is now possible to extract information about all stable isotopes in the Sm-Eu-Gd region from a single grain—hence, from a single star.

At the same time, at LANSCE we have the capability to measure the neutron-capture cross sections of all isotopes on the s-process path in that region, including the radioactive isotopes. Together, the isotopic ratios and neutron-capture cross sections from this region should enable us to constrain current stellar models of the main component of the s-process.

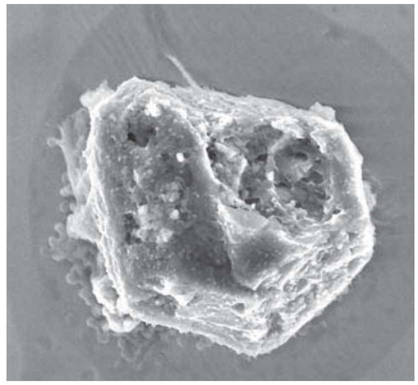


Figure 5. Single Grains from Giant Stars
The scanning electron micrograph is of a silicon-carbon (SiC) grain from the Murchison meteorite, named after the town in Australia where fragments of the meteorite fell in 1969. The grain is approximately 2 micrometers in diameter. Most presolar SiC is believed to have formed in Asymptotic Giant Branch stars (see Figure 6), which are very old Red Giant stars rich in carbon, but some grains have isotopic signatures indicating other stellar sources, such as supernovae and novae. Secondary ion-mass spectrometry is used to determine isotopic ratios in the grains. **(This photo is courtesy of Larry R Nittler, Carnegie Institute of Washington, Washington, D.C.)**

Current Stellar Models of the Main Component of the S-Process

Past precision measurements on the stable isotopes have revealed that the very sensitive branching regions, as for example in Figure 4, cannot be described with the simple classical s-process model but require the complicated physics of thermally pulsing low-mass Asymptotic Giant Branch (AGB) stars, also known as Giants. The mechanism for the s-process involves a series of helium shell flashes and the alternating presence of two neutron sources, as shown in Figure 6. During helium burning, three helium nuclei, called alpha particles, fuse into carbon via the famous triple-alpha process. The AGB stars are not heavy enough to ignite helium burning on a continual basis. Most of the time, these stars burn only hydrogen into helium, converting the inner parts of the envelope into the helium shell (the red layer converts into a yellow layer in Figure 6). But these quiescent phases are interrupted by flashes of helium burning in the helium shell around the core, which last only a few hundred years and convert helium shell material into a carbon and oxygen core (see the yellow region converting into a blue region in Figure 6). During these flashes, energy production of the star is significantly increased, and about 20 to 30 such flashes occur during the life of a Giant star.

The s-process occurs during both the helium flashes and the quiescent periods. Immediately after a helium flash, the convective mixing between the hydrogen and the helium layers introduces hydrogen and elements such as carbon, neon, and iron into the helium layer. With the fresh supply of hydrogen, proton capture on the always abundant carbon-12 produces nitrogen-13, which beta-decays to carbon-13. Although the temperature is relatively low during this quiescent period, the carbon-13 will fuse with alpha particles and produce neutrons through the reaction $^{13}C(\alpha,n)^{16}O$. Now, the main ingredients needed for the s-process are present—free neutrons and an iron seed. The neutron flux, however, ends as soon as all the freshly produced carbon-13 is burnt (see the ends of the horizontal red bars in Figure 6), and the s-process comes to a halt. The heavy-element abundances produced during the quiescent phase are subsequently modified during the next helium flash (dark blue region in the helium shell in Figure 6), when higher temperatures cause marginal activation of the alpha particle reaction with neon, $^{22}Ne(\alpha,n)^{25}Mg$, and this new source of free neutrons drives the s-process farther. During and following the helium flash, those freshly produced s-process materials get swept up into the convective hydrogen envelope and are brought to the surface of the Giant star, where they can be seen with telescopes, as was the technetium mentioned above. Because these Giant stars are relatively light but huge, the material brought to the surface by convection can then be carried into the interstellar medium by stellar winds.

During the final stages of the AGB phase, strong stellar winds will blow the entire hydrogen envelope, which had been enriched with elements produced by the s-process, into the interstellar medium. This freshly produced material will not only form new generations of stars and planets, like our sun and earth, but it is imprinted in the micrometer-sized dust grains mentioned above. Such dust grains can be found in meteorites on earth, and their heavy-element abundances contain an

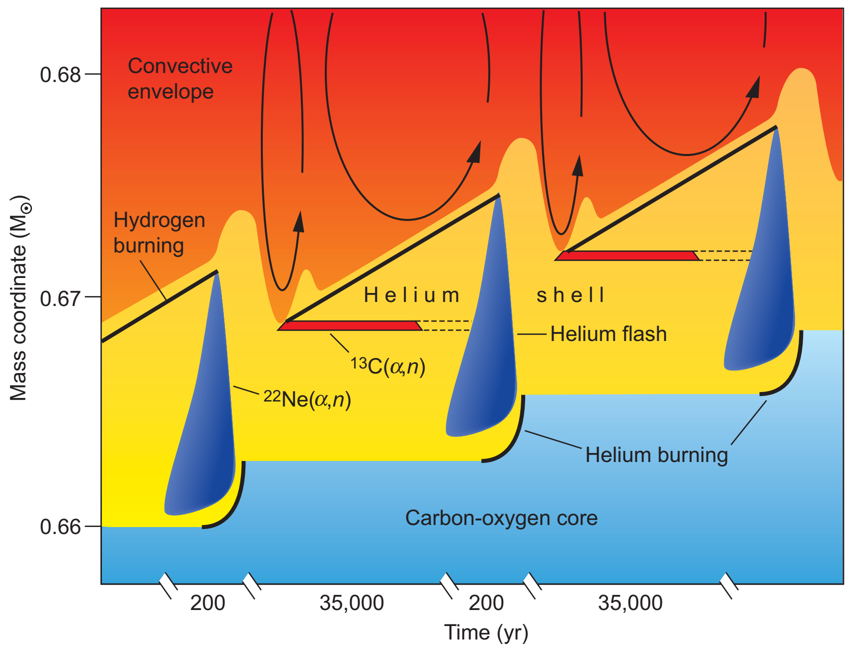


Figure 6. The S-Process during the AGB Phase
The breaks in the time axis illustrate the brevity of the helium shell flashes, only a few hundred years, compared with the duration of the quiescent phases, about 35,000 years. The mass coordinate (in solar masses, where 1 solar mass is the mass of our sun) indicates the extent of the thin helium shell, which is the site of the s-process. The $^{13}C(\alpha,n)^{16}O$ reaction is the dominant neutron source during the quiescent period, whereas during the convective helium shell flash, higher temperatures eventually activate the $^{22}Ne(\alpha,n)^{25}Mg$ reaction, the neutron source that is important for establishing the abundance patterns of the s-process branchings (Gallino et al. 1998).

almost undisturbed signature of the star in which they were formed. Those abundances, sometimes only a few thousand atoms, can now be revealed because of advancements in experimental techniques.

The Role of Neutron Capture Measurements

As isotopic abundances from the s-process are now observable in stellar grains, neutron capture measurements on the nuclei at the branch points of the s-process are the most-important missing experimental link to further improve our picture of the evolution of Giant stars and, hence, the history of the elements of which we and our world are made. In general, the main uncertainty in predicting heavy-element abundances arises from uncertainties in the physics of mixing, whether in the long-lasting quiescent phases of Giant stars or the terminating supernova explosions. Data from neutron capture measurements, combined with information from stellar grains, can be used to constrain models of mixing in Giant stars. Fortunately, the required neutron-capture measurements can now be carried out with the Detector for Advanced Neutron Capture Experiments (DANCE) at LANSCE.

The DANCE Array. DANCE is designed as a high-efficiency, highly segmented 4π barium fluoride (BaF_2) detector for detecting the energies of gamma rays emitted by a nucleus following neutron capture. DANCE is located on the 20-meter neutron flight path 14 (FP14) at the Lujan Neutron Scattering Center at LANSCE. For practical reasons, the detector modules do not really cover the entire solid angle. The design of the detector is such that a full 4π array would consist of 162 crystals of four different shapes, each shape covering the same solid angle—see Figure 7.

Two of the 162 crystals are left out in order to leave space for the neutron beam pipe. This combination of the strong neutron source at LANSCE and the high-efficiency gamma-ray detector DANCE allows us to measure neutron-capture cross sections of radioactive isotopes with half-lives as short as a few hundred days.

During the first year of experiments at DANCE, we measured the s-process branch point at the unstable isotope samarium-151, which has a half-life of 100 years (see Figure 4), as well as other stable isotopes important for nuclear astrophysics. An example is given in Figure 8. Stellar temperatures are on the order of 10^4 electron volts, or 10^8 kelvins. The data show that the uncertainty of the cross section at these energies was approximately a factor of 2, which makes the use of this branch point impossible as a tool to analyze the mixing in AGB stars. Therefore, sensitive high-precision measurements and sophisticated data analysis were needed. In the near future, we will also investigate the remaining radioactive isotopes in the Sm-Eu-Gd region.

The long-term goal of the DANCE collaboration is to perform neutron capture experiments on all feasible radioactive nuclides on the s-process path. This effort will establish an experimental basis for all relevant neutron-capture rates. When these uncertainties are resolved, the unknown parameters in the models, such as mixing parameters, can be adjusted according to the abundance distributions found in presolar grains and telescope-based observations. ■

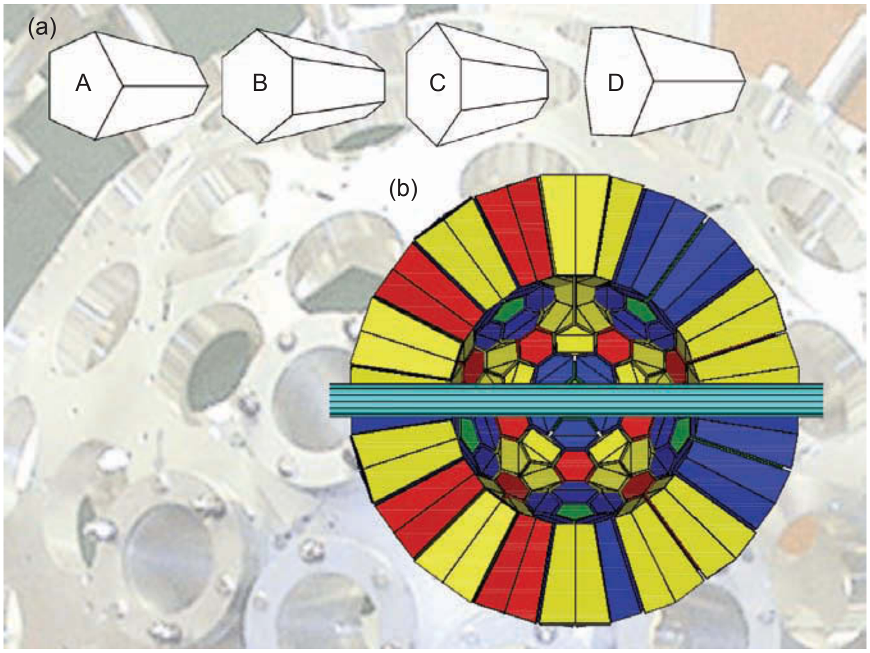


Figure 7. Design and Schematic Views of the DANCE Array
(a) The design of DANCE, a 160-module array, is based on 12 regular pentagon crystals of type A and requires three differently shaped hexagons, 60 irregular crystals of type B and C, and 30 regular crystals of type D. (b) Each color in the schematic corresponds to a different crystal type (A—green, B—dark blue, C—yellow, and D—red). Only half the sphere of crystals is shown to allow the beam pipe (light blue) to be seen.

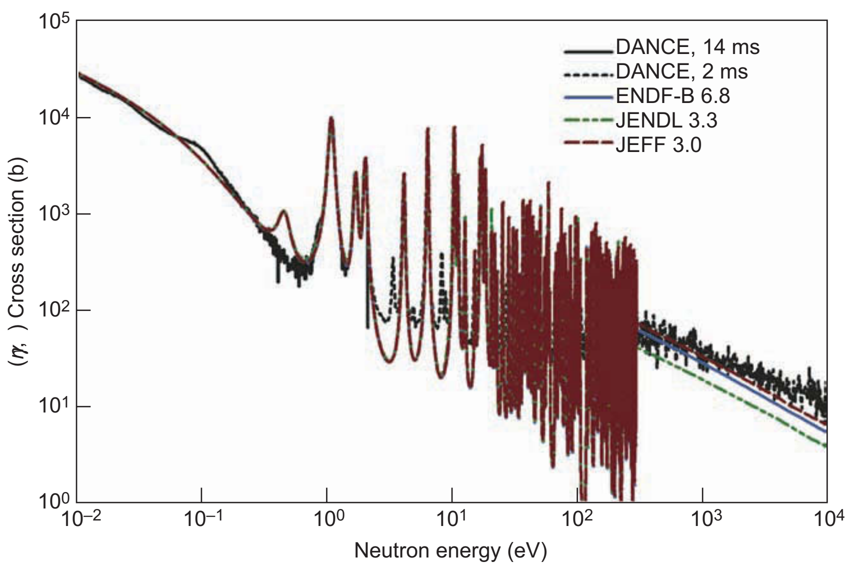


Figure 8. Measurement Performed with DANCE
A sample of samarium-151 weighing only 0.5 mg was placed in the center of DANCE and irradiated with neutrons. The black curves correspond to the neutron-capture cross section of samarium-151 as a function of neutron energy (preliminary data). The other curves show the recommended values for this reaction from different databases. Especially at energies above 1000 eV, data gained at DANCE help to resolve the big discrepancies between the databases.

Further Reading

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