MICROBIOLOGY: Enhanced: Ramping Up the Heat on Nitrogenase

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inward, engulfing part of the intershell region and dredging up nucleosynthesized elements to the star's surface; there they can be observed and are ejected into the interstellar medium by the stellar wind. After the helium shell flash dies away, hydrogen burning reignites, burning steadily until the next helium shell flash.

Another s-process neutron source results from incomplete mixing at the base of the convective envelope. During dredge-up, a little hydrogen (protons) is mixed some distance into the helium- and carbon-rich region below (purple region in the figure). When hydrogen burning reignites, these protons burn some of the ^{12}C to ^{13}C, leaving a ^{13}C pocket (sky blue). This pocket eventually gets hot enough for the $^{13}C(\alpha,n)$ reaction, yielding s-process elements (blue-green region). These are engulfed by intershell convection from the next helium shell flash and mixed throughout the intershell region (part of which is then dredged up to the stellar surface).

Theoretical mixing models are not good enough to predict the size of the ^{13}C pocket; in addition, rotational shear may yield further mixing in this region, in a manner that is likewise poorly understood (*1, 5*). The $^{22}Ne(\alpha,n)$ neutron source is easier to model, but this nuclear reaction rate is rather uncertain. The number of neutrons (and the amount of ^{12}C) produced are also affected by uncertainties in modeling the base of the flash-driven convective region (*1*). Fortunately, there are observational constraints.

The $^{22}Ne(\alpha,n)$ reaction produces a relatively high neutron density for a brief period (a few years). Even when neutron absorption yields an unstable isotope, this may absorb still another neutron before decaying unless its half-life is quite short. In contrast, the ^{13}C pocket yields a lower density of neutrons (over a much longer time period). Neutron-rich isotopes with relatively long half-lives have time to decay before they are likely to absorb another neutron, leading to a pattern of s-process isotopic and elemental abundances that differs from the pattern produced by the $^{22}Ne(\alpha,n)$ neutron source. In AGB stars with mass less than $4M_{\odot}$, s-process abundance observations indicate that the $^{13}C(\alpha,n)$ neutron source dominates (*1–5*). However, more massive stars burn hotter and faster, and the strong temperature sensitivity of the $^{22}Ne(\alpha,n)$ reaction rate suggests that it should be more important there. The observations of García-Hernández *et al.* (*6*) show that in fact the $^{22}Ne(\alpha,n)$ neutron source dominates in such stars. Not only do they demonstrate that these stars are sources of isotopes (such as ^{87}Rb) that are not produced in lower-mass stars; their observations also place new constraints on the physical processes involved, which will be beneficial to models of stars of all masses.

Our understanding of the s process is growing as a result of improvements in the theoretical models and in the observations that constrain them. We can look forward to a time when we will have a full understanding of how slow neutron capture produces elements from krypton to lead in giant stars.

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MICROBIOLOGY

Ramping Up the Heat on Nitrogenase

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A heat-tolerating archaeon from a deep-sea vent can convert N_2 into molecules usable by other organisms. This finding of nitrogen-fixing ability has implications from ecology to biotechnology.

On page 1783 of this issue, Mehta and Baross (*1*) describe a hyperthermophilic methanogen that can fix nitrogen (N_2). The authors isolated the organism from a deep (~1500 m) hydrothermal vent. Like other nitrogen-fixing bacteria and archaea, it uses the nitrogenase enzyme to tap the vast reservoir of dissolved N_2 gas for its nutritional needs for nitrogen. The discovery is noteworthy for several reasons: It establishes a new temperature maximum of 92°C for an active biological nitrogenase system, with biotechnological potential; it provides evidence for a new environment in which nitrogen fixation may occur; and it establishes yet another role for archaea in the marine nitrogen cycle. Furthermore, genomic analysis of this organism may provide important clues to the early evolution of the nitrogenase enzyme system.

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Hot-vent environments have piqued the imagination of scientists since their discovery in the 1970s. The biological diversity of these exotic and remote environments (see the figure) is largely sustained by chemoautotrophic microbes, which live on reduced inorganic chemical species released from vent fluids and thereby largely satisfy the carbon and energetic demands of the entire community (*2*). However, biological nitrogen fixation may also be operative in deep-vent environments (*3*). The organism found by Mehta and Baross, called FS406-22, provides further substance to this possibility.

Thus, nitrogen fixation may be a primary

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Life at a deep-sea vent. Hot hydrothermal vent fluid pours out of Vixen anhydrite chimney, located south of Axial caldera on the edge of an older (pre-1987) lava flow.

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source of nitrogen, a critical nutrient, in hydrothermal communities. Substantial nitrogen fixation would further increase the nutritional independence of these exotic ecosystems from from the surfaceof the ocean,where light drives the photosynthesis-based primary productionthat feeds the major marine food webs. The biogeochemical importance of nitrogen fixation in hot-vent communities must therefore be evaluated directly. The identification of novel sites of marine nitrogen fixation (such as hot vents, which are broadly distributed throughout the deep sea) may also help to determine the magnitude of oceanic nitrogen fixation, which is currently poorly constrained (*4*, *5*).

A large proportion of the microbial populations of the sea are archaea (largely of the Crenarchaeota lineage) (*6*, *7*). However, the physiological and ecological role of these organisms has remained elusive. Recent findings have shown that many marine Crenarchaeota have the ammonium monooxygenase gene and may in fact dominate marine nitrification, the biological oxidation of ammonium using oxygen as the electron acceptor (*8*). Nitrogen fixation in archaea was first reported in 1984 (*9*), and in 2003, Mehta *et al*. (*10*) retrieved the first marine archaeal *nifH* sequences from deep-sea environments, including a hot-vent system (*nifH* is a gene from the nitrogenase operon that codes for one of the enzymes of the nitrogenase complex, dinitrogenase reductase). The current report thus confirms a second role for archaea in the nitrogen cycle of the sea.

FS406-22 has an optimal growth temperature of 90°C and fixes dinitrogen at temperatures of up to 92°C, smashing the previous record of 64°C held by *Methanothermococcus thermolithotrophicus* (*11*) by a comfortable 28°C margin. Enzymes with high thermal stabilities have found broad use in molecular biology and biotechnology. Given the importance of nitrogen fixation in global agriculture and the creative exploitation of novel organisms by the biotechnology industry, a heat-stable nitrogenase system is likely to find a useful industrial application.

Recent analyses have suggested that nitrogenase may have first arisen either before the divergence of the three main branches of life (*12*) or, alternatively, more recently in a thermophilic archaeon (*13*). On the basis of genetic analysis of several of the structural and regulatory genes of the *nif* operon, as well as several related genes, Mehta and Baross argue that their archaeal nitrogen-fixing isolate may be representative of some of the earliest lineages of nitrogen fixation, thus lending support to the second scenario.

For a number of well-characterized enzyme systems of Archaea and Bacteria living at mesophilic temperatures (10° to 30°C), which use molybdenum at the active site, the analog enzyme in hyperthermophiles has replaced molybdenum with tungsten (*14*). Will FS406-22 reveal the first tungsten-based nitrogenase? And, for that matter, if the earliest precursors of life were hyperthermophiles, did tungsten enzyme catalysis predate catalysis based on molybdenum? A few more questions to ponder.

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PHYSICS

A New Spin on the Insulating State

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Theory suggests a practical method for producing a novel insulating state of matter.

Electrical insulators are usually appreciated for their ability to do nothing. Such materials either trap or restrict the motion of free charges in matter. This is useful in all kinds of applications, ranging from the wiring in your home to directing the flow of electrons in the tiny circuits of your iPod. Now, on page 1757 of this issue, Bernevig *et al*. have proposed a new kind of two-dimensional insulator, which permits the flow of charge only at its edges (*1*). This may lead to the development of a new kind of solid-state electronic device.

An insulator has an energy gap separating filled and empty bands of electronic states, and thus is electrically inert because a finite energy is required to dislodge an electron. In the 1960s, Kohn characterized the insulating state in terms of the sensitivity of electrons inside the material to effects on the sample boundary (*2*). His insight was that the electrons of an insulator can be regarded as occupying localized orbitals (see the figure), so that they are insensitive to perturbations on the boundary.

The presence of a bulk energy gap does not guarantee that electrons have this "nearsighted" property. A counter example is provided by the quantum Hall state of a two-dimensional electron gas in a perpendicular magnetic field. In the quantum Hall effect, an energy gap results from the quantization of the closed circular orbits that electrons follow in a magnetic field. The inside of a quantum Hall system is thus inert like an insulator. However, at the boundary of the material a different type of motion occurs, which allows charge to flow in one-dimensional edge states. These edge states are unique in that they allow for charge to flow in one direction only. This makes them insensitive to scattering from impurities and explains the observed precise quantization of the Hall resistance.

Because both have a bulk energy gap, the insulating state and the quantum Hall state appear similar. The difference was explained by Thouless *et al*. (*3*), who generalized Kohn's notion of boundary sensitivity to show that an occupied band is characterized by an integer topological index. This index, n, distinguishes the insulating state ($n = 0$) from the quantum Hall state ($n \neq 0$) in a manner similar to the way that the mathematical "genus" of a solid body—which counts the number of holes—distinguishes a marble from a donut or a coffee cup. For quantum Hall states, the conducting edge states are a consequence of this topological structure.

Recently a new class of topological insulators has been predicted to be possible at zero magnetic field. This occurs because electrons have a quantum property called spin, which can have two possible polarizations, "up" and "down." In 2005, we showed theoretically that a single two-dimensional sheet of graphite, called graphene, has a small energy gap that

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