February 2002: Nitrogenase

Nitrogen is needed by all living things to build proteins and nucleic acids. Nitrogen gas is very common on the earth, as it comprises just over 75% of the molecules in air. Nitrogen gas, however, is very stable and difficult to break apart into individual nitrogen atoms. Usable nitrogen, in the form of ammonia or nitrate salts, is scarce. Often, the growth of plants is limited by the amount of nitrogen available in the soil. Small amounts of usable forms of nitrogen are formed by lightning and the ultraviolet light from the sun. Significant amounts of nitrogen are fed to plants in the form of industrial fertilizers. But the lion’s share of usable nitrogen is created by bacteria, using the enzyme nitrogenase.

Fixing Nitrogen

Nitrogen-fixing bacteria have the ability to convert nitrogen gas into ammonia, which is easily combined with other raw materials to form the building blocks of proteins and nucleic acids. This process requires extreme measures, because nitrogen gas is so stable. The industrial process used to create ammonia requires high temperatures and pressures of 300 atmospheres, along with catalysts. In nitrogen-fixing bacteria, the enzyme nitrogenase drives the reaction with a large quantity of ATP, and uses a collection of metal ions, including an unusual molybdenum ion, to perform the reaction.

An Expensive Reaction

Nitrogenase is composed of two components, shown here from entry 1n2c. The MoFe protein, shown in blue and purple, contains all of the machinery to perform the reaction, but requires a steady source of electrons. The reaction requires the addition of six electrons for each nitrogen molecule that is split into two ammonia molecules. The Fe protein, shown in green, uses the breakage of ATP to pump these electrons into the MoFe protein. In the typical reaction, two molecules of ATP are consumed for each electron transferred. Nitrogenase also converts hydrogen ions to hydrogen gas at the same time (this might be an obligatory part of the nitrogen-splitting reaction, or it might be a simple side effect), thus consuming even more ATP in the process.
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This is a large investment in energy, but well worth the effort if nitrogen is not available in the environment. Fortunately, nitrogen-fixing bacteria are found throughout the world, and are often found in partnerships with plants. For instance, legumes build special nodules in their roots that provide a perfect home for the bacteria. The plants provide shelter and even a few essential nutrients, jealously guarding their guests, and the bacteria provide a steady supply of nitrogen.

The Nitrogen–splitting Anvil

At the heart of nitrogenase is an unusual complex of iron, sulfur and a molybdenum ion, which is thought to perform the nitrogen–fixing reaction. A string of cofactors feed electrons to this MoFe–cluster. As seen in the illustration on the left, electrons start at a pair of ATP molecules (two at each end of the dimeric complex), flow inwards into the iron–sulfur cluster, then to the P–cluster, and finally to the MoFe–cluster. The three metal clusters are shown in the close–up figure at right. The MoFe–cluster is at the bottom, with the molybdenum atom in bright red. A homocitrate molecule, shown with white carbon atoms and pink oxygen atoms, helps to stabilize this unusual metal ion. The P–cluster is in the middle and the iron–sulfur cluster of the Fe protein is at the top. In spite of the detailed knowledge provided by the beautiful structures of nitrogenase (1n2c is shown here), the actual binding site for nitrogen gas is still a subject of controversy and intense study.
Exploring the Structure

The metal clusters are the centerpiece of nitrogenase, and are the major attraction on any tour of the structures. PDB entry 1n2c is a good place to start—it contains both the MoFe protein (in blue and purple at the center) and two copies of the Fe protein dimer bound on either end (shown in green). The metal ions are easily displayed using a spacefilling representation, which reveals the iron–sulfur cluster, the P–cluster, and the FeMo–cluster arranged in a row. The ATP binding site is revealed in this structure by using an unusual analogue of ATP: an ADP molecule with an aluminum fluoride ion. Two of these molecules bind at each end, forming a stable but inactive complex with the Fe protein, essentially gluing the Fe protein to the FeMo protein so its structure can be solved.