Origin of Life on Earth: Anaerobic C-C Bond Synthesis
ANSWERS TO QUESTIONS ABOUT THE RESEARCH PAPER BELOW

Huber, C. and Wächtershäuser, G. Activated Acetic Acid by Carbon Fixation on(Fe,Ni)S Under Primordial Conditions. Science 276: 245-247 (1997). Review (Prebiotic Chemistry) by Crabtree, R. H. Where Smokers Rule. Science 276: 222 (1997).

1. Define the following terms: chemoautotropic, primordial, primordial soup, archaebacteria, catalyst, corrin, pterin, synthase, bimodal catalyst, acetyl CoA

Chemoautotropic ("chem self food") is an adjective meaning the autocatalytic generation of fuel (food) molecules by chemical mechanisms. According to the current theories of how life arose on Earth, earliest organisms were dependent upon the chemical synthesis in their environments of fuel molecules, much like bacteria are dependent upon today at the deep ocean vents.

Primordial ("first of all") is an adjective meaning primary or first.

Primordial soup is a term that refers to the complex mixture of organic molecules that existed at the beginning of the Earth, acomplex mixture or "soup" out of which life forms evolved.

Archaebacteria (ancient single cell) are a new branch of bacteria that have been recently discovered and which have growth conditions and genetic characteristics that suggest they are very primative and may be closely related to the original organisms from which all life arose.

Catalyst is a chemical substance that speeds up the rate of a chemical reaction. It may be converted to other forms during the chemical reaction, but the catalysts is not consumed overall by any of the chemical changes occurring in the system.

Corrin is the name of a fused ring heterocycle compound (related to heme) that binds cobalt to form the cofactor (coenzyme) known as vitamin B_{12}. This heterocycle is synthesized by bacteria that live in the human gut (near the exit from the stomach). Dietary sources of cobalt provide the metal for the cofactor. The cofactor operates in conjunction with an enzyme (hence the alternate name for the cofactor, coenzyme) that directs the transfer of a methyl groups.

Pterin is the name of fused ring heterocyclic compound (related to purines) that works in conjunction with enzymes to transfer C_1 units (CH_3 (methyl), CHO (formyl), CH=N (imino)). This cofactor carries reducing equivalents as well as the C_1 units.

Synthase is the name of a subclass of enzymes that catalyze bond formation without the utilization of a high energy phosphate compound like ATP. These enzymes are in a major class called lyases for which the bond formation results in the loss of a small molecule like water or ammonia (ATP synthase: ADP + Pi 6 ATP + H_2O). **Synthetase**, on the other hand, is the name of a subclass of enzymes that catalyze bond formation with the utilization of a high energy phosphate compound (ATP, GTP, etc). These enzymes are in a major class called ligases for which the bond formation results in the splitting of the high energy phosphate compound (ATP 6 AMP + PiPi).

Bimodal catalyst is a catalyst that requires two metal ions, for example the (FeNi)S cluster as the catalytic center in acetyl CoA synthase in archaebacteria.

Acetyl CoA is a small molecule thioester that results from the degradation of carbohydrates, fatty acids, and amino acids. It is used in a number of anabolic (biosynthetic) pathways as well as catabolic (degradative) ones for energy.

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2. What are the five postulates of the theory of chemoautotropic metabolism of primordial organisms?

(a) The earliest organisms fed on CO and/or CO_2 at deep ocean hydrothermal vents.
(b) Their metabolism depended upon reducing power to form CH_3SH and to utilize this CH_3SH in reactions with CO and/or CO_2 to make an activated thioacetic acid.
(c) The thioacetic acid was used to trap more C units to add to the food supplies "primordial soup".
(d) The reducing power was derived from $FeS + H_2S$ 6 $FeS_2 + 2\ H^+ + 2\ e^-$ (see 5 below)
(e) All primorial chemistry occurred within the ligand spheres of transition metal catalysts or other substances that may have had useful properties (clay minerals, Se-containing, etc.)

3. Why did Huber and Wächtershäuser choose the following reaction conditions:

(a) 100 °C, 1 bar CO
(b) FeS and NiS as starting materials
(c) CH_3SH and CO as starting materials
(d) A pH range of 1 to 10

The conditions/materials (a-c) are known to be available at the deep ocean hydrothermal vents. The wide range of pH was studied to understand the importance of $[H^+]$ in the catalysis.

4. Examine Figure 1:

(a) What catalyst combination gave the highest yield of acetic acid over the narrowest range of pH? Why do Huber and Wächtershäuser think this combination is important?

The (FeNi)S combination gave the highest yield of acetic acid over the narrowest range of pH. Huber and Wächtershäuser point out that a cluster with this mixed metal sulfide is found in the modern day archeabacteria that make methyl thioacetic acid. This coincidence is striking and suggests the importance of such catalysts for the beginning of life on Earth.

(b) Provide an explanation as to why the (Fe,Ni)S and (Ni,Co)S combinations were active as catalysts in acetic acid formation but the FeS or CoS alone were not.

General idea: the combination of the Fe and Ni metal ions (Fe Co Ni), which are 1st row transition elements periodic table, may have a unique combination of empty and (partly) filled orbitals that are best suited for catalyzing C-C bond formation.

(c) What can be said about the contribution of Ni in this catalytic system?

Nickel is a versitile element because it can form complexes as a metallic element ($3d^8 4s^2 4p^0$) as well as the Ni^{2+} ion. Nickel complexes have various geometries: Ni^0: $Ni(CO)_4$ tetrahedral; Ni^{2+}: $Ni(H_2O)_4^{2+}$ tetrahedral (paramagnetic), $Ni(CN)_4^{2-}$ square planar (diamagnetic), $(Ni(CN)_5^{3-}$ trigonal bipyramidal. The arrangement of Ni and S in the nonmagnetic mineral pentlandite, $(FeNi)_9S_8$, is complex but apparently the metal ions are in both tetrahedral and octahedral coordination sites surrounded by the S. Although it has a somewhat metallic appearance, this mineral comes intimately associated with FeS so the metals are likely to be present as ions with S^{2-}. The field provided by the S^{2-} may split the d levels such that the mineral is diamagnetic with empty orbitals that can be filled by electron pairs from various ligand that are binding to the surfaces of the mineral.

See: http://www.chem.ualberta.ca/courses/plambeck/p102/p02262.htm):

$Ni(CO)_4$	theory: 4s4p form sp^3 hybrid orbitals that are filled by CO, $4s^2$ electrons fill 3d level for $3d^{10}$, diamagnetic
$Ni(H_2O)_4^{2+}$	theory: 4s4p form sp^3 hybrid orbitals that are filled by H_2O; ion is d^8 ion 2 unpaired e^-, paramagnetic
$Ni(CN)_4^{2-}$	theory: $3d4s4p^2$ form dsp^2 square planar structure with CN- filling 3ds; ion is d^{10}, diamagnetic.
$(Ni(CN)_5^{3-}$	theory: similar to $Ni(CN)_4^{2-}$; extra ligand makes complex trigonal bipyramidal, diamagnetic

For reference: spectrochemical series (split d orbitals - weaker ligands give paramagnetic complexes):
$I < Br^{--} < S^{2-} < Cl^- < NO_3^- < OH$. $RCO_2^- < H_2O$. $RS^- < CN^- < CO$

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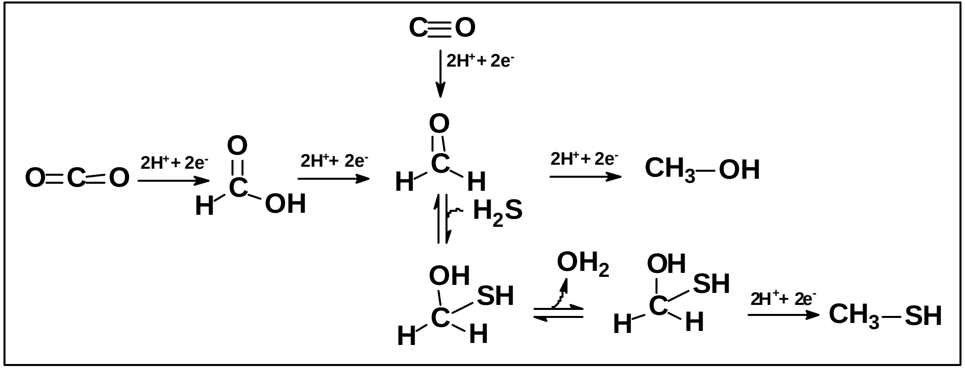
5. **(a) Write a balanced half reaction for the formation of pyrite (FeS_2) from H_2S and FeS (iron(II) sulfide; mineral name troilite).**

   $FeS + H_2S$ 6 $FeS_2 + 2\ H^+ + 2\ e^-$

   (b) Suggests a reaction sequence to account for the formation of CH_3SH from CO or CO_2 using H_2S and reducing power ($2\ e^- + 2\ H^+$) that would be provided from the oxidation you wrote in (a).

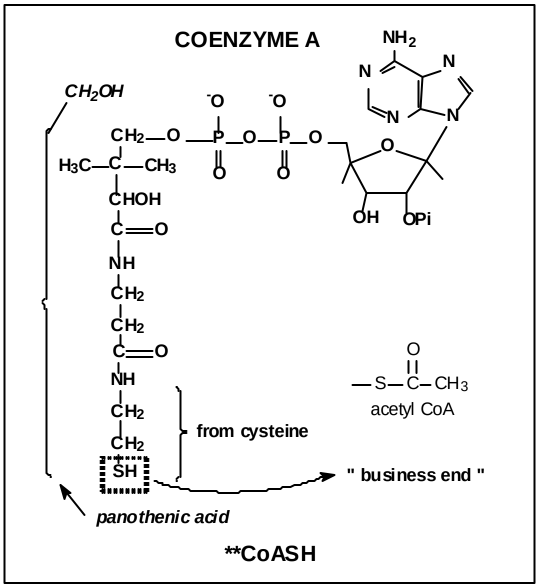


6. **What experiment was done that suggested to the authors that a metal-bonded thioacetate was an intermediate in the formation of methylthioacetate (CH_3COSCH_3) by the (Ni,Fe)S cluster?**

   The authors added aniline to a reaction mixture and identified acetanilide. This suggested to them that the bound thioacetate was an intermediate and that it was acting as an acetyl donor. Note that the aniline is not expected to be a good nucleophile. Why?

7. **Why do Huber and Wächtershäuser claim that methylthioacetate could not have been an energy source for primordial organisms? What experiments did they do to support their arguements?**

   The authors looked for the formation of the methylthioacetate ester under their reaction conditions as well as its stability at high temperatures. They did find this ester but also found that it was not stable at higher temperatures like those expected at the deep ocean geothermal vents. Therefore they conclude that it is unlikely that this ester was an early energy source (or carrier) for early life.



8. **What is the name of the thioester that is used by all living systems in energy pathways? What is the name of the enzyme that forms this thioester in archaebacteria? What is the function of the corrin in this enzyme?**

   The thioester that is used by all living organisms is called acetyl coenzyme A. It is composed of an acetyl group bound to the -SH group of an ADP derivativized with panothenic acid:

   Archaebacterial enzyme: acetyl CoA synthase

   Corrin in acetyl CoA synthase: CH_3- donor

9. **What do you think would be the effect of O_2 on this catalytic system?**

   The metal sulfides are all unstable to oxidation in the presence of water and oxygen. Some oxidize more rapidly than others. The Archeabacteria are all anaerobic organisms!