Biomimetic methane generation and disulfide formation by catalysis with a nickel complex

Masaru Tada* and Yoshihide Masuzawa

Department of Chemistry, Advanced Research Center for Science and Engineering and Materials Research Laboratory for Bioscience and Photonics, Waseda University, Shinjuku, Tokyo 169, Japan

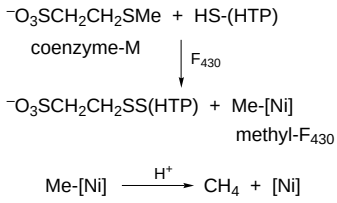
The final metabolic process of *methanogen*, methane generation and simultaneous disulfide formation, is simulated by the reaction of thioanisole with a toluenethiyl radical in the presence of a nickel complex, which is generated by the photolysis of a toluenethiolato–nickel complex.

Methanogens[1] are unique bacteria belonging to the Archae bacteria, which constitute the third domain of terrestrial life in addition to Eukaryotes and Prokaryotes.[2] A methanogen produces methane and water as metabolites to produce energy from hydrogen and carbon dioxide[3] [eqn. (1)]. The final step

$$4H_2 + CO_2 \xrightarrow{methanogen} CH_4 + 2H_2O \qquad (1)$$

$$\Delta G^0 = -131 \text{ kJ mol}^{-1}$$

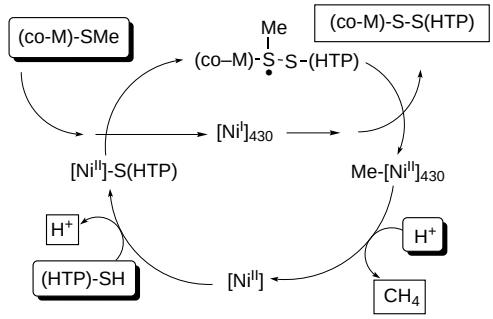
of this C_1-unit transformation is the generation of a mixed disulfide and methane (or methyl-F_{430}) from methyl-coenzyme M and 7-mercaptoheptanoylthreonine phosphate (HTP-SH) (Scheme 1).[3]



Scheme 1

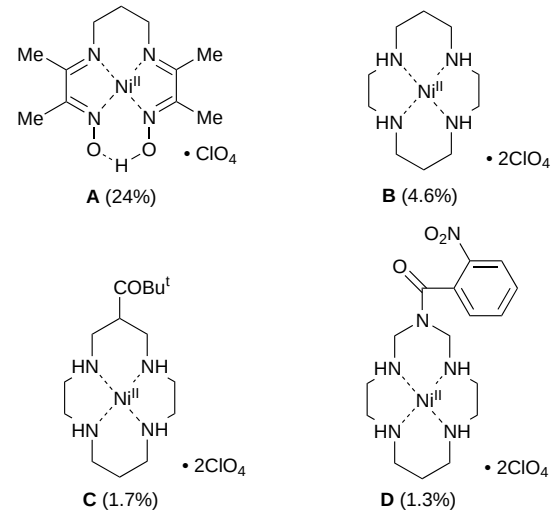
We have no analogy for this in organic or inorganic chemistry, and the main purpose of the present study is to establish a biomimetic reaction analogous to the biological methane production and gain insight into the biochemical reaction mechanism. Reported here is the first successful example of biomimetic production of methane and a mixed disulfide by catalysis with a nickel(II) complex, an F_{430} model.[4] F_{430} is a nickel complex having a modified corrin nucleus which is more flexible than the corrin nucleus in coenzyme B_{12}. This flexibility of F_{430} is considered to enable variation in coordination number during the catalysis.

On starting the experimental study, we adopted the working hypothesis shown in Scheme 2, which was originally proposed by Jaun[5a] and Berkessel.[5b] Thus the formation of a thiolato–nickel complex [Ni]–S(HTP) and a sulfuranyl radical (co-M)S•Me– S(HTP)and a final methyl transfer from the sulfuranyl radical to the nickel complex (F_{430}) are the crucial features of this mechanism.



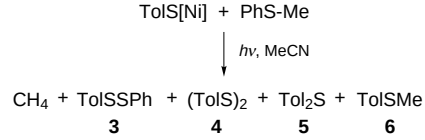
Scheme 2

Nickel(I) species have been reported to be active in an enzyme system;[6] therefore, we planned to produce the sulfuranyl radical and nickel(I) complex by the photolysis of the thiolato–nickel complex formed by the reaction of a nickel(II) complex and a thiolate ion. The colour of the MeCN solution of the nickel(II) complex **A** changed from orange to blue–violet on addition of the toluene-*p*-thiolate anion, which was prepared *in situ* from toluenethiol and NaH. A mixture of the toluene-*p*-thiolate ion (1.5×10^{-2} mol l^{-1}) and the nickel complex **A** (5.0×10^{-3} mol l^{-1}) was added to thioanisole (1.5×10^{-2} mol l^{-1}) in MeCN, and the mixture was irradiated at 350 nm under argon.†



Product analyses showed the formation of a mixed disulfide **3** in addition to ditolyl disulfide **4** and ditolyl sulfide **5** (Scheme 3). The time course of the formation of the mixed disulfide **3** and ditolyl disulfide **4** is shown in Fig. 1, which shows that the initial products **3** and **4** decompose on continuous irradiation. Reference irradiation showed the decomposition of these disulfides into the corresponding sulfides, and thus the initial products are the disulfides **3** and **4**.

Gas chromatography–mass spectral analysis (utilizing peaks at *m/z* 12 and 15 to avoid contamination by oxygen) of the top



Scheme 3

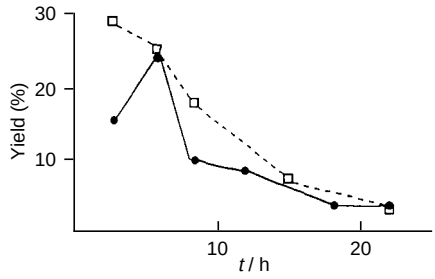
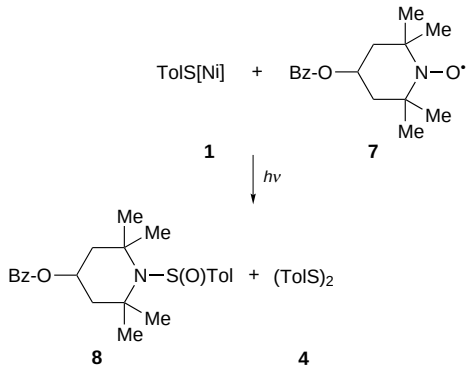


Fig. 1 The time course of the formationn of disulfides (●) **3** and (□) **4**

gas of the reaction vessel showed the evident formation of methane, although the yield could not be determined due to the solubility of methane in MeCN. Irradiation of the same mixture containing an equivalent amount of compound **7** gave compound **8**‡ in 12% yield. The formation of **8** and ditolyl disulfide **4** shows the intervention of the toluenethiyl radical (Scheme 4).

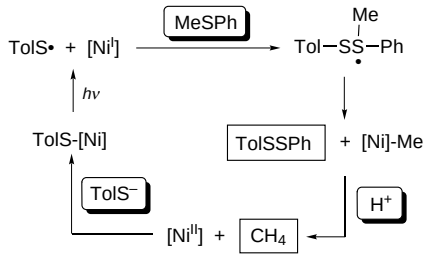


Scheme 4

Other nickel(II) complexes **B**–**D** showed some catalytic activity, although with less efficiency, and the yields of **3** after 6 h irradiation are shown in parentheses beneath their structures. Neutral complexes such as bis(dimethylglyoximato)nickel(II) and tetraphenylporphyrin–nickel(II) showed no activity.§ Formation of the mixed disulfide was not observed when either the nickel(II) complex or irradiation was absent. This reaction catalysed by the nickel(II) complex **A** is summarized by Scheme 5 and the net reaction is written as eqn. (2).

$$\mathrm{TolS^-} + \mathrm{MeSPh} + \mathrm{H^+} \rightarrow \mathrm{TolSSPh} + \mathrm{CH_4} \qquad (2)$$

There are two possible action modes of the nickel complex as shown in Fig. 2; (*a*) an S_H2 type substitution on the methyl group or (*b*) a ligand coupling on the hypervalent state sulfur.[7] We prefer mode (*a*) because the use of ω-phenylalkyl phenylsulfide instead of thioanisole yields no mixed sulfide and



Scheme 5

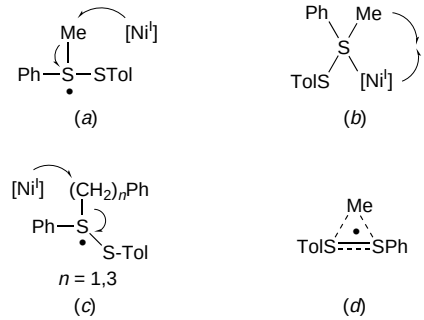


Fig. 2 Possible reaction modes of the sulfuranyl radical

phenylalkane. Thus the transition state (*c*) of the nickel attack must be more hindered than the transition state (*a*) in which the least bulky methyl group is the reaction centre, and the present reaction seems to be under severe steric control. On the other hand, steric control is less important for mode (*b*) because the reaction centre is a sulfuranyl radical.

Finally, we detected a trace amount of methyl tolyl sulfide **6** from the present model reaction, and the methyl group on the sulfuranyl radical (*a*) seems to swing to some extent through a transition state (*d*). We are studying the effect of this methyl migration on the present intramolecular methyl transfer of biomimetic type.

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Footnotes and References

* E-mail: mtada@mn.waseda.ac.jp

† An MeCN solution (10 cm^3) of the reaction mixture was irradiated by a Rayonett Photoreactor equipped with 350 nm lamps for the specified periods. The products were identified by comparison with authentic material. The time course of the product yields was determined by gas chromatography using internal standards.

‡ We prefer the sulfinylamide structure **8** formed by the rearrangement of the direct radical coupling product because the base peak in the mass spectrum is seen at *m/z* 139, showing the existence of TolS(O), but only a weak peak corresponding to (TolS) was seen.

§ Addition of piperidine to those neutral complexes did not produce a major spectral change, but the UV absorption maxima of complex **A** (385.0 and 409.5 nm in EtOH) were replaced by maxima at 340.0, 454.5 and 578 (broad) nm or by a broad absorption band at *ca*. 560 nm upon addition of piperidine or toluenethiolate ion.

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