DOI: 10.1002/ange.200602560

Methane Oxidation by Aqueous Osmium Tetroxide and Sodium Periodate: Inhibition of Methanol Oxidation by Methane**

*Takao Osako, Eric J. Watson, Ahmad Dehestani, Brian C. Bales, and James M. Mayer**

The direct oxidation of methane to methanol has long been one of the most important challenges in chemical reactivity.[1] Methane is the primary component of natural gas and is used both as a fuel and a feedstock. However, transportation and storage of methane are more demanding than for liquid

---

[*] Dr. T. Osako, Dr. E. J. Watson, Dr. A. Dehestani, Dr. B. C. Bales, Prof. Dr. J. M. Mayer
Department of Chemistry
University of Washington
Seattle, WA 98195-1700 (USA)
Fax: (+1) 206-685-8665
E-mail: mayer@chem.washington.edu

[**] This work was supported by the U.S. National Science Foundation (CHE-0204697 and CHE-0513023), the U.S. National Institutes of Health, and the Japan Society for the Promotion of Science (JSPS Postdoctoral Fellowship for Research Abroad to T.O.). We thank R. Morley for glassblowing.

Supporting information for this article is available on the WWW under http://www.angewandte.org or from the author.

methanol. Conversion of methane to methanol is difficult owing to the strong methane C–H bond (105 kcal mol^{-1})[2] and the ease of over-oxidation of methanol. Much effort has been devoted to this challenge, using both homogeneous and heterogeneous processes. Heterogeneous methane oxidation has been explored with many metal oxides, typically at high temperatures.[1,3] Studies of low-temperature, homogeneous methane oxidation have been inspired by the methane-oxidizing enzymes[4] and the discovery by Shilov et al. of the catalytic conversion of methane into CH_3OH and CH_3Cl with aqueous platinum salts.[5] Most of the enzymatic, biomimetic, and heterogeneous reactions are thought to follow free-radical pathways.[1,6,7] In contrast, the various Shilov-type systems utilizing soft heavy-metal ions are thought to have organometallic mechanisms initiated by methane binding to the metal.[8]

Herein, we describe a new approach to direct methane oxidation, using aqueous osmium tetroxide and sodium periodate ($OsO_4/NaIO_4$). Methanol overoxidation is still an issue in this system but remarkably methane inhibits the oxidation of methanol under these conditions. OsO_4 and RuO_4 could be the only two binary metal oxides whose reactivity with CH_4 has not been reported before, because their volatility and toxicity prevent heterogeneous, high-temperature studies. RuO_4 oxidizations of higher alkanes have been described[9] and we have reported OsO_4 oxidations of H_2[10] and higher alkanes (not methane) in basic aqueous solutions.[11]

Solutions of OsO_4 and $NaIO_4$ in D_2O react with CH_4 at 50 °C to give CH_3OH, $CH_2(OH)_2$, and CO_2 [Eq. (1)]. This

$$CH_4 \xrightarrow[D_2O\ \text{at}\ 50\,°C]{OsO_4/NaIO_4} CH_3OH + CH_2(OH)_2 + CO_2 \qquad (1)$$

reaction—and all of the reactions described herein—used 50 mM concentrations of OsO_4 and $NaIO_4$ in D_2O in a flame-sealed NMR tube containing 9.5 atm of methane (12 mM[12]) at 50 °C.[13] The products were observed and quantified by ^1H NMR spectroscopy, referenced to a solution of C_6Me_6 in C_6D_6 in a sealed capillary in the NMR tube: $\delta = 3.38$ ppm, CH_3OH, 0.32 mM; $\delta = 4.85$ ppm, $CH_2(OH)_2$, 0.24 mM (Figure 1 A). Oxidation of $^{13}CH_4$ (99 % ^{13}C) under the standard conditions occurs similarly, with the $^{13}C\{^1H\}$ NMR spectrum showing $^{13}CH_3OH$, $^{13}CH_2(OH)_2$, and $^{13}CO_2$ at $\delta = 49$, 82, and 125 ppm, respectively (Figure 1 B). Monitoring by ^1H NMR spectroscopy showed that the methanol concentration reached 0.28 mM within 4 h of reaction and rose only slightly over the following 5 days (Figure 1 C). The final methanol concentration is only 0.6 % of the starting OsO_4 and $NaIO_4$ concentrations, and 2.7 % of the starting methane concentration. The reactions are carried out anaerobically, so Os^{VIII} and I^{VII} are the only oxidants present.[14] No methane oxidation products are detected by ^1H and ^{13}C NMR spectroscopy using aqueous $NaIO_4$ without OsO_4, or in OsO_4 without IO_4^-. The latter experiment was performed with phosphate buffer to set the pH to 4.3, the characteristic pH value of 50 mM periodate solutions. Thus, both OsO_4 and $NaIO_4$ are needed for the formation of methanol.

Mechanistically, methane oxidation is unlikely to involve hydroxyl radicals given the mild conditions (OH• was ruled out in the higher-temperature, high-pH value oxidation of *iso*-butane based on the clean selectivity for oxidation of the tertiary C–H bond[11]). Methane coordination to osmium is also very unlikely given the limited affinity of OsO_4 for strong ligands, such as pyridine.[15] Perhaps the pathway involves [3+2] addition of a methane C–H bond to two oxo groups, as has been suggested in computational studies of CH_4 reactions with OsO_4 and RuO_4,[16] and in experimental and computational studies of OsO_4 and RuO_4 oxidations of H_2 and higher alkanes.[9–11,17]

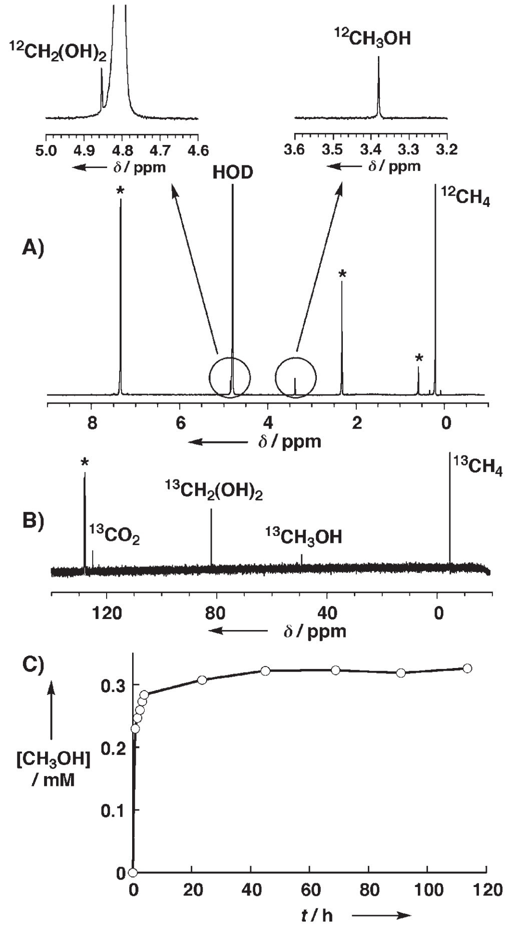

Figure 1. Oxidations of methane (9.5 atm) by OsO_4 and $NaIO_4$, both 50 mM in D_2O, at 50 °C. The asterisk peaks are due to the capillary standard (C_6Me_6 and H_2O in C_6D_6). A) ^1H NMR spectrum for $^{12}CH_4$ oxidation after 3 days. B) $^{13}C\{^1H\}$ NMR spectrum for $^{13}CH_4$ oxidation after 3 days. C) Time course for the oxidation of $^{12}CH_4$.

The oxidation of methanol by OsO_4 and/or $NaIO_4$ has also been examined. There are a number of reports of alcohol oxidations by OsO_4 and by iodates, and IO_4^- has been used as the terminal oxidant in OsO_4-catalyzed reactions.[18] We find that 5 mM $^{13}CH_3OH$ is completely oxidized within 3 h at 50 °C by $OsO_4/NaIO_4$ under 9.5 atm of argon (Figure 2 C). In contrast, oxidation of $^{13}CH_3OH$ under the same conditions except with 9.5 atm $^{12}CH_4$ instead of Ar, proceeds much more slowly: most of the methanol still present after 5 days at 50 °C (Figure 2 A, B). Methanol oxidation is slowed by a factor of approximately 10^3 by 9.5 atm CH_4.

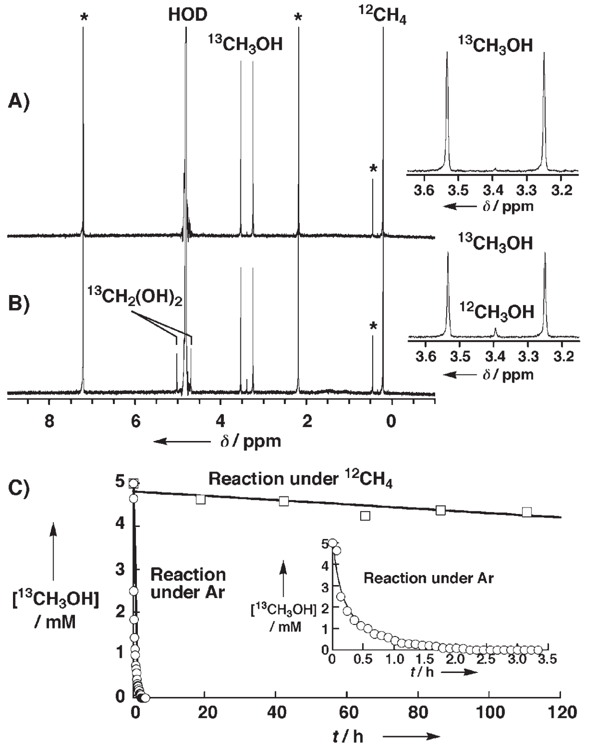

Figure 2. Oxidations of $^{13}CH_3OH$ (5 mM) by OsO_4 and $NaIO_4$, both 50 mM in D_2O, at 50 °C. The asterisk peaks are due to the capillary standard (C_6Me_6 and H_2O in C_6D_6). A,B) Under 9.5 atm $^{12}CH_4$: A) initial ^1H NMR spectrum, B) after 5 days. C) Time courses for the oxidations under 9.5 atm $^{12}CH_4$ (□) or 9.5 atm Ar (○). Inset: initial stage of the reaction under 9.5 atm Ar for 0–3.5 h.

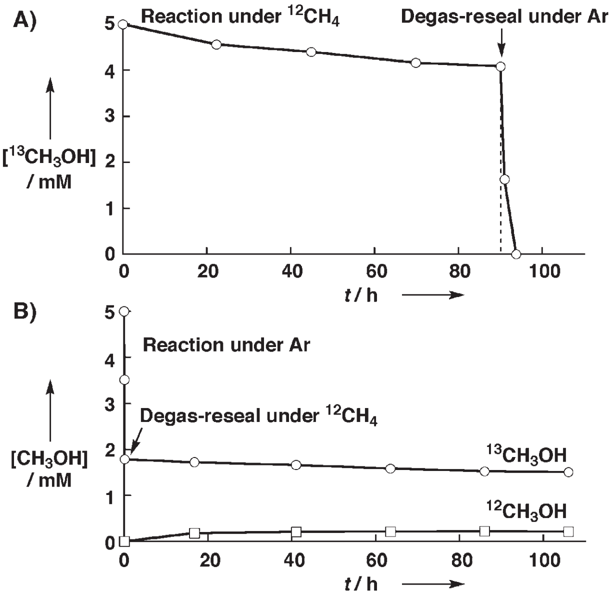

Figure 3. Time courses for the degas–reseal experiments at 50 °C (5 mM $^{13}CH_3OH$, 50 mM OsO_4, 50 mM $NaIO_4$ in D_2O). A) Reaction under 9.5 atm $^{12}CH_4$, which was then degassed and resealed under 9.5 atm Ar at the arrow/dotted line. B) Reaction under 9.5 atm Ar then 9.5 atm $^{12}CH_4$ at the arrow (10 min).

This very surprising inhibition by methane has been confirmed by two of the co-authors in a variety of experiments over more than a year. We have used $^{12}CH_4/^{13}CH_3OH$ and $^{13}CH_4/^{12}CH_3OH$, with different samples of OsO_4, periodate, and D_2O. The most dramatic observations come from degas–reseal experiments. A long medium-walled NMR tube was charged with 5.0 mM $^{13}CH_3OH$, OsO_4, and $NaIO_4$ in D_2O under our standard conditions. After three freeze-pump-thaw-degas cycles, $^{12}CH_4$ was added and the tube flame-sealed (all experiments carried out at 9.5 atm gas pressure[19]). After 4 days at 50 °C, only 18 % of the $^{13}CH_3OH$ had been consumed (Figure 3 A). The solution was then frozen, and the tube was cut open and returned to the vacuum line. The methane was removed with three freeze-pump-thaw cycles and replaced with argon, and the tube was re-sealed with a torch. Upon further heating of *the same solution*—having changed only the gas present—the methanol was consumed within 3 h. Figure 3 B shows the results of the complementary experiment: in the first stage under Ar, 64 % of the $^{13}CH_3OH$ is consumed after 10 min but after resealing under $^{12}CH_4$ the remaining $^{13}CH_3OH$ was preserved over 5 days and $^{12}CH_3OH$ was generated from $^{12}CH_4$.

Figure 3 A shows that the inhibition is caused by a material that is removed upon degassing. No inhibition is observed under argon in the presence of the volatile oxidation products CO or CO_2 (or formaldehyde or H_2). A degas–reseal experiment in which the initial methane was replaced with fresh methane showed no difference from a constant methane atmosphere. These experiments indicate that the inhibition is caused by methane, rather than products of methane oxidation.

Methanol oxidation by $OsO_4/NaIO_4$ is also inhibited by CD_4, but is not affected by 9.5 atm of Xe or Ar, 1 atm N_2, or 30 μL CCl_4. Preliminary experiments suggest that methanol oxidation at 50 °C is also inhibited by ethane and *iso*-butane but not by 30 μL of cyclohexane. Inhibition by methane is not observed in the presence of 500 mM phosphate buffer (maintaining the pH of 4.4 set by IO_4^- alone).

Under our standard conditions,[13] methanol oxidations by OsO_4 alone, or by $NaIO_4$ alone, are much slower than with the two oxidants together (36–43 % $^{13}CH_3OH$ consumed after 200 h versus completely consumed in 3 h). The presence of $^{12}CH_4$ does not affect $^{13}CH_3OH$ oxidation by OsO_4 alone and slows the oxidation by $NaIO_4$ by only a factor of about 4 (Supporting Information). Reactions of the separated oxidants are roughly as fast as observed for CH_4-inhibited OsO_4/$NaIO_4$. Thus an unusually active oxidant is formed from $OsO_4/NaIO_4$, consistent with the methane oxidation results. There is, however, no optical spectroscopic evidence for any interaction between OsO_4 and IO_4^-. It should be noted that under 9.5 atm CH_4, the methane concentration in D_2O is 9.5 ± 0.4 mM in all these solutions, varying only marginally with the other materials present in solution.

The inhibition of a reaction by a low concentration of methane is to our knowledge unprecedented. Methane is usually viewed as a very inert material. Under the conditions where inhibition is observed, only a small fraction of the OsO_4 and $NaIO_4$ are consumed, and there is no evidence from optical or NMR spectroscopy for any interaction of methane with any of the reagents. It is not clear whether the origin of this highly unusual inhibition is a chemical effect, inhibiting formation of the $OsO_4/NaIO_4$ active oxidant, or a physical effect related to unusual solvation in H_2O/CH_4 (perhaps related to H_2O/CH_4 clathrates[20]).

In conclusion, aqueous solutions of OsO_4 and $NaIO_4$ oxidize methane to give a small amount of methanol under very mild aqueous conditions: 50 °C, 9.5 atm CH_4. Further oxidation of methanol is competitive with methane oxidation. The presence of methane substantially inhibits the oxidation of methanol. Further studies are in progress to define the scope, kinetics, and mechanisms of both the methane oxidation and this unprecedented inhibition.

Received: June 27, 2006

Keywords: inhibition · methane · methanol · osmium · oxidation

---

[1] a) H. D. Gesser, N. R. Hunter in *Methane Conversion by Oxidative Processes* (Ed.: E. E. Wolf), Van Nostrand Reinhold, New York, **1992**, p. 403; b) M. G. Axelrod, A. M. Gaffney, R. Pitchai, J. A. Sofranko in *Natural Gas Conversion II*, Elsevier, Amsterdam, **1994**, p. 93; c) J. H. Lunsford, *Catal. Today* **2000**, *63*, 165; d) R. H. Crabtree, *Chem. Rev.* **1995**, *95*, 987.

[2] NIST Chemistry WebBook, http://webbook.nist.gov/chemistry/ National Institute of Standards and Technology, Gaithersburg MD, **2005**.

[3] a) H. D. Gesser, N. R. Hunter, C. B. Parkash, *Chem. Rev.* **1985**, *85*, 235; b) T. J. Hall, J. Hargreaves, G. J. Huncthing, R. W. Richard, W. Joyner, S. H. Taylor, *Fuel Process. Technol.* **1995**, *42*, 151; c) K. Tanaka, Y. Teng, T. Takemato, *Catal. Rev.* **2002**, *44*, 1.

[4] a) H. Zheng, J. D. Lipscomb, *Biochemistry* **2006**, *45*, 1685; b) M. H. Baik, M. Newcomb, R. A. Friesner, S. J. Lippard, *Chem. Rev.* **2003**, *103*, 2385; c) R. L. Lieberman, A. C. Rosenzweig, *Nature* **2005**, *434*, 177.

[5] a) N. F. Goldshleger, V. V. Eskova, A. E. Shilov, A. A. Shteinman, *Zh. Fiz. Khim.* **1972**, *46*, 1353; b) A. E. Shilov, G. B. Shul'pin, *Chem. Rev.* **1997**, *97*, 2897.

[6] see, for example, J. A. Labinger, *Catal. Lett.* **1988**, *1*, 371, and ref. [3c].

[7] a) *Biomimetic Oxidations Catalyzed by Transition Metal Complexes* (Ed.: B. Meunier), Imperial College Press, London **2000**; b) J. M. Mayer, E. A. Mader, J. P. Roth, J. R. Bryant, T. Matsuo, A. Dehestani, B. C. Bales, E. J. Watson, T. Osako, K. Valliant-Saunders, W. H. Lam, D. A. Hrovat, W. T. Bordon, E. R. Davidson, *J. Mol. Catal. A* **2006**, *251*, 24; c) Ref. [4a]; d) Ref. [4b] has an alternative view.

[8] a) *Activation and Functionalization of C–H Bonds* (Eds.: K. I. Goldberg, A. S. Goldman), American Chemical Society, Oxford University Press, Washington, DC, **2004**; b) R. A. Periana, O. Mironov, D. J. Taube, G. Bhalla, C. J. Jones, *Science* **2003**, *301*, 814; c) B. A. Arndtsen, R. G. Bergman, T. A. Mobley, T. H. Peterson, *Acc. Chem. Res.* **1995**. *28*, 154; d) J. S. Owen, J. A. Labinger, J. E. Bercaw, *J. Am. Chem. Soc.* **2006**, *128*, 2005.

[9] a) A. Tenaglia, E. Terranova, B. Waegell, *J. Org. Chem.* **1992**, *57*, 5523; b) A. Tenaglia, E. Terranova, B. Waegell, *J. Chem. Soc. Chem. Commun.* **1990**, 1344; c) A. Tenaglia, E. Terranova, B. Waegell, *Tetrahedron Lett.* **1989**, *30*, 5271; d) J. M. Bakke, A. E. Froehaug, *J. Phys. Org. Chem.* **1996**, *9*, 507; e) J. M. Bakke, A. E. Froehaug, *J. Phys. Org. Chem.* **1996**, *9*, 310.

[10] A. Dehestani, W. H. Lam, D. A. Hrovat, E. R. Davidson, W. T. Borden, J. M. Mayer, *J. Am. Chem. Soc.* **2005**, *127*, 3423.

[11] B. C. Bales, P. Brown, A. Dehestani, J. M. Mayer, *J. Am. Chem. Soc.* **2005**, *127*, 2832.

[12] Methane concentration calculated using: *IUPAC Solubility Data Series: Methane* (Eds.: H. L. Clever, C. L. Young), Pergamon, Oxford, **1987**.

[13] Typical procedure: A medium walled NMR tube was charged with 400 µL of a solution of OsO_4 (50 mM; Colonial Metal) and $NaIO_4$ (50 mM; Aldrich) in D_2O (Cambridge Isotope). After three cycles of freeze-pump thaw degassing, $^{12}CH_4$ (7.2 mL of 1 atm; 99.99 %, Matheson) at 25 °C was condensed into the tube with liquid N_2. The NMR tube was flame sealed to be 15 cm in length, shaken vigorously, and then placed in an oil bath at 50 °C.

[14] Other I^{VII} oxyanions are present in 50 mM aqueous $NaIO_4$ solutions: I. Kerezsi, G. Lente, I. Fábián, *Dalton Trans.* **2004**, 342.

[15] "Osmium": W. P. Griffith in *Comprehensive Coordination Chemistry*, *Vol. 4* (Ed.: G. Wilkinson), Pergamon, New York, **1987**, p. 519.

[16] a) W. H. Lam, A. Dehestani, D. A. Hrovat, E. R. Davidson, W. T. Borden, J. M. Mayer, unpublished results, **2004**; b) M. Drees, T. Strassner, *J. Org. Chem.* **2006**, *71*, 1755.

[17] J. P. Collman, L. M. Slaughter, T. A. Eberspacher, T. Strassner, J. I. Brauman, *Inorg. Chem.* **2001**, *40*, 6272.

[18] a) W. P. Griffith, M. Suriaatmaja, *Can. J. Chem.* **2001**, *79*, 598; b) A. M. Maione, A. Romeo, *Synthesis* **1984**, 955; c) B. Singh, A. K. Singh, M. B. Singh, A. P. Singh, *Tetrahedron* **1986**, *42*, 715; d) S. Singh, A. Gupta, A. K. Singh, *Transition Met. Chem.* **1998**, *23*, 277; e) G. A. Hiremath, P. L. Timanagoudar, R. B. Chougale, S. T. Nandibewoor, *J. Indian Chem. Soc.* **1998**, *75*, 363.

[19] The results are identical with 1 atm N_2 in place of 9.5 atm Ar.

[20] See a) S. F. Dec, K. E. Bowler, L. L. Stadterman, C. A. Koh, E. D. Sloan, Jr., *J. Am. Chem. Soc.* **2006**, *128*, 414; b) Z. Cao, J. W. Tester, K. A. Sparks, B. L. Trout, *J. Phys. Chem. B* **2001**, *105*, 10950.