Inorganic Chemistry

Article

pubs.acs.org/IC

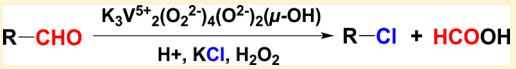
Decarbonylative Halogenation by a Vanadium Complex

Sujoy Rana, Rameezul Haque, Ganji Santosh, and Debabrata Maiti*

Department of Chemistry, Indian Institute of Technology Bombay, Powai, Mumbai 400076, India

Supporting Information

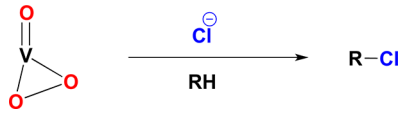
ABSTRACT: Metal-catalyzed halogenation of the C−H bond and decarbonylation of aldehyde are conventionally done in nature. However, metal-mediated decarbonylative halogenation is unknown. We have developed the first metal-mediated decarbonylative halogenation reaction starting from the divanadium oxoperoxo complex $K_3V^{5+}{}_2(O_2{}^{2-})_4(O^{2-})_2(\mu\text{-OH})$ (**1**). *Aconcerted* decarbonylative halogenation reaction was proposed based on experimental observations.



INTRODUCTION

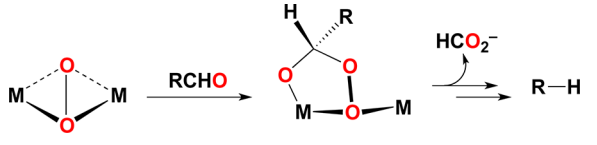
Halogenation occurs during biosynthesis of more than 4000 natural products that display biological activity of pharmacological interest including anticancer, antibacterial, antiviral, antifungal, and antiinflammatory activities. Chlorination is the predominant modification in nature, followed by bromination and iodination. Vanadium-dependent haloperoxidases (V-HPOs) are responsible for the majority of halogenation events in marine natural products.[1] A common feature of the haloperoxidases is generation of an η^2-peroxo intermediate, followed by the formation of vanadium-bound hypohalite, which is responsible for electrophilic halogenation reactions (Scheme 1).[2]

Scheme 1. Vanadium Oxoperoxo Catalyzed Halogenation in Nature



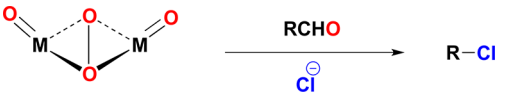
Like halogenation, aldehyde decarbonylation is another significant event in nature. The heme−peroxo intermediate of Cytochrome P450 catalyzes a number of C−C bond cleavage reactions via aldehyde decarbonylation.[3] Decarbonylation also occurs during biosynthesis of alka(e)ne by cyanobacteria (AD) in which a dinuclear nonheme−iron peroxo complex is the putative active species (Scheme 2).[3d,4] On a related note, an unknown deformylase is also suggested for the DNA demethylase activity.[5]

Scheme 2. Suggested Bimetallic Peroxo Species for Cyanobacterial AD



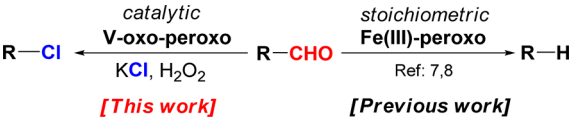
Although decarbonylation of aldehyde and halogenation of the C−H bond are common in nature, metal-mediated decarbonylative halogenation is unknown. Therefore, we set out to develop a synthetic system that would deliver a decarbonylative halogenation reaction. We postulated that a divanadium oxoperoxo complex (Scheme 3, M = V) could be a

Scheme 3. Proposed Decarbonylative Halogenation Reactions



suitable species based on the following: (1) bioinspired vanadium oxoperoxo complexes are known for halogenation reaction (Scheme 4);[2,6] (2) dimetallic peroxo species are

Scheme 4. Decarbonylative Halogenations by a Vanadium Catalyst



suggested to carry out a decarbonylation reaction in cyanobacterial aldehyde decarbonylase (AD; Scheme 2).[4b,c] Notably, Nam and co-workers reported decarbonylation of aldehyde by a nonheme−iron(III) peroxo complex.[7] Valentine also illustrated that a synthetic peroxoporphyrin complex, $[Fe^{III}(TMP)(O_2{}^{2-})]^-$, can promote direct nucleophilic attack on an aldehyde.[8]

RESULTS AND DISCUSSION

A bright-yellow divanadium oxoperoxo complex, $K_3(V^{5+})_2(O_2{}^{2-})_4(O^{2-})_2(\mu\text{-OH})$ [$K_3V_2O_{12}H_3$, **1**], was synthesized from V_2O_5/KOH at room temperature in 80% yield.[9] The

Received: October 18, 2012

   dx.doi.org/10.1021/ic302611a | Inorg. Chem. XXXX, XXX, XXX−XXX

structure of complex **1** has been reported previously, which we have further confirmed by X-ray crystallography (Figure 1).[9,10]

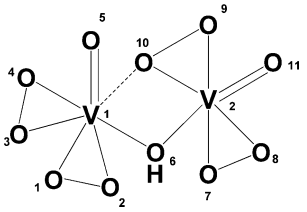
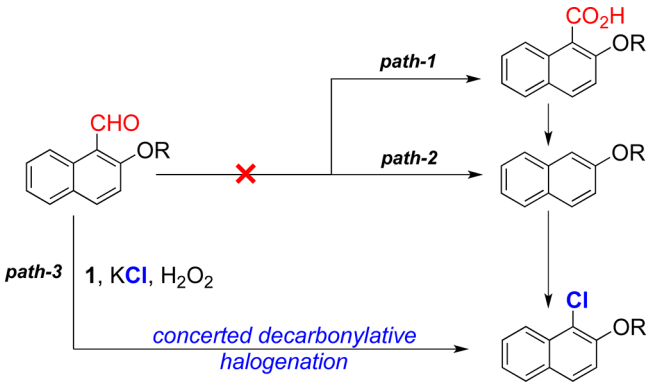


Figure 1. Structure of complex **1**.

In addition, we have characterized the compound by UV−vis (λ_{max} ∼ 320 nm; ε ∼ 1144 M^{-1} cm^{-1}) and IR [$\nu_{V1=O5}$ = 971 cm^{-1}, $\nu_{V2=O11}$ = 942 cm^{-1}, and ν_{O-O} = 886 and 869 cm^{-1}] spectroscopy.[9] The ^{51}V NMR spectra clearly suggested that two vanadium centers are inequivalent (δ = −731 and −765 ppm), which can also be inferred from the X-ray structure.[9]

Unlike in the iron complexes,[7,8] decarbonylation of aldehydes was *not* observed with **1**. Interestingly, when we reacted 2-hydroxy-1-naphthaldehyde with **1** in the presence of KCl (or KBr), we observed the formation of 1-chloronaphthalen-2-ol (Scheme 5 and Table 1, entry 1). Like 2-hydroxy-1-naphthaldehyde, 2-methoxy-1-naphthaldehye also gave similar decarbonylative halogenated products (Scheme 5 and Table 1, entry 2).[11]

Scheme 5. Reaction of 1 with 2-OR-naphthaldehyde

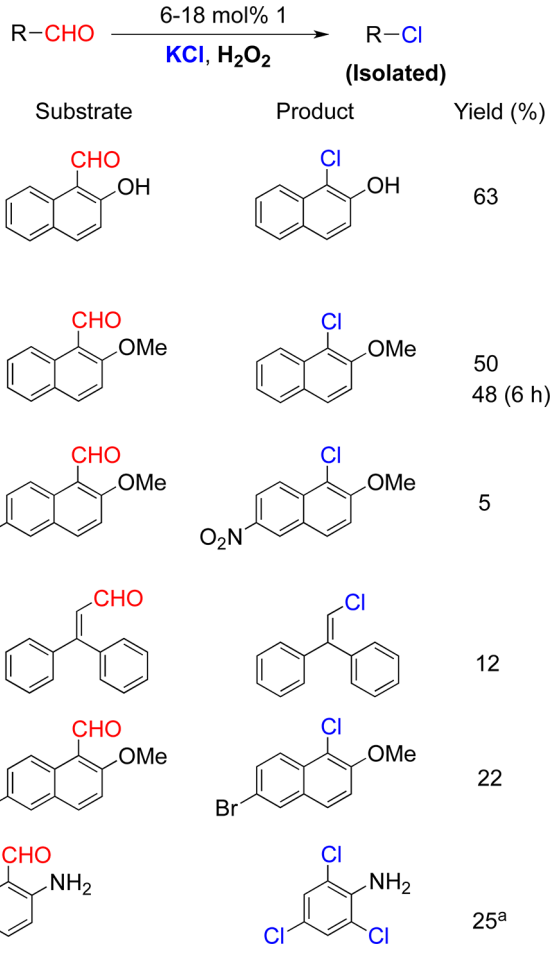


Although a methoxy (−OMe) or a hydroxy (−OH) group ortho to −CHO was successful (Scheme 6), bulkier substituents [R = allyl (−$CH_2CH{=}CH_2$), propargyl (−CH_2CCH), 2-chlorobenzyloxy (−OCH_2Ar)] failed to produce the desired decarbonylative chlorinated products. Such observations indicate that binding of the −OR group (Scheme 6) with the vanadium center is crucial for decarbonylative halogenation reactions.

Three possible pathways for decarbonylative halogenation of 2-hydroxy-1-naphthaldehyde (or 2-methoxy-1-naphthaldehye) could be envisioned (Scheme 5): (path 1) oxidation of a −CHO moiety to form −CO_2H and subsequent decarboxylation to generate β-naphthol (or 2-methoxynaphthalene), which then can be chlorinated;[12] (path 2) decarbonylation of a −CHO moiety to generate β-naphthol (or 2-methoxynaphthalene) and chlorination (stepwise); (path 3) a *concerted* decarbonylative chlorination.

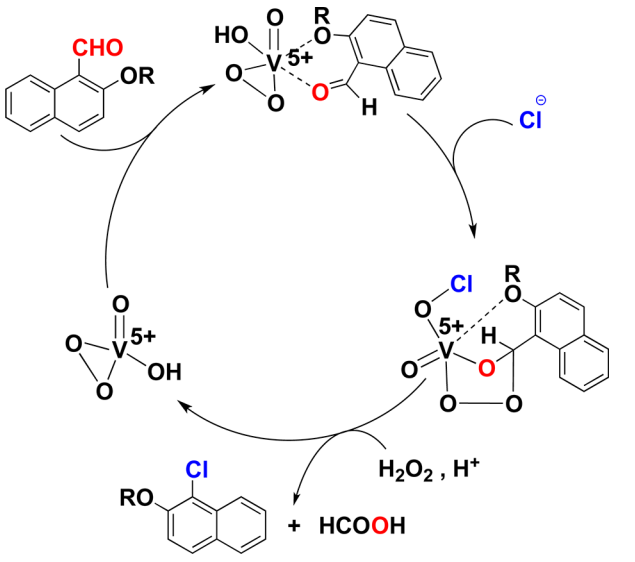
However, 2-hydroxy-1-naphthaldehyde failed to generate even a trace of 2-hydroxy-1-naphthoic acid (path 1) or β-

Table 1. Decarbonylative Chlorination by the Vanadium Complex 1[a]



[a]A total of 0.5 mmol of substrate, KCl (12 mmol), citrate−phosphate buffer (1.5 mL), 6.5 equiv of 30% H_2O_2, 1.22 M HCl (1.5 mL), acetone (1 mL), room temperature, 24 h. Recovered starting materials are accounted for in the mass balance. GC yield. H_2SO_4/KCl can also be used with catalyst **1** for decarbonylative chlorination reaction.[9].

Scheme 6. Concerted Decarbonylative Chlorination Reactions



dx.doi.org/10.1021/ic302611a | Inorg. Chem. XXXX, XXX, XXX−XXX

naphthol (path 2) with or without KCl (Scheme 5). We found that 2-hydroxy-1-naphthoic acid can be decarboxylated (with or without KCl) and 1-chloronaphthalen-2-ol can be generated in the presence of KCl (Scheme 5).[9] Also, 2-methoxy-1-naphthoic acid can be decarboxylated and/or chlorinated to form 1-chloro-2-methoxynaphthalene. We further found that β-naphthol or 2-methoxynaphthalene produced the desired chlorinated product (with or without KCl and with or without catalyst **1**).[9]

On a similar note, 2-methoxy-1-naphthaldehyde did not produce any 2-methoxy-1-naphthoic acid or 2-methoxynaphthalene (Scheme 5). On the basis of these experimental observations, we propose a *concerted* decarbonylative chlorination reaction by **1** (Schemes 5 and 6).

The role of H_2O_2 was probed for the proposed transformation. It was concluded that hydrogen peroxide (H_2O_2) is required for the (re)generation of vanadium oxoperoxo species $[V^{5+}(O^{2-})(O_2^{2-})]^+$. Without H_2O_2, a decarbonylative halogenated product was not detected. The Amount of desired decarbonylative chlorinated product formation increases while using up to 3.25 mmol of H_2O_2. Any further increase of the H_2O_2 amount is detrimental for product formation. Apart from acetone, methanol (42% for entry 1 in Table 1) and ethanol (44% for entry 1 in Table 1) were also used as the solvent, and acceptable yields of the desired products were obtained.[9] Note that the formation of acetone peroxide, a well-known explosive,[13] cannot be ruled out completely while using acetone as the solvent.

Next we have explored the scope of this decarbonylative chlorination reaction (Table 1). Various substituents such as −OH, −OMe, −Br, $-NH_2$, and $-NO_2$ were tolerated. Without catalyst **1**, desired decarbonylative halogenated products were not observed. The low yield of the electron-withdrawing nitro analogue is likely due to an unfavorable electrophilic aromatic substitution reaction (Table 1, entry 3). Trichloroarene was generated with amino analogues (entry 6) because of the strong *o*- and *p*-directing ability of the $-NH_2$ functional. Control experiments with either aniline or 2-chloroaniline as the substrate produced 2,4,6-trichloroaniline (40%). Thus, in the case of 2-aminobenzaldehyde (entry 6), a combination of a decarbonylative chlorinated reaction and electrophilic chlorination led to the formation of 2,4,6-trichloroaniline. Note that trihalogenation of aniline under acidic conditions has previously been reported in the literature.[12]

A monomeric vanadium oxoperoxo species, $[V^{5+}(O^{2-})(O_2^{2-})]^+$ (^{51}V NMR, δ −543; IR, 960 cm^{-1} for $\nu_{V=O}$ and 878 cm^{-1} for ν_{O-O}; UV−vis, λ_{max} ∼ 330 nm; Figure 2), was detected and characterized under the reaction conditions.[9,14,15] This species is likely to be responsible for the *concerted* decarbonylative halogenation reactions (Scheme 6). Note that a structurally related dimeric complex, $(NH_4)_4[(V^{5+})_2(O_2^{2-})_4(O^{2-})_2(\mu\text{-}O^{2-})]$, is known to generate such a monomeric V^{5+} complex in acidic conditions.[9,15] Further, a V^{5+} species, $V^{5+}(O^{2-})(O_2^{2-})(^-OH)$, has previously been suggested in the literature as the active species formed under acidic conditions.[6a,16,17]

Hypochlorite (OCl^-) formation under the present reaction conditions (with catalyst **1**; Scheme 7) was proposed based on detailed reports with a structurally related compound, $(NH_4)_4[V^{5+}{}_2(O_2^{2-})_4(O^{2-})_2(\mu\text{-}O^{2-})]$.[15]

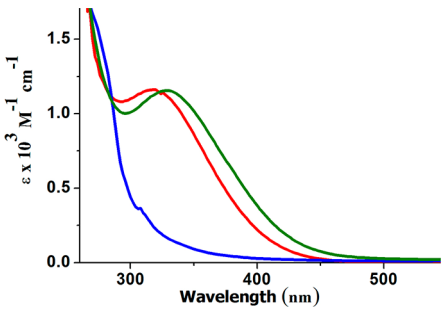
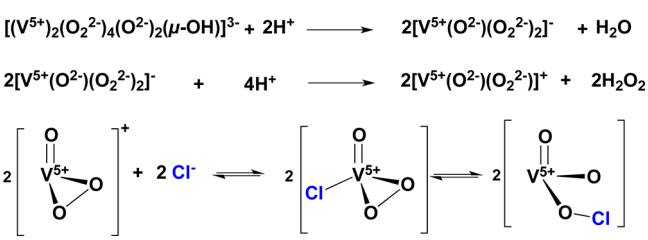


Figure 2. UV−vis spectra of **1** (red, λ_{max} = 320 nm), the formation of $[V^{5+}(O^{2-})(O_2^{2-})]^+$ species from **1** (green, λ_{max} = 330 nm), and the catalytically inactive species after completion of the reaction (blue).

Scheme 7. Formation of Vanadium Hypochlorite



Similar to cyanobacterial AD,[4,18] formic acid was detected and quantified (yield 52%) from decarbonylative halogenation of 2-hydroxy-1-naphthaldehyde (63%; Table 1, entry 1) by **1** (Scheme 6).[9] At the end of the catalytic reactions (Table 1), ^{51}V NMR of the resulting solution was found to contain V^{5+} species. The IR data showed two characteristic peaks at 937 cm^{-1} ($\nu_{V=O}$) and 887 cm^{-1} (ν_{O-O}), indicating the existence of a vanadium oxoperoxo moiety. All of these observations are consistent with the proposed mechanism in Scheme 6.[9] Such a V^{5+} state is also maintained in V-HPOs throughout the catalytic cycle.[1,2]

CONCLUSION

In summary, we have developed the first metal-mediated decarbonylative halogenation reaction starting from the divanadium oxoperoxo complex **1**. A *concerted* decarbonylative halogenation reaction was proposed based on experimental observations. Characterization of the intermediates and a detailed understanding of the reaction mechanism is presently underway in our laboratory.

EXPERIMENTAL SECTION

Reagent Information. Unless otherwise stated, all of the reactions were carried out at room temperature in a 20 mL screw-capped reaction tube. Chemicals and solvents were purchased from Aldrich, Merck, and Alfa Aesar. A gradient elution using petroleum ether and ethyl acetate was performed, based on Merck Aluminum TLC sheets (silica gel $60F_{254}$).

Analytical Information. All isolated compounds were characterized by ^1H and ^{13}C NMR spectroscopy, high-resolution mass spectrometry (HRMS), and gas chromatography−mass spectrometry (GC−MS). IR spectra were recorded on a Fourier transform infrared (FT-IR) spectrophotometer with samples prepared as KBr pellets. NMR spectra were recorded either on a Bruker 400 MHz or on a Varian 400 MHz instrument. Copies of the ^1H, ^{13}C, and ^{51}V NMR spectra are attached at the end of this document. All ^1H NMR spectra were reported in units of parts per million (ppm) and measured relative to the signals for residual chloroform (7.26 ppm) in a deuterated solvent, unless otherwise stated. All ^{13}C NMR spectra were reported in ppm relative to $CDCl_3$ (77.23 ppm), unless otherwise

dx.doi.org/10.1021/ic302611a | Inorg. Chem. XXXX, XXX, XXX−XXX

stated, and all were obtained with ^{1}H decoupling. All ^{51}V NMR spectra were recorded in D_2O and reported in ppm relative to NH_4VO_3 (−573.27 ppm). All GC analyses were performed on an Agilent 7890A GC system with a flame ionization detector using a J&W DB-1 column (10 m × 0.1 mm i.d.). All GC−MS analyses were done by an Agilent 7890A GC system connected with a 5975C inert XL EI/CI MSD (with a triple-axis detector).

Preparation of $K_3V_2O_{12}H_3$ (1).[9] A solution of V_2O_5 (1.82 g, 10 mmol) in 20 mL of distilled water was taken in a 100 mL round-bottomed flask and heated to 50−60 °C. Then KOH (2.3 g, 41 mmol) was added to the reaction mixture, and 1 mL of H_2O_2 (30%) was added to ensure dissolution. The reaction mixture was stirred for 1 h at 0 °C, and 6 mL of 30% H_2O_2 was added dropwise. Then it was warmed to room temperature and stirred for 6 h. The resulting mixture was filtered through sintered glass under reduced pressure, washed with cold water twice, and dried under vacuum. From the aqueous filtrate part, some amount of the complex was recovered by recrystallization. The yield of the desired product was 80% (3.28 g). **1** was crystallized from a saturated solution of water.

General Reaction Procedure (A) for the Reaction Setup. Vanadium catalyst **1** (40 mg, 18 mol %) was taken in a 20 mL reaction tube along with 1.5 mL of a 1.22 M HCl solution and 1.5 mL of a citrate−phosphate buffer solution. Then KCl (12 mmol, 0.895 g) and aldehyde (or alcohol) (0.5 mmol) were added, followed by 1 mL of acetone. Subsequently, 30% H_2O_2 (330 μL, 3.25 mmol) was added to the resulting reaction mixture. The reaction mixture was stirred at room temperature. After 24 h, CH_2Cl_2 (50 mL) was added to the reaction mixture and an organic component was extracted (2 × 50 mL of CH_2Cl_2). The organic extract was combined, dried over Na_2SO_4, and concentrated under reduced pressure in a rotary evaporator. The crude product thus obtained was further purified by column chromatography.

Preparation of 2-Methoxy-1-naphthoic acid..[9,19,20] A solution of 2-hydroxy-1-naphthoic acid (0.376 g, 2 mmol) in 10 mL of dry acetone was taken in a 100 mL two-neck round-bottomed flask. Potassium carbonate (0.828 g, 6 mmol) was added to the flask. The reaction mixture was heated at 60 °C, and Me_2SO_4 (0.378 mL, 4 mmol) was added dropwise by syringe. The resulting reaction mixture was refluxed overnight. It was cooled to room temperature, filtered through a funnel plugged with cotton/Celite, and washed with acetone/ethyl acetate. The organic filtrate was combined, dried over Na_2SO_4, and concentrated. Methyl 2-methoxy-1-naphthoate (0.410 g, 95% yield) was isolated by column chromatography (5% ethyl acetate in petroleum ether). The brown oily ester was refluxed for 12 h with 40% NaOH (5 mL) to generate the naphthoic acid derivative. The reaction mixture was neutralized with 10 N HCl at room temperature, and the organic part was extracted with ethyl acetate (3 × 50 mL). The organic extract was combined, dried over Na_2SO_4, and concentrated under reduced pressure in a rotary evaporator. The desired compound, 2-methoxy-1-naphthoic acid (0.307 g, 80%), was isolated by column chromatography (40% ethyl acetate in petroleum ether). ^{1}H NMR (400 MHz, $CDCl_3$): δ 4.02−4.11 (s, 3H), 7.24−7.28 (d, 1H), 7.29−7.35 (d, J = 9.1 Hz, 1H), 7.38−7.46 (m, 1H), 7.55−7.61 (m, 1H), 7.79−7.84 (m, 1H), 7.94−8.00 (d, J = 9.1 Hz, 1H), 8.34−8.42 (d, J = 8.6 Hz, 1H). ^{13}C NMR (101 MHz, $CDCl_3$): δ 57.35, 113.00, 115.11, 124.72, 124.84, 128.42, 128.47, 129.11, 131.76, 133.61, 155.91. GC−MS: m/z 202.1 ($[M]^+$).

Preparation of a Nitro Derivative of 2-Methoxy-1-naphthaldehyde.[9] A solution of 2-methoxy-1-naphthaldehyde (1 g, 5.37 mmol) was taken in a 100 mL round-bottomed flask, and it was kept at −5 °C in an ice bath. Then concentrated HNO_3 (10 mL, d = 1.47) was added portionwise so that the temperature did not rise above−5 °C (addition was continued for 35 min portionwise). The mixture was stirred for another 1 h at room temperature and poured into ice-cold water. The yellow precipitate was filtered off and subsequently washed with ethyl acetate. The organic filtrate was collected. The aqueous part was also extracted with ethyl acetate (2 × 50 mL) to recover the organic component. Organic extracts were combined, dried over Na_2SO_4, and concentrated under reduced pressure in a rotary evaporator. Finally, 2-methoxy-6-nitro-1-naphthaldehyde (0.496 g, 40%) was isolated by column chromatography using ethyl acetate in petroleum ether. ^{1}H NMR (400 MHz, $CDCl_3$): δ 4.12−4.15 (s, 3H), 7.46−7.51 (d, J = 9.2 Hz, 1H), 8.21−8.27 (d, J = 9.3 Hz, 1H), 8.30−8.37 (m, 2H), 8.69−8.73 (d, J = 2.4 Hz, 1H), 9.38−9.43 (d, J = 9.7 Hz, 1H), 10.83−10.90 (d, J = 1.0 Hz, 1H). ^{13}C NMR (101 MHz, $CDCl_3$): δ 56.98, 114.85, 122.53, 123.09, 124.75, 126.77, 127.23, 134.86, 139.16, 166.14, 191.47. GC−MS: m/z 231.1 ($[M]^+$).

Preparation of 6-Bromo-2-methoxy-1-naphthaldehyde..[9,21] Methylation of 6-bromo-2-naphthol was carried out by following the methylation step described in the synthesis of 2-methoxy-1-naphthoic acid. 6-Bromo-2-methoxynaphthalene (0.711 g, 3 mmol) was added in 10 mL of dry toluene along with *N*-methylformanilide (2.2 mL, 18 mmol) and phosphorus oxychloride (2.8 mL, 30 mmol) at room temperature. Then, the reaction mixture was refluxed for 12 h at 100 °C. A solution of potassium acetate (4.57 g) in 15 mL of distilled water was added to neutralize the resulting reaction mixture. Subsequently, it was dried under reduced pressure in a rotary evaporator, 30 mL of water was added, and it was extracted with ethyl acetate (2 × 50 mL). The organic extract was combined, dried over Na_2SO_4, and concentrated under reduced pressure in a rotary evaporator. The desired compound, 6-bromo-2-methoxy-1-naphthaldehyde (0.238 g, 30%), was isolated by column chromatography using 5% ethyl acetate in petroleum ether (silica gel, 60−120 mesh). ^{1}H NMR (400 MHz, $CDCl_3$): δ 3.96−3.98 (s, 3H), 7.14−7.24 (d, J = 9.2 Hz, 1H), 7.55−7.62 (dd, J = 9.3 and 2.2 Hz, 1H), 7.74−7.86 (m, 2H), 9.05−9.15 (d, J = 9.2 Hz, 1H), 10.75−10.80 (s, 1H). GC−MS: m/z 264.1 ($[M]^+$).

Characterization of 1.[9] FT-IR bands (KBr pellet, cm^{-1}): $\nu_{V1=O5}$ = 971 cm^{-1} and $\nu_{V2=O11}$ = 942 cm^{-1} for V=O bonds; ν_{O-O} = 886 and 869 cm^{-1} for peroxo O−O bonds. A 1.18 × 10^{-4} M solution of **1** was prepared, and the UV−vis spectrum was taken, which showed an absorption maximum at 320 nm with an absorption coefficient of $\varepsilon \sim$ 1144 M^{-1} cm^{-1}. The UV−vis feature is characteristic of oxoperoxo species in the complex. After preparation of complex **1**, ^{51}V NMR studies were done. ^{51}V NMR (300 MHz, D_2O): δ −731, −765. Our findings matched well with the literature report.[22,23]

Characterization of $VO(O_2)^+$ in Solution.[9] Under our standard reaction conditions, after the addition of H_2O_2, the resulting solution was tested by ^{51}V NMR, UV−vis, and FT-IR spectroscopy. The ^{51}V NMR study showed a single peak at −543.7 ppm, while the UV−vis spectrum showed an absorption maximum at 330 nm.[14] FT-IR studies showed two characteristic peaks at 960 cm^{-1} ($\nu_{V=O}$) and 878 cm^{-1} (ν_{O-O}), indicating the presence of $VO(O_2)^+$ formation in solution.[14]

Characterization of the Final Complex.[9] After decarbonylative halogenation reaction, the aqueous part was dried properly and the IR spectrum was taken. The IR data showed two characteristic peaks at 937 cm^{-1} ($\nu_{V=O}$) and 887 cm^{-1} (ν_{O-O}), indicating the presence of oxoperoxo in the final vanadium complex.[22] After reaction, the aqueous part was dried under reduced pressure in a rotary evaporator and ^{51}V NMR was recorded in D_2O and reported in ppm relative to NH_4VO_3 (−573.8 ppm).^{51}V NMR showed peaks at −520.1, −502.1, and −423.6 ppm, which indicate the presence of a V^{5+} oxidation state at the end of the catalytic cycle.[22]

Formic Acid Test. Citric acid (0.5 g, 2.6 mmol) and acetamide (10 g, 169.5 mmol) were dissolved in 100 mL of isopropyl alcohol (**R1**). Potassium acetate (30 g) was dissolved in 100 mL of distilled water. The reaction of **1** with 2-hydroxy-1-naphthaldehyde was carried out following general procedure A, using 1.5 mL of 0.75 M acid solutions without adding citrate−phosphate buffer. From the reaction mixture, 0.5 mL of the aqueous part was taken and was neutralized by a KOH solution; subsequently, 1 mL of **R1** and 1 drop of a potassium acetate solution were added. Subsequently, acetic anhydride (3.5 mL) was added. The solution was kept at room temperature until a red color appeared. Then the red solution was diluted with isopropyl alcohol up to 25 mL in a volumetric flask. The UV−vis spectrum was recorded with this solution and compared with the red solution obtained from a standard formate solution's color test. The molar extinction coefficient is 212 M^{-1} cm^{-1}. The yield of formic acid was calculated based on UV−vis spectra (52%).[9]

dx.doi.org/10.1021/ic302611a | Inorg. Chem. XXXX, XXX, XXX−XXX

1-Chloro-2-hydroxynaphthalene (Table 1, entry 1). General procedure A was followed with 1% ethyl acetate in petroleum ether as the eluent for column chromatography (silica gel, 100−200 mesh), and as a white solid (56 mg, 63%) was isolated. The starting material was recovered (16%). In a separate experiment, a 40% yield of 1-chloro-2-hydroxynaphthalene was obtained with 6 mol % catalyst **1**. ^{1}H NMR (400 MHz, $CDCl_3$): δ 5.94−6.02 (m, 1H), 7.26−7.32 (d, J = 8.9 Hz, 1H), 7.38−7.45 (m, 1H), 7.56−7.62 (m, 1H), 7.70−7.74 (d, J = 8.8 Hz, 1H), 7.77−7.85 (dd, J = 8.2 and 1.1 Hz, 1H), 8.06−8.10 (m, 1H). ^{13}C NMR (101 MHz, $CDCl_3$): δ 113.46, 117.36, 122.90, 124.27, 127.70, 128.34, 128.56, 129.58, 131.18, 149.47. GC−MS: m/z 178.1 ($[M]^+$).

1-Chloro-2-methoxynaphthalene (Table 1, entry 2). General procedure A using 6 mol % catalyst **1** was followed with 1% ethyl acetate in petroleum ether as the eluent for column chromatography (silica gel, 60−120 mesh), and white crystals (50%, 46 mg) were isolated. The starting material was recovered (20%).^{1}H NMR (400 MHz, $CDCl_3$): δ 3.79−4.10 (s, 3H), 7.21−7.25 (d, J = 9.0 Hz, 1H), 7.34−7.40 (m, 1H), 7.51−7.56 (m, 1H), 7.69−7.76 (m, 2H), 8.17−8.22 (m, 1H). ^{13}C NMR (101 MHz, $CDCl_3$): δ 57.01, 76.88, 77.20, 77.51, 113.71, 116.87, 123.52, 124.40, 127.57, 128.08, 128.12, 129.58, 131.95, 152.62. GC−MS: m/z 192.1 ($[M]^+$).

1-Chloro-2-methoxy-6-nitronaphthalene (Table 1, entry 3). General procedure A was followed with 1% ethyl acetate in petroleum ether as the eluent for column chromatography (silica gel, 100−200 mesh), and a yellow powder (6 mg, 5%) was isolated. The starting material was recovered (80%). ^{1}H NMR (400 MHz, $CDCl_3$): δ 3.97−4.23 (s, 3H), 7.42−7.49 (d, J = 9.1 Hz, 1H), 7.97−8.03 (d, J = 9.1 Hz, 1H), 8.28−8.36 (m, 2H), 8.76−8.79 (m, 1H). GC−MS: m/z 237.1 ($[M]^+$). HRMS (ESI). Calcd for $C_{11}H_8NO_3Cl$: 238.0262. Found: 238.0271.

(2-Chloroethene-1,1-diyl)dibenzene (Table 1, entry 4). General procedure A was followed with 1% ethyl acetate in petroleum ether as the eluent for column chromatography, and a yellow powder (14 mg, 12%) was isolated. Benzophenone (10%) was obtained as a byproduct, and the starting material was recovered (60%). ^{1}H NMR (400 MHz, $CDCl_3$): δ 6.54−6.64 (d, J = 4.7 Hz, 1H), 7.04−7.45 (m, 10H). ^{13}C NMR (101 MHz, $CDCl_3$): δ 116.03, 127.87, 127.91, 128.12, 128.22, 128.27, 128.36, 128.41, 128.58, 130.02, 137.75, 140.30, 144.05. GC−MS: m/z 214.1 ($[M]^+$). HRMS (ESI). Calcd for $C_{12}H_{10}Cl_2O_2$: 215.063. Found: 215.0635.

6-Bromo-1-chloro-2-methoxynaphthalene (Table 1, entry 5). General procedure A was followed with 5% ethyl acetate in petroleum ether as the eluent for column chromatography, and a brownish powder (30 mg, 22%) was isolated. The starting material was recovered (65%). ^{1}H NMR (400 MHz, chloroform-d): δ 3.94−4.08 (q, J = 4.0, 3.9, and 3.9 Hz, 3H), 7.21−7.32 (m, 1H), 7.54−7.67 (m, 2H), 7.84−7.96 (m, 1H), 7.98−8.10 (m, 1H). ^{13}C NMR (101 MHz, $CDCl_3$): δ 57.09, 114.69, 117.11, 118.32, 125.53, 127.19, 130.02, 130.51, 130.60, 130.88, 152.92. GC−MS: m/z 272.1 ($[M]^+$).

2,4,6-Trichloroaniline (Table 1, entry 6). General procedure A was followed for 24 h. After workup, the GC yield was determined using n-decane as the internal standard (25%). The unreacted starting material (43%) was determined by GC analysis. Product formation was confirmed by GC−MS [m/z 195 ($[M]^+$)].

■ ASSOCIATED CONTENT

Ⓢ Supporting Information

Additional data, together with NMR characterization of the compounds. This material is available free of charge via the Internet at http://pubs.acs.org.

■ AUTHOR INFORMATION

Corresponding Author

*E-mail: dmaiti@chem.iitb.ac.in.

Author Contributions

All authors have given approval to the final version of the manuscript.

Notes

The authors declare no competing financial interest.

■ ACKNOWLEDGMENTS

This activity was supported by DST-India. Financial support was received from CSIR-India (fellowship to S.R.), and Indian Institute of Technology Bombay is gratefully acknowledged by G.S. D.M. thanks Dr. Rahul Banerjee (NCL-Pune) for helpful discussions.

■ REFERENCES

(1) (a) Butler, A.; Sandy, M. *Nature* **2009**, *460*, 848−854. (b) Fujimori, D. G.; Walsh, C. T. *Curr. Opin. Chem. Biol.* **2007**, *11*, 553−560. (c) Vaillancourt, F. H.; Yeh, E.; Vosburg, D. A.; Garneau-Tsodikova, S.; Walsh, C. T. *Chem. Rev.* **2006**, *106*, 3364−3378. (d) Blasiak, L. C.; Drennan, C. L. *Acc. Chem. Res.* **2009**, *42*, 147−155.

(2) (a) Schneider, C. J.; Zampella, G.; Greco, C.; Pecoraro, V. L.; De Gioia, L. *Eur. J. Inorg. Chem.* **2007**, 515−523. (b) Schneider, C. J.; Penner-Hahn, J. E.; Pecoraro, V. L. *J. Am. Chem. Soc.* **2008**, *130*, 2712−2713. (c) Podgorsek, A.; Zupan, M.; Iskra, J. *Angew. Chem., Int. Ed.* **2009**, *48*, 8424−8450. (d) Kravitz, J. Y.; Pecoraro, V. L. *Pure Appl. Chem.* **2005**, *77*, 1595−1605. (e) Colpas, G. J.; Hamstra, B. J.; Kampf, J. W.; Pecoraro, V. L. *J. Am. Chem. Soc.* **1996**, *118*, 3469−3478. (f) Colpas, G. J.; Hamstra, B. J.; Kampf, J. W.; Pecoraro, V. L. *J. Am. Chem. Soc.* **1994**, *116*, 3627−3628.

(3) (a) Henry, K. M.; Townsend, C. A. *J. Am. Chem. Soc.* **2005**, *127*, 3724−3733. (b) Roberts, E. S.; Vaz, A. D. N.; Coon, M. J. *Proc. Natl. Acad. Sci. U.S.A.* **1991**, *88*, 8963−8966. (c) Sen, K.; Hackett, J. C. *J. Am. Chem. Soc.* **2010**, *132*, 10293−10305. (d) Patra, T.; Manna, S.; Maiti, D. *Angew. Chem., Int. Ed.* **2011**, *50*, 12140−12142.

(4) (a) Schirmer, A.; Rude, M. A.; Li, X. Z.; Popova, E.; del Cardayre, S. B. *Science* **2010**, *329*, 559−562. (b) Li, N.; Norgaard, H.; Warui, D. M.; Booker, S. J.; Krebs, C.; Bollinger, J. M. *J. Am. Chem. Soc.* **2011**, *133*, 6158−6161. (c) Krebs, C.; Bollinger, J. M.; Booker, S. J. *Curr. Opin. Chem. Biol.* **2011**, *15*, 291−303.

(5) (a) Ladwein, K. I.; Jung, M. *Angew. Chem., Int. Ed.* **2011**, *50*, 12143−12145. (b) Pfaffeneder, T.; Hackner, B.; Truss, M.; Munzel, M.; Muller, M.; Deiml, C. A.; Hagemeier, C.; Carell, T. *Angew. Chem., Int. Ed.* **2011**, *50*, 7008−7012. (c) Wu, S. C.; Zhang, Y. *Nat. Rev. Mol. Cell Biol.* **2010**, *11*, 607−620.

(6) (a) Conte, V.; Coletti, A.; Floris, B.; Licini, G.; Zonta, C. *Coord. Chem. Rev.* **2011**, *255*, 2165−2177. (b) Wischang, D.; Brucher, O.; Hartung, J. *Coord. Chem. Rev.* **2011**, *255*, 2204−2217.

(7) (a) Park, M. J.; Lee, J.; Suh, Y.; Kim, J.; Nam, W. *J. Am. Chem. Soc.* **2006**, *128*, 2630−2634. (b) Annaraj, J.; Suh, Y.; Seo, M. S.; Kim, S. O.; Nam, W. *Chem. Commun.* **2005**, 4529−4531.

(8) Wertz, D. L.; Sisemore, M. F.; Selke, M.; Driscoll, J.; Valentine, J. S. *J. Am. Chem. Soc.* **1998**, *120*, 5331−5332.

(9) See the Supporting Information for a detailed description.

(10) (a) Grzywa, M.; Rafalska-Lasocha, A.; Lasocha, W. *Powder Diffr.* **2003**, *18*, 248−251. (b) Zhang, H. Y.; Huang, Z. X.; Guo, H. X. *Chin. J. Struct. Chem.* **2004**, *23*, 1252−1255.

(11) (a) Wang, Z.; Zhu, L.; Yin, F.; Su, Z.; Li, Z.; Li, C. *J. Am. Chem. Soc.* **2012**, *134*, 4258−4263. (b) Johnson, R. G.; Ingham, R. K. *Chem. Rev.* **1956**, *56*, 219−269. (c) Bhatkhande, B. S.; Adhikari, M. V.; Samant, S. D. *Ultrason. Sonochem.* **2002**, *9*, 31−35. (d) Perumal, P. T.; Bhatt, M. V. *Tetrahedron Lett.* **1979**, 3099−3100.

(12) (a) Vyas, P. V.; Bhatt, A. K.; Ramachandraiah, G.; Bedekar, A. V. *Tetrahedron Lett.* **2003**, *44*, 4085−4088. (b) Moon, B. S.; Choi, H. Y.; Koh, H. Y.; Chi, D. Y. *Bull. Korean Chem. Soc.* **2011**, *32*, 472−476. (c) Muathen, H. A. *Helv. Chim. Acta* **2003**, *86*, 164.

(13) (a) Acree, F.; Haller, H. L. *J. Am. Chem. Soc.* **1943**, *65*, 1652−1652. (b) Schulte-Ladbeck, R.; Kolla, P.; Karst, U. *Anal. Chem.* **2003**, *75*, 731−735. (c) Laird, T. *Org. Process Res. Dev.* **2004**, *8*, 815−815.

(14) (a) Waidmann, C. R.; DiPasquale, A. G.; Mayer, J. M. *Inorg. Chem.* **2010**, *49*, 2383−2391. (b) Sivak, M. *Chem. Pap.* **1987**, *41*, 311−319. (c) Ramasarma, T. *Proc. Ind. Natl. Sci. Acad.* **2003**, *B69*.

(15) Totaro, R. M.; Williams, P. A. M.; Apella, M. C.; Blesa, M. A.; Baran, E. J. *J. Chem. Soc., Dalton Trans.* **2000**, 4403−4406.
(16) Butler, A. *Coord. Chem. Rev.* **1999**, *187*, 17−35.
(17) The formation of hypervalent chlorine, hypochlorite (OCl^-; metal-bound or free), has been suggested as the active species for electrophilic halogenation reactions in synthetic systems as well as in biological halogenation.[1,2]
(18) Warui, D. M.; Li, N.; Norgaard, H.; Krebs, C.; Bollinger, J. M.; Booker, S. J. *J. Am. Chem. Soc.* **2011**, *133*, 3316−3319.
(19) Lichtenstein, B. R.; Jose, C. F.; Cerda, Koder, R. L.; Dutton, P. L. *Chem. Commun.* **2009**, 168.
(20) Huang, Y.; Luedtke, R. R.; Freeman, R. A.; Wu, L.; Mach, R. H. *J. Med. Chem.* **2001**, *44*, 1815.
(21) Gaslonde, T.; Covello, F.; Velazquez-Alonso, L.; Léonce, S.; Pierré, A.; Pfeiffer, B.; Michel, S.; Tillequin, F. *Eur. J. Med. Chem.* **2011**, *46*, 1861.
(22) Rehder, D. *Bull. Magn. Reson.* **1982**, *4* (1−2), 33−82.
(23) Molinari, J. E.; Wachs., I. E. *J. Am. Chem. Soc.* **2010**, *132*, 12559.

dx.doi.org/10.1021/ic302611a | *Inorg. Chem.* XXXX, XXX, XXX−XXX