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[9] H. Nakagawa, S. Sakaguchi, Y. Ishii, 81st Annual Meeting of the Chemical Society of Japan, 1G549 (**2002**). In our present study, the reaction of (4-MeC$_6$H$_4$)EtSi(OH)$_2$ (0.3 mmol) with butyl acrylate **2a** (0.9 mmol) in toluene/H$_2$O at 120 °C in the presence of [{Ir(OMe)(cod)}$_2$] (3 mol %) afforded the Mizoroki–Heck-type product(46 %), in which 36 % of **2a** was converted into **9**.

[10] The rhodium-catalyzed reaction under similar conditions (3 mol % of [{Rh(OH)(cod)}$_2$], 4-MeC$_6$H$_4$SiEt(OH)$_2$ (0.6 mmol), **2a** (0.3 mmol), and **3b** (0.6 mmol) in THF (3 mL) at 70 °C for 24 h) afforded 27 % of the Mizoroki–Heck-type product **3a** and 3 % of **4b** with 75 % recovery of **3b**.

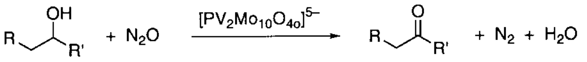
Polyoxometalate Catalysts

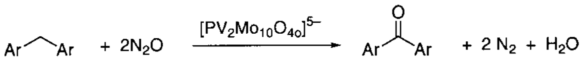
Activation of Nitrous Oxide and Selective Oxidation of Alcohols and Alkylarenes Catalyzed by the $[PV_2Mo_{10}O_{40}]^{5-}$ Polyoxometalate Ion**

*Revital Ben-Daniel and Ronny Neumann**

Nitrous oxide is a potentially interesting oxidant for selective oxidation of organic substrates since it contains 36 wt % oxygen, and the by-product of an oxidation reaction would be environmentally benign molecular nitrogen. These advantages are difficult to realize since N$_2$O is generally considered to be both inert[1] and a poor ligand.[2] Thus, very few catalysts have been reported for the activation of N$_2$O and its use as a selective oxidant in hydrocarbon oxidation. In the area of heterogeneous catalysis, various metal oxides have been investigated.[3] The most effective catalysts appear to be iron-containing acidic zeolites[4] which at elevated temperatures are thought to yield surface-activated iron–oxo species (α-oxygen).[5] These species are capable of oxygen transfer to rather inert hydrocarbons, such as benzene and methane, to yield phenol and methanol, respectively.[6] In homogeneous media, noncatalytic oxygen transfer from nitrous oxide to alkyl, alkyne, and imido ligands of transition-metal complexes has been observed.[7] Molybdenum(III) complexes have cleaved nitrogen–nitrogen bonds[8] and N$_2$O has been decomposed at subambient temperatures to N$_2$ and O$_2$ using a ruthenium complex.[9] More relevant to the work reported herein is the reported oxygen transfer from nitrous oxide to form metal–oxo species.[10] In one particular case,[11] a ruthenium porphyrin has been used to prepare a high-valent ruthenium–dioxo species capable of oxygen-transfer to nucleophiles such as alkenes and sulfides. Under more extreme conditions (140 °C, 10 atm N$_2$O), the ruthenium porphyrin has recently been shown to catalyze oxygen transfer to trisubstituted alkenes,[12] and the oxidation of alcohols to ketones.[13]

With regard to the ongoing interest in the catalytic activity of polyoxometalates in oxidation reactions,[14] especially with benign oxidants such as O$_2$ and H$_2$O$_2$, we have very recently found that a manganese-substituted "sandwich"-type polyoxometalate can also activate N$_2$O and lead to the highly selective epoxidation of alkenes.[15] In this paper we will describe a different set of N$_2$O-activation reactions involving the vanadium-containing Keggin-type polyoxomolybdate, [{nBu$_4$N}$_5${PV$_2$Mo$_{10}$O$_{40}$}]. In this case, selective oxidation by C–H bond activation was possible leading to the oxidation of a) primary and secondary alcohols to aldehydes and ketones, respectively (Equation (1)) and b) alkyl aromatics to ketones (Equation (2)), or alternatively leading to their oxydehydrogenation (Equation (3)).


(1)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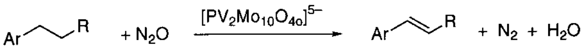
(3)

For the oxidation of alcohols (Table 1) it was shown that secondary and primary alcohols were oxidized selectively (greater than 99.9 %) to ketones and aldehydes, respectively,

Table 1: Oxydehydrogenation of alcohols with N$_2$O catalyzed by [{nBu$_4$N}$_5${PV$_2$Mo$_{10}$O$_{40}$}].[a]

Substrate	Product	Conversion [mol %]
1-octanol	1-octanal	42.5
2-octanol	2-octanone	48.1
cyclohexanol	cyclohexanone	68.2
cyclooctanol	cyclooctanone	89
cis-2-hexen-1-ol	2-hexenal[b]	50.5
trans-2-hexen-1-ol	2-hexenal[b]	50.3
1-octene-3-ol	1-octen-3-one	56.8
benzyl alcohol	benzaldehyde	> 99

[a] Reaction conditions: alcohol (1 mmol), [{nBu$_4$N}$_5${PV$_2$Mo$_{10}$O$_{40}$}] (0.02 mmol), N$_2$O (1 atm), benzonitrile (1 mL), 150 °C, 15 h. Selectivity to the aldehyde or ketone was > 99.9 %. [b] The configuration of the unsaturated aldehyde was not definitively determined. However, since the catalytic system is inert to alkenes it is likely, but not certain, that the configuration was retained.

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[**] This research was supported by the Basic Research Foundation administered by the Israeli Academy of Science and Humanities and the Israeli Ministry of Science. Dr. Lev Weiner is thanked for the ESR measurements. R.N. is the Rebecca and Israel Sieff Professor of Organic Chemistry.

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

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with no further oxidation of aldehydes to carboxylic acids.[16] Acyclic primary, secondary, and allylic alcohols showed similar reactivity; yields between approximately 40–60% were possible. Higher yields were obtained for cyclic secondary alcohols (approximately 60–80%), while benzylic alcohols gave quantitative yields of products. Attempts at increasing the conversion in the cases of 1-octanol and 2-octanol by lengthening the reaction time, coupled with addition of more N_2O or increasing the reaction temperature were not successful. Similar reaction conversions and selectivity were obtained. An increase in the amount of catalyst to 5 mol% unfortunately led to a decrease in reaction selectivity. Importantly, when using O_2 in place of N_2O there was no reaction. One should note that in the past we have reported on the use of the $[PV_2Mo_{10}O_{40}]^{5-}$ polyoxometalate ion in the aerobic oxidation of alcohols; however in those cases the catalyst is only active when supported on active carbon;[17] $[\{n\text{Bu}_4\text{N}\}_5\{PV_2Mo_{10}O_{40}\}]$ is inactive.

The results of the oxidation of alkyl aromatic compounds are summarized in Table 2. For substrates without a hydrogen atom at the α-position, with respect to the position of the benzylic carbon atom, there was oxygenation at the benzylic position and selective formation (greater than 99.9%) of the diaryl ketone or triaryl alcohol as sole products. Lengthening the reaction time coupled with repressurization of the reaction vessel could increase the yields. For other substrates, such as ethylbenzene and *i*-propylbenzene, the presence of an α-hydrogen atom led to oxydehydrogenation and the formation of vinyl benzene products. Control reactions with molecular oxygen gave much lower yields and reaction mixtures typical for autooxidation pathways. $[\{n\text{Bu}_4\text{N}\}_5\{PV_2Mo_{10}O_{40}\}]$ did not catalyze the alkene epoxidation of 1-octene, cyclooctene, or cyclohexene. In the latter case, some oxydehydrogenation, 3 mol% conversion to 1,3-cyclohexadiene and then to benzene was observed. It should also be noted that although the examples given in Table 1 and Table 2 describe the use of quite polar benzonitrile as solvent, similar reactions with alcohol and alkylaromatic substrates such 1-octanol, 2-octanol, and diphenylmethane with apolar decalin (decahydronaphthalene) as solvent gave almost identical results. In contrast fluorobenzene, which was previously used in epoxidation reactions with nitrous oxide,[15] did not lead to selective oxidation, especially in the case of the oxidation of alkylaromatic substrates.

Table 2: Oxidation of alkylaromatics with N_2O catalyzed by $[\{n\text{Bu}_4\text{N}\}_5\{PV_2Mo_{10}O_{40}\}]$.[a]

Substrate	Product	Conversion [mol%][a]
triphenylmethane	triphenylmethanol	52.4 (89)
diphenylmethane	benzophenone	6.2 (32)
toluene	no product	0
fluorene	fluoren-9-one	11.1 (50)
xanthene	xanthen-9-one	14.0 (54)
ethylbenzene	styrene	6.8
i-propylbenzene	α-methylstyrene	27.6

[a] Reaction conditions: substrate (1 mmol), $[\{n\text{Bu}_4\text{N}\}_5\{PV_2Mo_{10}O_{40}\}]$ (0.01 mmol), N_2O (1 atm), benzonitrile (1 mL), 150 °C, 8 h. Selectivity to the product was > 99.9%. [b] Yields in parentheses are those after 48 h, with reintroduction of N_2O after 24 h.

Another notable observation is that the quantification of N_2O, N_2, and O_2 by gas chromatography showed no non-productive decomposition of N_2O to N_2 and O_2 at 150–180 °C in the absence or presence of a reaction substrate such as benzyl alcohol or xanthene. In the presence of the aforementioned substrates, N_2 formation was consistent with the degree of reaction of the organic substrate within a 10% margin of error.

Some preliminary insight into the mode of N_2O activation and the reaction pathway is most warranted. First, heating $[\{n\text{Bu}_4\text{N}\}_5\{PV_2Mo_{10}O_{40}\}]$ (0.01 M) in benzonitrile or decalin at 150 °C in a N_2O atmosphere (1 atm) yielded a green solution (UV/Vis shows an absorption at 750 nm) indicative of the oxidation of N_2O by the polyoxometalate, which is reduced accordingly (Figure 1).

The degree of reduction, calculated by calibration with the reduction of pure $[n\text{Bu}_4\text{N}]_5[PV_2Mo_{10}O_{40}]$ by Zn, is approximately 55% after 6 h. In the absence of N_2O, that is, by heating $[\{n\text{Bu}_4\text{N}\}_5\{PV_2Mo_{10}O_{40}\}]$ in benzonitrile or decalin only, slight polyoxometalate reduction (approximately 5%) was observed within 6 h. Importantly, the apparent reduction of the $[\{n\text{Bu}_4\text{N}\}_5\{PV_2Mo_{10}O_{40}\}]$ polyoxometalate is reversible, that is, upon removal of N_2O, the $[\{n\text{Bu}_4\text{N}\}_5\{PV_2Mo_{10}O_{40}\}]$ is reoxidized. Additionally, an ESR spectrum of this solution yielded an anisotropic spectrum which can be assigned to a reduced $[PV_2Mo_{10}O_{40}]$ species (see Supporting Information). Under the same reaction conditions the ^{15}N NMR peaks of $^{15}N_2O$ at $\delta = 150$ and 210 ppm disappeared, apparently because of a paramagnetic peak-broadening effect caused by the reduction of the polyoxometalate by N_2O. These lines of evidence seem to suggest an unusual and unexpected redox or donor–acceptor (D–A) interaction between N_2O and $[\{n\text{Bu}_4\text{N}\}_5\{PV_2Mo_{10}O_{40}\}]$ (Equation (4)).

$$\text{POM}^0 + \text{N}{\equiv}\overset{+}{\text{N}}{-}\overset{-}{\text{O}} \rightleftharpoons \text{POM}^{1-} \,\Big|\, \text{N}{\equiv}\overset{+}{\text{N}}{-}\overset{\bullet}{\text{O}} \quad (4)$$

Such a reaction is rather surprising considering the high ionization potential of N_2O (approximately 12.8 eV),[18] but may conceivably be explained by an outer-sphere electron transfer, in which the polyanionic nature of polyoxometalates energetically increases the favorability of such D–A inter-

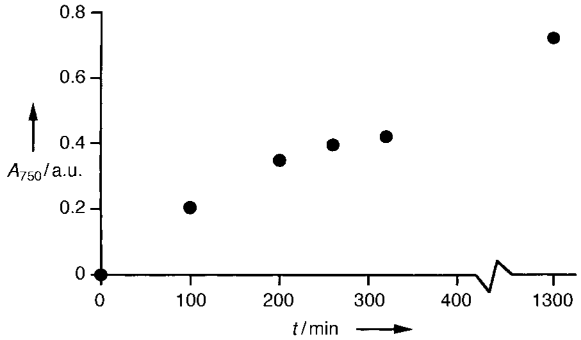

Figure 1. The reduction of $[\{n\text{Bu}_4\text{N}\}_5\{PV_2Mo_{10}O_{40}\}]$ by N_2O. Reaction conditions: $[\{n\text{Bu}_4\text{N}\}_5\{PV_2Mo_{10}O_{40}\}]$ (0.01 M) in benzonitrile, 150 °C, N_2O (1 atm).

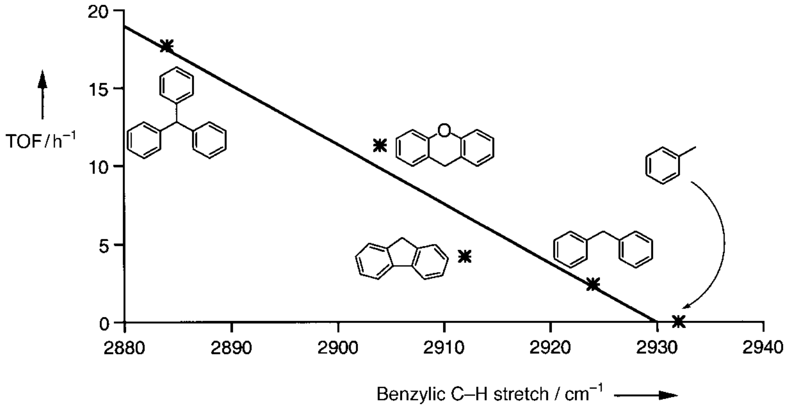

Figure 2. Reactivity for oxygenation of alkyl aromatics as a function of benzylic C–H bond energy (from gas phase IR C–H stretch vibration). Reaction conditions: alkylarene (1 mmol), $[\{n\mathrm{Bu_4N}\}_5\{\mathrm{PV_2Mo_{10}O_{40}}\}]$ (0.01 mmol), N_2O (1 atm), benzonitrile (1 mL), 150 °C.

actions and the formation of D–A complexes.[19] A similar redox interaction has been recently observed between a manganese(III)-substituted polyoxometalate and N_2O.[15]

For further insight into the mode of activation of the alkyl arene and alcohol substrate, a correlation between reactivity and a relevant property of the substrates was sought. In the oxidation of alkyl arenes, the conversion initially increased linearly as a function of time indicating a zero-order reaction in the organic substrate. Using these data, one may observe that the relative reactivity towards the oxidation of alkyl arenes was in the order: triphenylmethane > xanthene > fluorene > diphenylmethane > toluene, and was well correlated ($r^2 = 0.96$) to C–H homolytic bond strength at the benzylic position (Figure 2).[20] Notably, the use of approximately 70 % ^{18}O-labeled $[\{n\mathrm{Bu_4N}\}_5\{\mathrm{PV_2Mo_{10}O_{40}}\}]$ (xanthene (1 mmol), $[\{n\mathrm{Bu_4N}\}_5\{\mathrm{PV_2Mo_{10}O_{40}}\}]$ (1 mmol), N_2O (1 atm), benzonitrile (1 mL), 150 °C) yielded only the unlabeled product indicating that the source of oxygen in the product was N_2O.[21]

Similarly, a Hammett plot of the oxidation of a series of benzylic alcohols yielded $\rho = 0.59$ ($r^2 = 0.97$, Figure 3). The low ρ value is consistent with the formation of a radicaloid species at the benzylic carbon in the transition state of the rate-determining step. Thus, for both alkyl arenes and alcohols, there is initial evidence indicating homolytic C–H bond cleavage in the rate-determining oxidation step. This is supported by kinetic isotope effects (KIE) which gave $k_H/k_D = 11.0$ and 15.9 for benzyl alcohol/[D$_2$]benzyl alcohol and xanthene/[9-D$_2$]xanthene, respectively.

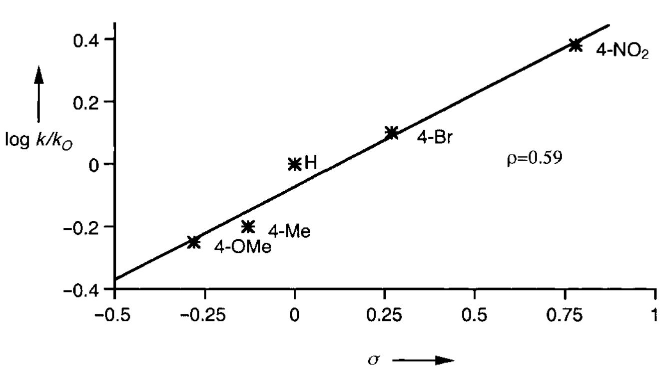

Figure 3. Hammett plot for the oxidation of benzylic alcohols. Reaction conditions: benzylic alcohol (1 mmol), $[\{n\mathrm{Bu_4N}\}_5\{\mathrm{PV_2Mo_{10}O_{40}}\}]$ (0.01 mmol), N_2O (1 atm), benzonitrile (1 mL), 150 °C.

Although it is premature to present a full picture of the reaction scheme, the initial results on the novel selective oxidation reactions presented above indicate that initially there is activation by the electron transfer of N_2O by the polyoxometalate species, as suggested by UV/Vis, ESR, and ^{15}N NMR spectroscopy. The activated N_2O then reacts with (or activates) the organic substrate leading to H abstraction from the latter, as supported by the correlation between the rate of alkyl arene oxidation, the C–H homolytic bond strength, and the low ρ value obtained for benzylic alcohol oxidation; the measured KIEs support such a scheme. In the case of alcohol oxidation, initial H abstraction is presumably followed by additional dehydrogenation to yield the aldehyde or ketone. In the case of alkyl arene oxidation, the intermediate radical species is probably oxidized through oxygen transfer from nitrous oxide.

Experimental Section

Reactions were carried out in 15-mL glass pressure tubes. Typically, appropriate amounts (see Table and Figure captions) of the substrate (all highest purity commercial products) and the $[\{n\mathrm{Bu_4N}\}_5\{\mathrm{PV_2Mo_{10}O_{40}}\}]$ catalyst were dissolved in the reaction solvent. N_2O (greater than 99.95 % purity) was introduced to the pressure tube by four consecutive pump–thaw cycles using a Schlenk line. Conversions of the organic substrate were measured by GLC (HP 6890) using a 5 % phenylmethylsilicone (30 m, 0.32 mm internal diameter, 0.25 μm coating) column. The identity of the products was verified by GC-MS.

Received: July 10, 2002
Revised: October 8, 2002 [Z19706]

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[21] The inverse experiment using $N_2{}^{18}O$ is also desirable; $N_2{}^{18}O$ was not commercially available and is prohibitively expensive to synthesize.

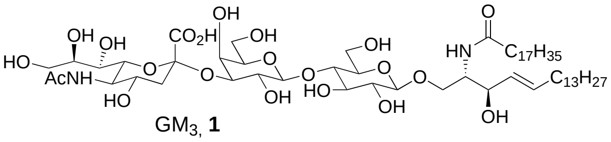
Carbohydrate–Carbohydrate Interactions

Probing Specificity in Carbohydrate–Carbohydrate Interactions with Micelles and Langmuir Monolayers**

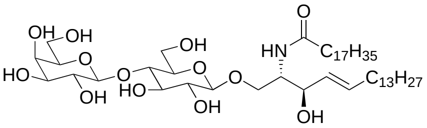
*Paul V. Santacroce and Amit Basu**

Carbohydrate–carbohydrate interactions (CCIs) between cell surface glycolipids are important mediators of cell adhesion during development, metastasis, and signal transduction.[1] CCIs are also important for the higher-order structure of polysaccharides, compaction of the myelin sheath, sperm–egg cell adhesion, and proteoglycan-mediated sponge cell aggregation.[2] The interaction has been studied by a variety of techniques including vesicle adhesion,[3a,b] surface plasmon resonance (SPR) spectroscopy,[3c,d] atomic force microscopy (AFM),[3e] nuclear magnetic resonance (NMR) spectroscopy,[3f,g] mass spectrometry (MS),[3h,i] infrared (IR) spectroscopy,[3j] surface force measurements,[,3k] quartz crystal microbalance (QCM) measurements,[3l] and Langmuir monolayer compression isotherms.[3m] These interactions, which are generally calcium ion dependent, require multivalent carbohydrate–-carbohydrate contacts, and the oligomeric nature of the association has hampered efforts to structurally characterize the carbohydrate aggregates at high resolution. In this communication we report a new method for detecting CCIs by monitoring the interactions of glycolipid micelles with a glycolipid monolayer. We show that small changes in carbohydrate structure significantly affect glycolipid association.

The adhesion of a melanoma cell to an endothelial cell is mediated by carbohydrate–carbohydrate recognition between the melanoma cell surface ganglioside sialosyllactosylceramide (GM$_3$, **1**) and the glycosphingolipid lactosylcera-



GM$_3$, **1**



LacCer, **2**

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[**] We gratefully acknowledge financial support from Brown University (startup funds; Salomon Faculty Research Award), Rhode Island Foundation, Research Corporation (Research Innovation Award), and the Petroleum Research Fund administered by the American Chemical Society. A.B. is an NSF Faculty Early CAREER awardee. P.V.S. is a Department of Education GAANN Fellow. We thank Professor Zimmt for the use of his spectrofluorometer.