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Carbonyl-Inserted Organo-Hybrids of a Dawson-Type Phosphovanadotungstate: Scope and Chemoselective Oxidation Catalysis

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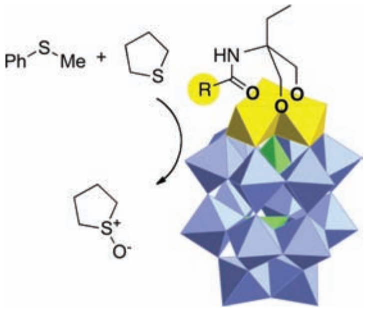
ABSTRACT



The Dawson-type polyoxometalate (POM) $[P_2V_3W_{15}O_{62}]^{9-}$ is a prototype for inclusion of carbonyls of amides, ureas, carbamates, and thiocarbamates into polyoxometallic structures. The carbonyl-inserted POMs catalyze the oxidation of sulfides. Chemoselectivity depends primarily on the proton content of the POM, but it is also influenced by the organic substituent.

Because of their diversity, polyoxometalates (POMs) form a rich family of molecular transition metal clusters, which can be adapted for applications in chemistry and biology.[1] Grafting of organics to POMs to generate organic–inorganic hybrids is a prime tool to modulate or expand their properties.[2]

The $[P_2V_3W_{15}O_{62}]^{9-}$ phosphovanadotungstate **1** is an attractive platform. The three capping vanadium atoms make it an oxidant, which can be used catalytically.[3] Hybrids can be generated upon coupling with tris-hydroxymethylmethane derivatives $RC(CH_2OH)_3$.[4]

We recently reported that exchanging one sp^3 oxygen in that triol family with a suitably positioned sp^2 one from amide carbonyls led to incorporation of the latter into

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$[P_2V_3W_{15}O_{62}]^{9-}$.[5] This makes it complementary to the seminal triol-capping of the same structure[4] because it allows π-conjugation between the organic and inorganic parts.

Herein we report that (i) the carbonyl of trivalent functions (ureas, carbamates, thiocarbamates) can also be inserted into **1** and (ii) the new organo-hybrids not only retain the oxidative properties of $[P_2V_3W_{15}O_{62}]^{9-}$ but also can lead to improved chemoselectivity in the oxidation of sulfides.

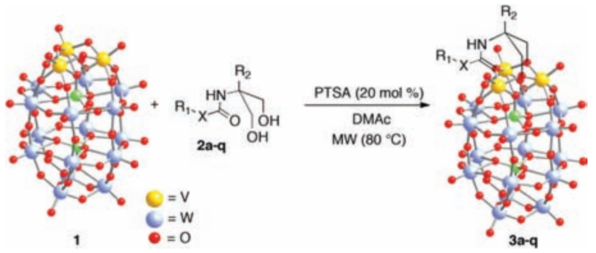
The diol-carbonyl ligands **2a**–**q** used in this work were prepared from commercially available amino-diols which were functionalized at nitrogen with isocyanates (ureas), chloroformates (carbamates), or isothiocyanates (thiocarbamates, see Supporting Information (SI) for details).

All ligands were subjected to the conditions devised for the coupling of diolamide derivatives to TBA_5H_4-**1**, *i.e.* 20 mol % of *p*-toluenesulfonic acid (PTSA) in dimethylacetamide (DMAc) under microwave heating at 80 °C. The new POMs **3a**–**q** were obtained in high yields in all but two cases in the carbamate series (Table 1, entries 12 and 16). Ligand **2l** led too rapidly to an unreactive oxazolidinone under the reaction conditions, and ligand **2p** gave a complex mixture of POMs. Thus, other sp^2 oxygens than amides can be included into polyoxometalates.[6]

To check whether an acidic proton on the nitrogen was required for the insertion to happen, we carried out the reaction first onto tertiary *amide* **4a**. The previous conditions (20 mol % PTSA) afforded a mixture of **5a** and another unidentified POM (Table 2, entry 1). Gratifyingly, **5a** was obtained in high yield when excess PTSA was used (1.5 equiv, 82%, entry 2). These modified conditions were applied to the preparation of the tertiary carbamate (**5b**, 85%, entry 3) and urea (**5c**, 87%, entry 4) derivatives. All reactions worked smoothly.

The new products were characterized by NMR, IR, and ESI-MS, which gave concurring proof of the carbonyl insertion into the inorganic framework. The POMs were obtained mostly as TBA salts with varying amounts of dimethylammonium cations (DMA) coming from the decomposition of dimethylacetamide. Those amounts were quantified by NMR and elemental analyses (SI).

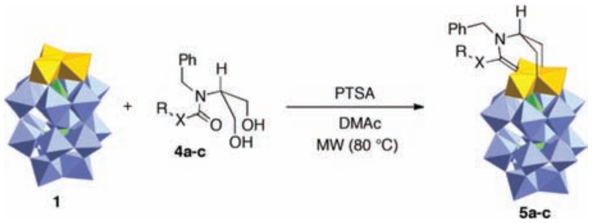
Table 1. Insertion of Ureas, Carbamates, and Thiocarbamates into $(TBA)_5H_4$-**1**



entry^a	diol	X	R_1	R_2	prod., yield (%)
1	**2a**	NH	Et	Et	**3a**, 86
2	**2b**	NH	pNO$_2$-C$_6$H$_4$	Et	**3b**, 89
3	**2c**	NH	pCF$_3$-C$_6$H$_4$	Et	**3c**, 84
4	**2d**	NH	Ph	Et	**3d**, 90
5	**2e**	NH	*p*Tol	Et	**3e**, 88
6	**2f**	NH	pMeO-C$_6$H$_4$	Et	**3f**, 96
7	**2g**	NH	pPh-C$_6$H$_4$	Et	**3g**, 70
8	**2h**	NH	2,5-Me$_2$-C$_6$H$_4$	Et	**3h**, 72
9	**2i**	NH	Et	H	**3i**, 82
10	**2j**	NH	Ph	H	**3j**, 87
11	**2k**	O	Bn	Et	**3k**, 92
12	**2l**	O	mCF$_3$C$_6$H$_4$	Et	–
13	**2m**	O	Ph	Et	**3m**, 80
14	**2n**	O	*p*Tol	Et	**3n**, 90
15	**2o**	O	pMeO-C$_6$H$_4$	Et	**3o**, 87
16	**2p**	O	Ph	H	–
17	**2q**	S	Et	Et	**3q**, 78

[a] Cations of **1** are TBA_5H_4 (TBA = tetra-*n*-butylammonium; PTSA = *p*-toluene sulfonic acid; DMAc = dimethylacetamide).

Table 2. Insertion of Tertiary Amides and Carbamates



entry^a	diol	X, R	equiv PTSA	prod., yield (%)
1	**4a**	–, Ph	0.2	–
2	**4a**	–, Ph	1.5	**5a**, 82
3	**4b**	O, pMeOC$_6$H$_4$	1.5	**5b**, 85
4	**4c**	NH, Ph	1.5	**5c**, 87

[a] Cations of **1** are TBA_5H_4 (TBA = tetra-*n*-butylammonium; PTSA = *p*-toluene sulfonic acid; DMAc = dimethylacetamide).

Because of the presence of the three vanadiums, vanadotungstate **1** is used for oxidations.[3] However, there is to

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date only one example of use of a catalytically active triol-hybrid reported.[4a]

The redox properties of representative examples of urea and carbamate hybrids were investigated by cyclovoltammetry. Two reductions were observed between 0 and -1 V *vs* Fc^+/Fc (Fc = ferrocene) in acetonitrile at a fast scan rate. Whereas the first reduction is pseudoreversible, the second wave is large and likely corresponds to the superposition of two redox processes. Indeed, at a slow scan rate and on a freshly polished electrode, the second process splits into two waves. Detailed analysis of the second process is hampered by the strong adsorption of the compounds on the electrode surface.

The electrochemical potentials fall into the same range as those for triol- and diol-amide substituted $[P_2V_3W_{15}O_{62}]^{9-}$ (Table 3).[4a,5a] The new hybrid compounds should therefore be able to promote the same redox reactions as the previously reported derivatives. One notes variations of the potential with different substituents in the *para* position of the aromatic ring. However, in contrast to what was observed with diol-amide ligands, there is no direct correlation between the electron-donating or -accepting properties (Hammett parameters) and the value of the reduction potential. This indicates that, in ureas and carbamates, there is no through-bond interaction between the R groups and the polyoxometallic framework.

Table 3. Redox Potentials for the First Two Reduction Processes of Representative Urea and Carbamate-Inserted Vanadotungstates[a]

	1st process		2nd process
POM	E_1 (mV vs Fc)	ΔE_p (mV)	E_2 (mV vs Fc)
3b	−273	84	−620
3d	−353	168	−659
3e	−246	108	−621
3f	−323	162	−630
3m	−332	132	−538
3n	−343	239	−611
3o	−307	102	−600

[a] Redox potentials were measured by cyclovoltammetry at rt in MeCN (0.1 M $TBAPF_6$) on glassy carbon electrode at 300 $mV \cdot s^{-1}$. Values are quoted *vs* ferrocene as internal standard. For the quasi-reversible first process the half-wave potentials and peak differences are given. Broad waves were observed for the second process, and only the reduction peak potential is reported.

The known POM-catalyzed oxidation of sulfides[7] to sulfoxides is a good benchmark for catalytic oxidations with the carbonyl-inserted organo-POMs, provided they retain some activity after the replacement of one sp^3 oxo of the POM framework with an sp^2 one.

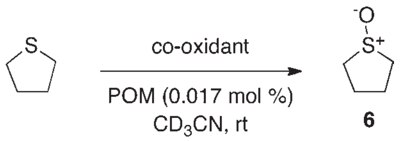
Four POMs (one urea (**3i**), two carbamates (**3k**, **3o**), and one amide[5a] (**3r**, R_1 = *p*-Me-C_6H_4)) derivatives were selected across the board for that purpose. In a typical experiment tetrahydrothiophene was treated with *t*BuOOH in the presence of POM **3k** (0.017 mol %) in acetonitrile at rt. This delivered 88% of the corresponding sulfoxide **6** (Table 4, entry 1; the yields were measured by NMR using trimethoxybenzene as internal standard). No sulfone was observed in any of those reactions.

Control experiments showed that no reaction took place without a POM using either TBHP or H_2O_2. Also, tetrabutylammonium (as TBABr or TBAOH, 1 equiv) alone did not catalyze the oxidation. This unambiguously demonstrates that the POM is a catalyst which needs to be reactivated by a stoichiometric reoxidant. The reaction was not limited to **3k** but worked well also with **3o** (77%, entry 3), **3i** (entry 4), and **3r** (entry 5). Gratifyingly, the catalyst could be recycled upon precipitation in diethyl ether and reused (90%, entry 6).

Most interestingly, the reaction also worked in the presence of H_2O_2 (30% in water) as an oxidant (entry 2). This is important from a green chemistry point of view and shows that the hybrids are not much sensitive to water. For H_2O_2 also the POM acted as a catalyst. Our hybrids compare in fact very well to the purely inorganic **1** (entry 7).

In the hypothesis that the vanadium sites of the POM are involved in the oxidation, one can anticipate that organic ligands on the vanadiums might modify the reactivity of the system and allow fine-tuning of the catalyst. We thus decided to approach this issue from the chemoselectivity angle.

Table 4. Use of Carbonyl-Inserted POMs As Catalysts for the Oxidation of Sulfides



entry	POM	cations	oxidant	yield (%)
1	**3k**	$(TBA)_{4.8}(DMA)_{0.2}$	*t*BuOOH	88
2	**3k**	$(TBA)_{4.7}(DMA)_{0.3}$	H_2O_2	96
3	**3o**	$(TBA)_{4.6}(DMA)_{0.4}$	*t*BuOOH	77
4	**3i**	$(TBA)_{4.6}(DMA)_{0.4}$	*t*BuOOH	97
5	**3r**	$(TBA)_{4.6}(DMA)_{0.4}$	*t*BuOOH	85
6	**3r**	$(TBA)_{4.6}(DMA)_{0.4}$	*t*BuOOH	90[a]
7	**1**	$(TBA)_{5.3}H_{3.7}$	*t*BuOOH	75

[a] Reaction carried out after recycling of **3r** by precipitation.

Two different sulfides (tetrahydrothiophene and phenyl methyl sulfide, 1 equiv each) were reacted with 1 equiv of *tert*-butyl hydroperoxide in acetonitrile at rt. After consumption of the co-oxidant (50% complexion with regard to **6** + **7**), the **6**:**7** ratio was measured by NMR.

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(7) Selected recent examples: (a) Carraro, M.; Nsouli, N.; Oelrich, H.; Sartorel, A.; Soraru, A.; Mal, S. S.; Scorrano, G.; Walder, L.; Kortz, U.; Bonchio, M. *Chem.—Eur. J.* **2011**, *17*, 8371–8378. (b) Jahier, C.; Coustou, M.-F.; Cantuel, M.; McClenaghan, N. D.; Buffeteau, T.; Cavagnat, D.; Carraro, M.; Nlate, S. *Eur. J. Inorg. Chem.* **2011**, 727–738. (c) Khenkin, A. M.; Leitus, G.; Neumann, R. *J. Am. Chem. Soc.* **2010**, *132*, 11446–11448. (d) Mizuno, N.; Uchida, S.; Kamata, K.; Ishimoto, R.; Nojima, S.; Yonehara, K.; Sumida, Y. *Angew. Chem., Int. Ed.* **2010**, *49*, 9972–9976. (e) Nisar, A.; Lu, Y.; Zhuang, J.; Wang, X. *Angew. Chem., Int. Ed.* **2011**, *50*, 3187–3192. See also ref 4a.

When $(TBA)_{5.3}H_{3.7}$-**1** was used, almost no selectivity was observed (**6**:**7** = 60:40, Table 5, entry 1). The selectivity was improved to 70:30 after cation metathesis to all TBAs (entry 2). This set the standard to which some of the hybrids were compared. To get a broad picture of all types of carbonyl-inserted POMs, we added two amides to the selection (**3s**–**t**; Table 5,[5a]). For easy comparison of the diversely substituted POMs, and unless otherwise noted, *t*-BuOOH was selected as stoichiometric oxidant because it works in a purely organic medium (no water).

In the urea-inserted series, alkyl (entries 3–4), electron-poor (entries 5–7), electron-rich (entries 10–11), and neutral (entries 8–9) aromatic substituents all led to noticeable improvement in the selectivities. Those depended on the cation distribution. With around two protons, the selectivities were close to 70:30 (entries 3 and 8). With 0.3–0.4 dimethylammoniums (DMAs), the selectivities improved to approximately 85:15 (entries 5, 9–10), with the exception of **3c**, which was more selective (93:7, entry 7). Gratifyingly, the all-TBA POMs were highly selective, independently of the nature of the urea substituent (entries 4, 6, 11).

A similar behavior was observed with carbamates (entries 12–16). The DMA salts led to chemoselectivities around 80:20 (entries 12, 13, 15), while the TBA salts of **3m** and **3o** worked with increased selectivities (up to 96:4, entries 14 and 16).

Amides behaved like the urea and carbamate hybrids (entries 17–21). While the DMA-containing salts were still less chemoselective than the TBA ones (compare entries 17 and 20 to 19 and 21), some differences appeared. *p*-Nitroaryl substituted **3s** was substantially less selective than *p*-methoxyaryl **3t**, even, or especially, their TBA salts (compare entries 19 and 21).

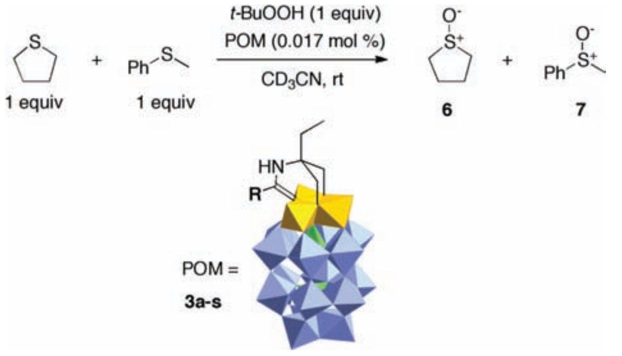
Switching to H_2O_2 as a stoichiometric oxidant led to a slightly diminished, but similar, selectivity for the one example we selected to carry out (entry 18).

Overall the hybrid catalysts have two main features.

- The chemoselectivity is primarily correlated to the proton content in the cations of the salts. The more protons, the less selective the system. When all protons are removed, then the catalysts are highly selective, much more than the purely inorganic polyanion.
- The chemoselectivity can in some cases be potentially tuned by a simple change of the electronic properties of the organic substituents, albeit with a less wide amplitude than with the protons. This is true for the amides, which agrees with our previously published observations.[5a] With ureas and carbamates, the presence of the additional heteroelement attached to the carbonyl probably buffers the electronic influence of the organic substituents, which explains the lack of tunability in those cases.

To conclude, we have expanded the nature of the carbonyl oxygens that can be inserted into phosphovanadotungstate $[P_2V_3W_{15}O_{62}]^{9-}$. Secondary and tertiary amides, ureas, carbamates, and thiocarbamates are suitable functional groups. This generalization of our method significantly widens the diversity of organo-POMs accessible in that way. We also showed that carbonyl insertion did not block the catalytic activity of the vanadium core of the POMs. On the contrary, one can fine-tune the chemoselectivity of the sulfide oxidation upon appropriate choice of cations and organic substituents. Grafting of organics to POMs thus proves again to be a good way to access new or enhanced properties. Further work on these organo-POMs will focus on asymmetric oxidations.

Table 5. Chemoselective Oxidations



ent.	R (POM)	cations[a]	**6**[b]	**7**[b]
1	– (**1**)	$TBA_{5.3}H_{3.7}$	60	40
2	– (**1**)	TBA_9	70	30
3	EtNH (**3a**)	$TBA_{2.85}H_{2.15}$	67	33
4	EtNH (**3a**)	TBA_5	96	4
5	$pNO_2C_6H_4NH$ (**3b**)	$TBA_{4.7}DMA_{0.3}$	82	18
6	$pNO_2C_6H_4NH$ (**3b**)	TBA_5	93	7
7	$pCF_3C_6H_4NH$ (**3c**)	$TBA_{4.65}DMA_{0.35}$	93	7
8	PhNH (**3d**)	$TBA_{3.45}H_{1.55}$	72	28
9	PhNH (**3d**)	$TBA_{4.7}DMA_{0.3}$	87	13
10	$pMeOC_6H_4NH$ (**3f**)	$TBA_{4.7}DMA_{0.3}$	83	17
11	$pMeOC_6H_4NH$ (**3f**)	TBA_5	95	5
12	BnO (**3k**)	$TBA_{4.7}DMA_{0.3}$	86	14
13	PhO (**3m**)	$TBA_{4.6}DMA_{0.4}$	78	22
14	PhO (**3m**)	TBA_5	96	4
15	$pMeOC_6H_4O$ (**3o**)	$TBA_{4.6}DMA_{0.4}$	72	28
16	$pMeOC_6H_4O$ (**3o**)	TBA_5	96	4
17	$pNO_2C_6H_4$ (**3s**)	$TBA_{4.7}DMA_{0.3}$	79	21
18[c]	$pNO_2C_6H_4$ (**3s**)	$TBA_{4.7}DMA_{0.3}$	72	28
19	$pNO_2C_6H_4$ (**3s**)	TBA_5	88	12
20	$pMeOC_6H_4$ (**3t**)	$TBA_{4.65}DMA_{0.35}$	90	10
21	$pMeOC_6H_4$ (**3t**)	TBA_5	95	5

[a] Measured by NMR and elemental analysis. DMA = dimethyl ammonium. [b] NMR ratios. [c] H_2O_2 was used as the oxidant.

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Supporting Information Available. Characterization of all new compounds and cyclic voltammograms. This material is available free of charge via the Internet at http://pubs.acs.org.