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Highly Selective and Efficient Lewis Acid–Base Catalysts Based on Lanthanide-Containing Polyoxometalates for Oximation of Aldehydes and Ketones

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Keywords: Polyoxometalates / Lanthanides / Oximation / Lewis acids / Homogeneous catalysis

Two lanthanide-containing polyoxometalates (POMs) have been developed as Lewis acid–base catalysts for highly selective and efficient oximation of various aldehydes and ketones under mild conditions.

Introduction

Aldoximes and ketoximes have been widely utilized in medicine, industry, and analytical chemistry, and they are very useful and versatile intermediates in synthetic organic chemistry. For example, aldoximes and ketoximes can be reduced to amines or oxidized to nitrile oxides, which are important precursors.[1,2] In general, these oximes can be industrially synthesized by nucleophilic addition of various mineral salts of hydroxylamine [$(NH_2OH)_x\cdot H_xB$, B = SO_4^{2-}, PO_4^{3-}, NO_3^-, and Cl^-; x = 1, 2, and 3] to aldehydes or ketones.[3,4] However, three serious disadvantages of the above method largely restrict its further application in industry: (1) the relatively high cost of hydroxylamine, (2) the large amounts of inorganic salt byproducts,[5] and (3) the poor yields of the corresponding oximes because the resulting oximes can undergo either acid-catalyzed Beckmann rearrangement to amides or dehydration to nitriles. From the industrial viewpoint, it is significant to develop recyclable, highly selective and efficient catalysts that can suppress the formation of byproducts and increase the yields of the corresponding oximes as much as possible through in situ synthesis of hydroxylamine for oximation of aldehydes and ketones.

Among the catalysts developed for the oximation reaction,[6–8] most studies are focused on the ammoximation of cyclohexanone, and a very limited range of substrates have been investigated. Interestingly, Neumann and co-workers reported a sandwich-type polyoxometalate (POM) cluster, $Na_{12}[WZn_3(H_2O)_2(ZnW_9O_{34})_2]\cdot 46H_2O$ (Na-Zn_5W_{19}), which not only catalyzes the reaction of NH_3 and H_2O_2 to in situ synthesize hydroxylamine but also activates the nucleophilic surfaces of the resulting hydroxylamine to promote the reaction.[8] The bare Lewis base nucleophilic surfaces result from the external oxygen atoms of W–O–W and W=O species, and they can act as nucleophilic sites as well as stabilizers of cationic intermediates.[9–12] However, the application of Na-Zn_5W_{19} for oximation led to relatively low yields of the corresponding aromatic aldoximes, because of the formation of byproducts (amides and nitriles) and because they solely afford the corresponding aliphatic carboxylic acids with aliphatic aldehydes as substrates. Therefore, the search for highly selective and efficient catalysts to solve the above problems is very important. Herein, lanthanide-containing POMs $K_{11}[Ln(PW_{11}O_{39})_2]$ {K-Ln-$(PW_{11})_2$; Ln = La and Ce},[13] which introduce lanthanide ions as Lewis acidic metal centers into the POMs,[14,15] have been developed as Lewis acid–base catalysts for the oximation of aldehydes and ketones. It should be mentioned that the ions La^{3+} and Ce^{3+} have been selected for economic reasons. The catalytic results suggest that the highly selective and efficient oximation of various aldehydes and ketones can be realized by using K-Ln$(PW_{11})_2$ as catalyst under mild conditions.

Results and Discussion

Initially, cyclohexanone ammoximation catalyzed by lanthanide-containing POMs K-Ln$(PW_{11})_2$ (Ln = La and Ce) was performed as a model reaction under optimized conditions, and the catalytic results indicate that the corresponding oximes could be obtained in high yields of approximately 97% (Table 1, Entries 1 and 2). In contrast, the monolacunary Keggin POM $K_7[PW_{11}O_{39}]$ (K-PW_{11}), the Keggin POM $Na_3PW_{12}O_{40}$ (Na-PW_{12}), and the peroxometalate $K_2[\{WO(O_2)_2(H_2O)\}_2(\mu\text{-}O)]\cdot 2H_2O$ (K-W_2) provide yields of 78, 77, and 76%, respectively (Entries 3–5). Commonly used catalysts such as $LaCl_3$ and La_2O_3 are not effec-

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tive (Entries 6 and 7). The physical mixture of $LaCl_3$ and $Na\text{-}PW_{12}$ gives a yield of 77% (Entry 8). Tungsten oxide WO_3 is not effective for this oximation reaction (Entry 9). In the absence of catalysts, the oximation reaction does not proceed (Entry 10). It is worth noting that further increase of the oximation time from 6 hours to 12 hours, 24 hours, or 48 hours does not increase the yield when $Na\text{-}PW_{12}$, $K\text{-}PW_{11}$, or $K\text{-}W_2$ are applied as catalysts. It is clear that, although the monolacunary Keggin POM $K\text{-}PW_{11}$, Keggin POM $Na\text{-}PW_{12}$, and peroxometalate POM $K\text{-}W_2$ are efficient as catalysts for this oximation reaction, they cannot meet the requirement for industrial catalysts with yields of approximately 77%. In contrast, $K\text{-}Ln(PW_{11})_2$ (Ln = La and Ce) functions as a highly efficient catalyst for the ammoximation of cyclohexanone with yields of approximately 97% at room temperature. Therefore, the above results reveal that the La^{3+} and Ce^{3+} ions play significant roles in increasing the yields of the oximes from 77 to 97%. More importantly, no byproducts were observed when $Ln(PW_{11})_2$ (Ln = La and Ce) were used as catalysts.

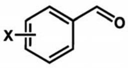
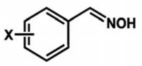
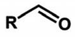
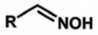
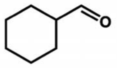
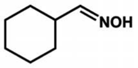
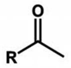
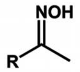
Table 1. The effect of catalysts on the ammoximation of cyclohexanone.[a]

Entry	Catalyst	Yield (%)
1	$K\text{-}La(PW_{11})_2$	98
2	$K\text{-}Ce(PW_{11})_2$	97
3	$K\text{-}PW_{11}$	78
4	$Na\text{-}PW_{12}$	77
5	$K\text{-}W_2$	76
6	$LaCl_3$	1.1
7	La_2O_3	0.2
8	mixture of $LaCl_3$ and $Na\text{-}PW_{12}$	77
9	WO_3	8
10	none	0

[a] Reaction conditions: cyclohexanone (1 mmol), catalyst (0.25 mol-% with respect to cyclohexanone), H_2O_2 (30% aq. solution, 5 mmol), NH_3 (25% aq. solution, 2 mmol), 1-butanol (0.2 mL), room temperature, 6 h. Yields were determined by GC analysis with comparison to reference standards. Assignments of cyclohexanone oximes were performed by ^1H NMR spectroscopy.

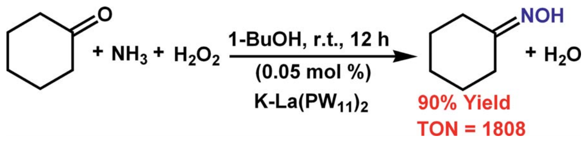
The oximation of various aldehydes and ketones catalyzed by $K\text{-}La(PW_{11})_2$ under optimized conditions has been investigated. All the corresponding oximes can be obtained in good yields. For aromatic aldehydes, benzaldehyde can be converted into the corresponding oxime in an excellent yield of 99% (Table 2, Entry 1). Methyl-substituted aromatic aldehydes including 2-methylbenzaldehyde, 3-methylbenzaldehyde, and 4-methylbenzaldehyde could be converted into the corresponding oximes with yields of 97, 96, and 97%, respectively (Table 2, Entries 2–4). In terms of methoxy-substituted aromatic aldehydes such as 2-methoxybenzaldehyde, 3-methoxybenzaldehyde, and 4-methoxybenzaldehyde, the corresponding oximes can be obtained in high yields of 94, 87, and 86%, respectively (Table 2, Entries 5–7). In contrast, previous experiments showed that only carboxylic acids of the methoxy-substituted aromatic aldehydes can be prepared by using $Na\text{-}Zn_5W_{19}$ as catalyst in the biphasic system.[8] The above results indicate that the catalytic oximation of electron-donating substituted aromatic aldehydes gives excellent yields. In the case of the electron-withdrawing substituted aromatic aldehydes including 2-chlorobenzaldehyde, 3-chlorobenzaldehyde, 4-chlorobenzaldehyde, 2-bromobenzaldehyde, 3-bromobenzaldehyde, and 4-bromobenzaldehyde, good yields in the range 75–80% could be achieved by using Lewis acid–base catalysts $K\text{-}La(PW_{11})_2$ (Table 2, Entries 8–13).

Table 2. Oximation of various aldehydes and ketones catalyzed by $K\text{-}La(PW_{11})_2$.[a]

Entry	Substrate	Product	Yield (%)
			
1	X = H	X = H	99
2	X = 2-Me	X = 2-Me	97
3	X = 3-Me	X = 3-Me	96
4	X = 4-Me	X = 4-Me	97
5	X = 2-MeO	X = 2-MeO	94
6	X = 3-MeO	X = 3-MeO	87
7	X = 4-MeO	X = 4-MeO	86
8	X = 2-Cl	X = 2-Cl	80
9	X = 3-Cl	X = 3-Cl	82
10	X = 4-Cl	X = 4-Cl	72
11	X = 2-Br	X = 2-Br	83
12	X = 3-Br	X = 3-Br	81
13	X = 4-Br	X = 4-Br	75
			
14	R = n-C_5H_{11}	R = n-C_5H_{11}	94
15	R = n-C_6H_{13}	R = n-C_6H_{13}	99
16	R = n-C_7H_{15}	R = n-C_7H_{15}	92
17	R = n-C_8H_{17}	R = n-C_8H_{17}	97
18	R = n-C_9H_{19}	R = n-C_9H_{19}	95
19			98
			
20	R = n-C_5H_{11}	R = n-C_5H_{11}	77

[a] Reaction conditions: substrate (1 mmol), $K\text{-}La(PW_{11})^2$ (0.25 mol-% with respect to substrate), H_2O_2 (30% aq. solution, 5 mmol), NH_3 (25% aq. solution, 2 mmol), 1-butanol (0.2 mL), room temperature, 6 h. Yields were determined by GC analysis with use of reference standards. Assignments of the corresponding oximes were performed by ^1H NMR spectroscopy.

In the case of the aliphatic aldehydes, the oximation of hexanal, heptanal, octanal, nonanal, and decanal gives the corresponding oximes with yields of 94, 99, 92, 97, and 95%, respectively (Table 2, Entries 14–18). These results are quite different from those of reactions catalyzed by $Na\text{-}Zn_5W_{19}$, which oxidize the substrates to the corresponding carboxylic acids.[8] The oximation of the cyclic aliphatic aldehyde cyclohexanecarboxaldehyde proceeds efficiently with a yield of 98% (Table 2, Entry 19). The oximation yield of alkyl ketone 2-heptanone is 77% without the formation of amides or nitriles (Table 2, Entry 20). It should be pointed out that cyclohexanone ammoximation can proceed efficiently with 90% yield at room temperature in 12 hours with only 0.05 mol-% of K-La$(PW_{11})_2$, and the turnover number (TON) can reach values as high as 1808 (Scheme 1). To the best of our knowledge, K-La$(PW_{11})_2$ is one of the most efficient catalysts for cyclohexanone ammoximation reported so far in the literature.



Scheme 1. The ammoximation of cyclohexanone with 0.05 mol-% K-La$(PW_{11})_2$.

It is instructive to compare cyclohexanone ammoximation through in situ synthesis of hydroxylamine catalyzed by different compounds reported so far (Table 3). Though Ti-Meso-MOR (Entry 1), Ti-MOR (Entry 2), and TS-1 (Entry 3) are highly efficient for cyclohexanone ammoximation,[6] these catalytic systems require the cumbersome synthesis of Ti-Meso-MOR, Ti-MOR, and TS-1 and a relatively high reaction temperature of 60 °C. In the case of clay-based TS-1, a high reaction temperature of 80 °C is necessary (Entry 5), as a much lower yield of cyclohexanone oxime is obtained at 50 °C (Entry 4).[7] Another problem with the above catalytic systems is the quite limited scopes of the substrates. The POM catalyst Na-Zn_5W_{19} was reported to catalyze oximation of some substrates, but the resulting oximes underwent acid-catalyzed Beckmann rearrangement or dehydration, resulting in the low yields. As a result, Na-Zn_5W_{19} was intercalated into layered double hydroxides (LDHs) to overcome its shortcomings (Entry 7).[16] Nevertheless, the relatively difficult preparation of Mg_3Al-LDHs-Zn_5W_{19} and the unsatisfying yields of aldoximes restrict the further application of this intercalated system. In contrast, K-Ln$(PW_{11})_2$ (Ln = La and Ce) show high yields of 97 and 98% at room temperature (Entries 8 and 10). It should be noted that the yield of cyclohexanone oxime can reach 97% in 1.5 h at 50 °C (Entry 9). Additionally, POM catalysts K-Ln$(PW_{11})_2$ (Ln = La and Ce) were demonstrated to be highly efficient not only for the ammoximation of cyclohexanone but also for that of various other aldehydes and ketones.

Table 3. Oximation of cyclohexanone with different catalysts.[a]

Entry	Catalyst[b]	Cat./Sub. (g/mmol)	*T* (°C)	*t* (h)	Yield (%)	Ref.
1	Ti-Meso-MOR	0.005	60	2	97	[6]
2	Ti-MOR	0.005	60	2	99	[6]
3	TS-1	0.015	60	2	96	[6]
4	clay-Based TS-1	0.330	50	2.5	14	[7]
5	clay-Based TS-1	0.330	80	2.5	97	[7]
6	Na-Zn_5W_{19}	0.012	25	6	90	[8]
7	Mg_3Al-LDHs-Zn_5W_{19}	0.003	25	6	90	[16]
8	K-La$(PW_{11})_2$	0.015	25	6	97	this work
9	K-La$(PW_{11})_2$	0.015	50	1.5	97	this work
10	K-Ce$(PW_{11})_2$	0.015	25	6	97	this work

[a] Solvents: Entries 1–5 in a 1:6 mixture of *tert*-butyl alcohol and water; Entry 6 in water; Entries 7–10 in 1-butanol. [b] Ti-Meso-MOR: mesoporous titanosilicate with the MOR topology; Ti-MOR: titanosilicate with MOR topology; TS-1: titanium silicalite-1; LDHs: layered double hydroxides.

Recycling experiments were performed for K-La$(PW_{11})_2$ to check its stability. In this catalytic system, K-La$(PW_{11})_2$ can be recovered simply by extracting the obtained cyclohexanone oxime, and the recycling experiments were carried out by re-addition of cyclohexanone, 30% H_2O_2 and 25% $NH_3{\cdot}H_2O$ over 6 hours at room temperature. The yields of cyclohexanone oxime (1st: 96%, 2nd: 94%, 3rd: 93%, 4th: 93%, 5th: 93%, and 6th: 91%) do not show a significant decrease after six cycles (Figure S2). The slight loss of activity can be accounted for some minor loss of the POM catalyst K-La$(PW_{11})_2$. The strong peak appearing at –12.0 ppm in the ^{31}P NMR spectrum and indicating the structure of $[La(PW_{11}O_{39})_2]^{11-}$ is the same for both fresh and reused K-La$(PW_{11})_2$ samples (Figure 1A). In addition, FTIR spectra of the fresh and reused K-La$(PW_{11})_2$ sample also exhibit the same peaks at 1092, 1050, 951, 890, 835, 771, 593, and 515 cm^{-1} (Figure 1B), which could be as-

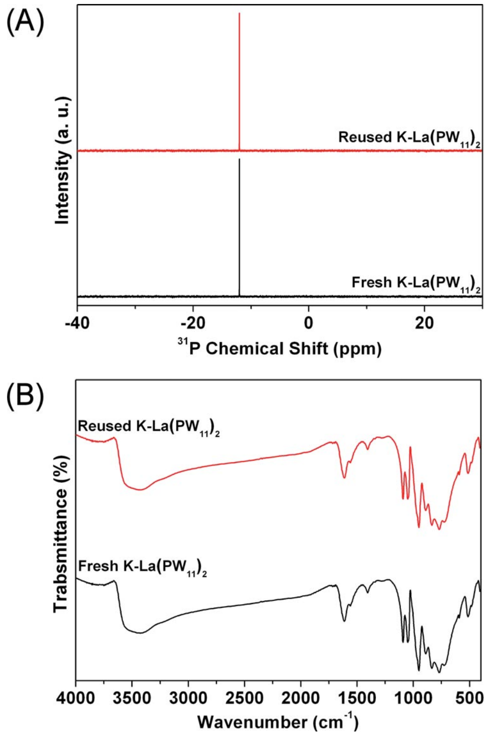
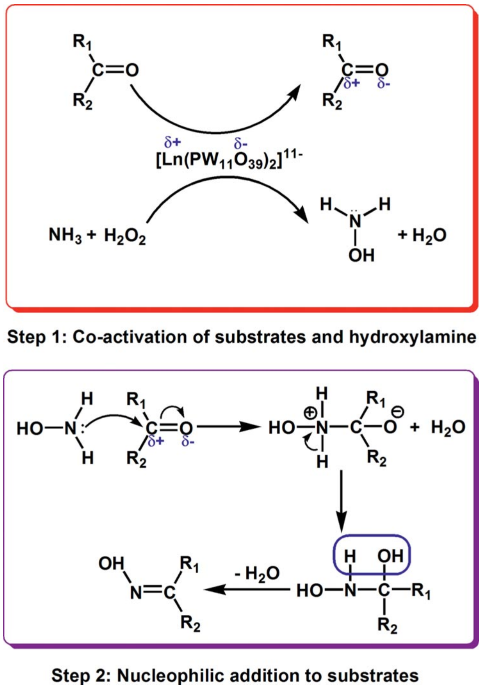


Figure 1. (A) The ^{31}P NMR spectra of fresh and reused K-La$(PW_{11})_2$; (B) the FTIR spectra of fresh and reused K-La$(PW_{11})_2$.

signed to the vibration associated with the $[La(PW_{11}O_{39})_2]^{11-}$ cluster.[14] All these results reveal that the structure of K-La$(PW_{11})_2$ is not affected by the oximation reaction.

Combining the nucleophilic Lewis base surface of POMs with Lewis acid metal centers, these two POMs of K-Ln$(PW_{11})_2$ (Ln = La and Ce) could function as Lewis acid–base catalysts[14,15] and effectively promote the oximation of various aldehydes and ketones. As shown in Scheme 2, the lanthanide-containing POMs K-Ln$(PW_{11})_2$ (Ln = La and Ce) possess both electrophilic centers (lanthanide ions) and bare nucleophilic surfaces (surface oxygen atoms). Aldehydes or ketones could be activated by the lanthanide centers, and the in situ synthesized hydroxylamine is also activated by surface oxygen atoms (Step 1). In other words, co-activation of both aldehyde or ketone and in situ synthesized hydroxylamine can be achieved by using K-Ln$(PW_{11})_2$ as catalyst, and the nucleophilic addition of in situ hydroxylamine to aldehydes or ketones leads to the formation of the corresponding oximes, as indicated by Step 2.



Scheme 2. The proposed mechanism of the oximation reaction. [Step 1: co-activation of aldehydes or ketones and the hydroxylamine in situ synthesized by using K-Ln$(PW_{11})_2$ as catalyst; Step 2: the nucleophilic addition of hydroxylamine to aldehydes or ketones leads to the formation of the oximes.].

Conclusions

In summary, the application of the Lewis acid–base catalysts K-Ln$(PW_{11})_2$ (Ln = La and Ce) with lanthanide ions as electrophilic centers and nucleophilic surfaces to the oximation reaction leads to the co-activation of both aldehydes or ketones and hydroxylamine. As a result, K-Ln$(PW_{11})_2$ are able to realize highly selective and efficient oximation of various substrates under mild conditions. The corresponding oxime products can be extracted from the system, and the catalysts can then be directly used for the next run over six times without a significant decrease in catalytic activity. In addition, the structures of K-Ln$(PW_{11})_2$ remain unchanged after the oximation reaction, as evidenced by the ^{31}P NMR and FTIR spectra. The easy preparation, recyclability, high selectivity, and efficiency of the lanthanide-containing POM catalysts provide great potential for their further application.

Experimental Section

Synthesis of $K_{11}[Ln(PW_{11}O_{39})_2]$ {K-Ln$(PW_{11})_2$, Ln = La and Ce}:[13] $H_3PW_{12}O_{40}\cdot xH_2O$ (10.0 g, 3.47 mmol) in H_2O (20 mL) was added dropwise to warm concentrated solutions of $LaCl_3\cdot 7H_2O$ (0.6 g, 1.85 mmol) or $CeCl_3\cdot 6H_2O$ (0.7 g, 1.85 mmol) and CH_3COOK (8.0 g, 0.08 mol, pH adjusted to 7.0 with CH_3COOH). The mixture was stirred at 90 °C until a clear solution was obtained. The clear solution was cooled to room temperature and then kept in the refrigerator (ca. 4 °C) overnight. The obtained precipitate was filtered and recrystallized twice. From the TGA and ICP analysis, the formulas of K-Ln$(PW_{11})_2$ (Ln = La and Ce) should be $K_{11}[La(PW_{11}O_{39})_2]\cdot 13H_2O$ and $K_{11}[Ce(PW_{11}O_{39})_2]\cdot 14H_2O$.

Procedure for Oximation of Aldehydes and Ketones: In a typical experiment, ketones or aldehydes (1 mmol), aqueous H_2O_2 solution (30%), aqueous NH_3 solution (25%), K-Ln$(PW_{11})_2$ (Ln = La and Ce) as catalyst (0.25 mol-%), and solvents (0.2 mL) were placed in a 20 mL glass bottle at room temperature, and the reaction mixture was stirred vigorously. The reaction was effectively quenched after 6 h. The resulting oily products were extracted with diethyl ether, analyzed by GC, and identified by ^{1}H NMR spectroscopy to determine the yield by comparison to reference standards.

Supporting Information (see footnote on the first page of this article): Experimental details and catalytic results.

Acknowledgments

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[1] B. A. Mendelsohn, S. Lee, S. Kim, F. Teyssier, V. S. Aulakh, M. A. Ciufolini, *Org. Lett.* **2009**, *11*, 1539–1542.
[2] N. A. Owston, A. J. Parker, J. M. J. Williams, *Org. Lett.* **2007**, *9*, 3599–3601.
[3] A. Pohjakallio, P. M. Pihko, *Chem. Eur. J.* **2009**, *15*, 3960–3964.
[4] C. L. Allen, S. Davulcu, J. M. J. Williams, *Org. Lett.* **2010**, *12*, 5096–5099.
[5] J. Le Bars, J. Dakka, R. A. Sheldon, *Appl. Catal. A* **1996**, *136*, 69–80.
[6] H. Xu, Y. Zhang, H. Wu, Y. Liu, X. Li, J. Jiang, M. He, P. Wu, *J. Catal.* **2011**, *281*, 263–272.
[7] A. C. K. Yip, X. Hu, *Ind. Eng. Chem. Res.* **2009**, *48*, 8441–8450.

[8] D. Sloboda-Rozner, R. Neumann, *Green Chem.* **2006**, *8*, 679–681.

[9] Special issue on "polyoxometalates", *Chem. Rev.* **1998**, *98*, 1–390.

[10] R. Neumann, *Prog. Inorg. Chem.* **1998**, *47*, 317–370.

[11] I. V. Kozhevnikov, *Catalysis by Polyoxometalates*, John Wiley & Sons, Chichester, **2002**.

[12] D. L. Long, R. Tsunashima, L. Cronin, *Angew. Chem.* **2010**, *122*, 1780–1802; *Angew. Chem. Int. Ed.* **2010**, *49*, 1736–1758.

[13] R. D. Peacock, T. J. R. Weakley, *J. Chem. Soc. A* **1971**, 1836–1839.

[14] Y. Kikukawa, K. Suzuki, M. Sugawa, T. Hirano, K. Kamata, K. Yamaguchi, N. Mizuno, *Angew. Chem.* **2012**, *124*, 3746–3750; *Angew. Chem. Int. Ed.* **2012**, *51*, 3686–3690.

[15] K. Suzuki, M. Sugawa, Y. Kikukawa, K. Kamata, K. Yamaguchi, N. Mizuno, *Inorg. Chem.* **2012**, *51*, 6953–6961.

[16] S. Zhao, L. Liu, Y. F. Song, *Dalton Trans.* **2012**, *41*, 9855–9858.

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Lanthanide-Containing POMs

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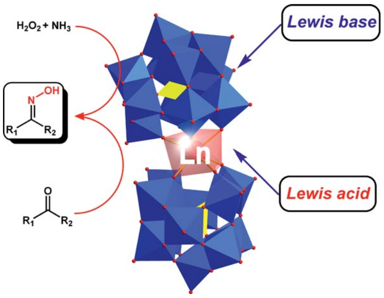

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