



New copper(II) dimer with 3-(2-hydroxy-4-nitrophenylhydrazo)pentane-2,4-dione and its catalytic activity in cyclohexane and benzyl alcohol oxidations

Kamran T. Mahmudov^a, Maximilian N. Kopylovich^a, M. Fátima C. Guedes da Silva^{a,b}, Paweł J. Figiel^a, Yauhen Yu. Karabach^a, Armando J.L. Pombeiro^{a,*}

^a Centro de Química Estrutural, Complexo I, Instituto Superior Técnico, TU Lisbon, Av. Rovisco Pais, 1049-001 Lisbon, Portugal

^b Universidade Lusófona de Humanidades e Tecnologias, ULHT Lisbon, Campo Grande 376, 1749-024 Lisbon, Portugal

ARTICLE INFO

Article history:

Received 30 September 2009

Received in revised form 6 November 2009

Accepted 9 November 2009

Available online 14 November 2009

Keywords:

3-(2-Hydroxy-4-nitrophenylhydrazo)pentane-2,4-dione complexes

Azoderivatives of β -diketones

Copper

X-ray structure

Oxidation of cyclohexane

Oxidation of benzyl alcohol

TEMPO

ABSTRACT

3-(2-Hydroxy-4-nitrophenylhydrazo)pentane-2,4-dione (H_2L , **1**) was synthesized by azocoupling of diazonium salts of 2-hydroxy-4-nitroaniline with pentane-2,4-dione and shown to exist in the hydrazone tautomeric form in the free state and in its new dicopper(II) complex $[Cu_2(H_2O)_2(\mu-L)_2]$ (**2**) whose X-ray crystal structure was determined. Complex **2** acts as a catalyst, under mild conditions, for the peroxidative oxidation (with H_2O_2) of cyclohexane to cyclohexanol, cyclohexanone and cyclohexyl hydroperoxide, in MeCN/ H_2O , and for the aerobic TEMPO-mediated selective oxidation of benzylic alcohols to the corresponding aldehydes, thus showing that azoderivatives of β -diketones can be the suitable ligands for such types of reactions.

© 2009 Elsevier B.V. All rights reserved.

1. Introduction

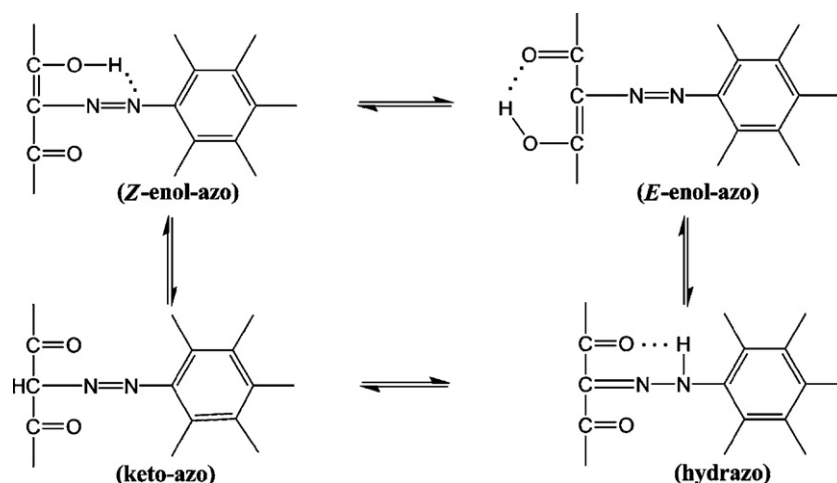
The coordination chemistry of azoderivatives of β -diketones (ADB) is still a little explored area of research, notwithstanding their interesting chemical and structural features [1]. Thus, these compounds having several coordination modes with a high flexibility, can exist in various tautomeric forms involving hydrogen bonds (Scheme 1) and potentially can be used, e.g. as materials with smart hydrogen bonding [2,3] or as bistate molecular switches [4]. Complexes of these ligands or their analogs have been applied for spectrophotometric determination of some metal ions [5,6], as photoluminescent materials [7], light transmitters [8] and sensors [9], in high-density recordable optical storage [10] or spin-coating films [11]; they also can exhibit semi-conducting [12] and liquid crystal [13] properties. Hence, the knowledge of characteristics of deprotonation, tautomerization and complexation in solution as well as the structural details of coordination with metal ions in solid state is fundamental for

forecasting the properties of this class of organonitrogen reagents [14–16].

However, the available data on complexes of this interesting type of ligands are still very limited and mainly concern rather simple examples [17,18], although it was observed [19,20] that ADB containing a 2-hydroxyphenyl group can show a high complexing ability in solution. Thus, in order to further explore the coordination properties of such a class of compounds, in this work we have synthesized a new *ortho*-hydroxy substituted azoderivative of pentane-2,4-dione, i.e. 3-(2-hydroxy-4-nitrophenylhydrazo)pentane-2,4-dione H_2L (**1**, Scheme 2), investigated the complexation of this ADB in solution with copper(II) ion and shed light on structural details and coordination modes to Cu(II) in the solid state.

Another main aim of the current work concerns the extension of the application of ADB ligands to a new field, i.e. oxidation catalysis, and the focus on that particular metal (copper) and on **1** is justified as follows. It is known [21,22] that particulate methane monooxygenase (pMMO), a multicopper enzyme, catalyzes the partial oxidation of alkanes to alcohols, and this type of action can be mimicked by some copper complexes with N,O-type or related ligands [23–39] that can typically act as catalysts for the peroxida-

* Corresponding author. Tel.: +351 21 841 9237; fax: +351 21 846 4455.
E-mail address: pombeiro@ist.utl.pt (A.J.L. Pombeiro).



Scheme 1. Possible tautomeric equilibria for ADB.

tive oxidation of cyclohexane to cyclohexanol and cyclohexanone [28–39]. The industrial significance of the partial oxidation of this cycloalkane to those products is well recognized since the latter find important applications for the synthesis of Nylon-6,6 and caprolactams [24,40].

Different types of N,O- or O,O-ligands (e.g. aminopolyalcohols, aminocarboxylates, polycarboxylates, etc.) have been used for those catalysts but, to our knowledge, ADB ligands have not yet been reported for such a purpose. Hence, a relevant objective of the current work was to design an ADB compound that could act as a N,O- or N,O,O-ligand for a copper complex that would behave as a catalyst for such an oxidation reaction, *i.e.* the peroxidative oxidation of cyclohexane. Moreover, TEMPO radical (2,2,6,6-tetramethylpiperidine-1-oxyl), combined with a suitable metal species, is a well-known efficient mediator for aerobic oxidation of alcohols [41–46], and hence it would also be interesting to associate it to an ADB–Cu complex towards the aerobic selective oxidation of benzylic alcohols to aldehydes. The choice of those model reactions was justified by their importance in organic synthesis and chemical industry [40].

2. Experimental

2.1. Materials and instrumentation

All of the chemicals were obtained from commercial sources and used as received. ^1H NMR and ^{13}C NMR spectra were recorded on a Bruker Avance II+ 300.130 (UltraShieldTM Magnet) spectrometer at ambient temperature using tetramethylsilane as an internal reference. Infrared spectra ($4000\text{--}400\text{ cm}^{-1}$) were recorded on a BIO-RAD FTS 3000MX instrument in KBr pellets. Carbon, hydrogen, and nitrogen elemental analyses were carried out by the Micro-

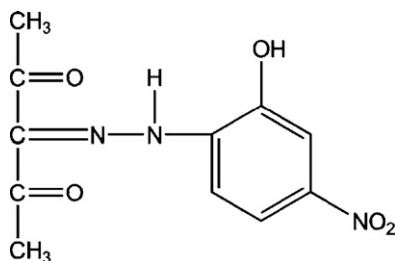
analytical Service of the Instituto Superior Técnico. To maintain the required pH, a commercial volumetric concentrate of HCl (pH 1–2) was used. The acidity of the solutions was measured using an I-130 potentiometer with an ESL-43-07 glass electrode and an EVL-1M3.1 silver–silver chloride electrode. The solution of copper ions was prepared from $\text{Cu}(\text{NO}_3)_2 \cdot 2.5\text{H}_2\text{O}$. In the aqueous solutions of the salt, the concentrations of Cu(II) were determined by atomic absorption spectroscopy. The pH-metric titration of mixtures of **1** with the copper salts was carried out in aqueous-ethanol (40/60 v/v, %) solution with consideration of the Bates correction [47] at different temperatures (298 ± 0.5 , 308 ± 0.5 and $318 \pm 0.5\text{ K}$) (for details, see [Supplementary information](#)). Constant temperature was maintained within 0.5 K by using an ultrathermostat (Neslab 2 RTE 220). The conductivities of solutions were measured with a KEL-1M2 conductometer. All of the synthetic work was performed in air and at room temperature. Chromatographic analyses were undertaken by using a Fisons Instruments GC 8000 series gas chromatograph with a DB-624 (J&W) capillary column (FID detector) and the Jasco-Borwin v.1.50 software. The internal standard method was used to quantify the organic products.

2.2. Synthesis of H_2L (**1**) and $[\text{Cu}_2(\text{H}_2\text{O})_2(\mu\text{-L})_2]$ (**2**)

The ligand **1** was synthesized according to the Japp–Klingemann reaction [48] between the corresponding diazonium salt and pentane-2,4-dione, while the synthesis of the complex **2** was performed directly by mixing copper(II) nitrate $\text{Cu}(\text{NO}_3)_2 \cdot 2.5\text{H}_2\text{O}$ with **1** in aqueous-ethanol solution in the presence of 0.01 M HCl (for details see [Supplementary information](#)).

2.3. X-ray structure determination

X-ray quality single crystals of **2** were grown by slow evaporation at room temperature of a water–ethanol solution. They were immersed in cryo-oil, mounted in a Nylon loop and measured at a temperature of 150 K. Intensity data were collected using a Bruker AXS-KAPPA APEX II diffractometer with graphite monochromated $\text{Mo-K}\alpha$ (λ 0.71073) radiation. Data were collected using omega scans of 0.5° per frame and full sphere of data were obtained. Cell parameters were retrieved using Bruker SMART software and refined using Bruker SAINT [49] on all the observed reflections. Absorption corrections were applied using SADABS [49]. Structures were solved by direct methods by using the SHELXS-97 package [50] and refined with SHELXL-97 [51]. Calculations were performed



Scheme 2. 3-(2-Hydroxy-4-nitrophenylhydrazo)pentane-2,4-dione (H_2L , **1**).

Table 1
Selected distances (Å) and angles (°) of compound **2**.

C2–O1	1.218(3)	N1–N2–Cu1	130.74(13)
C3–N1	1.354(2)	C11–N2–Cu1	112.54(12)
C4–O2	1.269(2)	C4–O2–Cu1	127.90(13)
C11–N2	1.408(2)	C16–O3–Cu1	111.49(11)
C16–O3	1.332(2)	C16–O3–Cu1 ⁱ	133.17(12)
N1–N2	1.292(2)	Cu1–O3–Cu1 ⁱ	99.60(6)
N2–Cu1	1.9139(16)	O2–Cu1–N2	90.52(6)
O2–Cu1	1.9062(14)	O2–Cu1–O3	173.21(6)
O3–Cu1	1.9424(14)	N2–Cu1–O3	84.90(6)
O3–Cu1 ⁱ	2.0502(14)	O2–Cu1–O3 ⁱ	100.59(6)
Cu1–Cu1 ⁱ	3.0503(7)	N2–Cu1–O3 ⁱ	143.73(6)
O10–Cu1	2.1463(15)	O3–Cu1–O3 ⁱ	80.40(6)
N1–C3–C4	125.90(16)	O2–Cu1–O10	92.21(6)
O2–C4–C3	123.22(17)	N2–Cu1–O10	119.03(5)
N2–C11–C16	112.64(16)	O3–Cu1–O10	94.44(6)
O3–C16–C11	118.34(16)	O10–Cu1–Cu1 ⁱ	95.17(4)
N2–N1–C3	120.91(17)	O3–Cu1–Cu1 ⁱ	41.51(4)
		O3–Cu1 ⁱ –Cu1 ⁱ	38.89(4)

ⁱTranslation of symmetry code to equivalent positions: 1 – x, 1 – y, 1 – z.

using the WinGX System-Version 1.80.03 [52]. All hydrogens were inserted in calculated positions. Least square refinements with anisotropic thermal motion parameters for all the non-hydrogen atoms and isotropic for the remaining atoms were employed. Crystallographic and selected structural details are listed in Table S1 and Table 1, respectively. CCDC 734862 contains the supplementary crystallographic data for this paper. These data can be obtained free of charge from The Cambridge Crystallographic Data Centre via www.ccdc.cam.ac.uk/data_request/cif.

2.4. Catalytic activity studies

2.4.1. Oxidation of cyclohexane

The reaction mixtures were prepared as follows: to 3.12–20.00 μmol of the complex **2** contained in the reaction flask were added 4 mL MeCN, 0.031–0.200 mmol HNO₃, 1.00 mmol C₆H₁₂ and 10.00 mmol H₂O₂ (30% in H₂O), in this order. The reaction mixture was stirred for 6 h at room temperature (ca. 298 K) and air atmospheric pressure, then 90 μL of cycloheptanone (as internal standard) and 9.0 mL of diethyl ether (to extract the substrate and the products from the reaction mixture) were added. The resulting mixture was stirred for 15 min and then a sample taken from the organic phase was analyzed by GC. Subsequently, PPh₃ was added to the final organic phase (to reduce the cyclohexyl hydroperoxide, if formed), the mixture was analyzed again to estimate the amount of cyclohexyl hydroperoxide, according to Shul'pin's method [53,54]. The GC analyses of the aqueous phase showed the presence of only traces (less than 0.05%) of oxidation products. Catalyst recycling experiments were performed according to a previously reported technique [55]. Blank experiments were performed and confirmed that no cyclohexane oxidation products (or only traces, below 0.3%) were obtained in the absence of the metal catalyst.

2.4.2. Aerobic oxidation of alcohols in aqueous media

The reactions were carried out in 50 mL round-bottom flasks equipped with condensers under atmospheric pressure of air. Typically, to a 10 mL of 0.1 mol L⁻¹ aqueous solution of K₂CO₃ were added 3.0 mmol of alcohol, 0.03 mmol (1 mol% vs substrate) of catalyst **2** and 0.15 mmol (5 mol% vs substrate) of TEMPO. The reaction solutions in all cases were vigorously stirred using magnetic stirrers, and an oil bath was used to achieve the desired reaction temperature. After the oxidation reaction, reaction mixtures were neutralized by 1 mol L⁻¹ HCl, and then extracted with 10 mL of EtOAc. The organic phase was used for chromatographic analyses using acetophenone as the internal standard.

3. Results and discussion

3.1. Synthesis and characterization of H₂L (**1**) and [Cu₂(H₂O)₂(μ-L)₂] (**2**)

The new 3-(2-hydroxy-4-nitrophenylhydrazo)pentane-2,4-dione (H₂L, **1**) ligand was synthesized via the Japp–Klingemann reaction [48] between the respective aromatic diazonium salt and pentane-2,4-dione in an ethanolic solution containing sodium acetate. The ¹H NMR spectrum of **1** in dimethylsulfoxide-*d*⁶ solution at room temperature shows a signal at δ 14.17 which is assigned to the proton of the protonated nitrogen atom adjacent to the aryl unit (=N–NH–hydrazo form, Scheme 1) [17]. The two methyl groups of the pentane-2,4-dione moiety yield separate singlets in the proton spectrum. These data support the predominance of the hydrazo form (Scheme 1) with a six-membered H-bonded ring involving one of the carbonyl groups and the protonated nitrogen moiety of the hydrazone structure. The IR spectrum of the isolated compound shows ν(OH) and ν(NH) vibrations at 3461 and 3095 cm⁻¹ respectively, while ν(C=O), ν(C=O···H) and ν(C=N) are observed at 1638, 1626 and 1598 cm⁻¹, correspondingly, also supporting the existence of the H-bonded hydrazone structure in the solid state.

The copper(II) complex [Cu₂(H₂O)₂(μ-L)₂] (**2**) was obtained upon refluxing for a short time (10 min) an ethanol/water solution of **1** and copper(II) nitrate hydrate, whereafter it was isolated in a good yield (67%) as greenish-black crystals formed upon slow solvent evaporation at room temperature. Its IR spectrum displays ν(OH), ν(C=O), ν(C=O···H) and ν(C=N) at 3468, 1652, 1611 and 1602 cm⁻¹, respectively, values that are significantly shifted in relation to the corresponding ones (see above) of the free ligand. No bond assignable to ν(NH) was observed, indicating that the ligand is coordinated in the deprotonated hydrazo form.

The X-ray structural analysis of **2** showed that the complex is binuclear in the solid state (Fig. 1) and contains a crystallographically imposed centre of inversion. It crystallizes in the centrosymmetric triclinic space group *P*-1 with one molecule per unit cell and half a molecule in the asymmetric unit. The coordination sphere of the penta-coordinated copper is best described as a distorted square-pyramid; the copper atom is 0.337 Å above the basal O3–O3–O2–N2 plane, shifted towards the apical position which is occupied by a coordinated water molecule. Each copper atom belongs to three different metallacycles: the Cu₂O₂ core, which is the central planar ring of the molecule, and two fused six- and five-membered metallacycles, Cu1–O2–C4–C3–N1–N2 and Cu1–N2–C11–C16–O3. In agreement, the O2–Cu1–N2 and the N2–Cu1–O3 angles are of 90.52(6)° and 84.90(6)°, respectively. Within the Cu(μ-O)₂Cu core, the Cu–Cu distance is of 3.0503(7) Å, the Cu–O distances are of 1.9424(14) and 2.0502(14) Å and the internal angles are of 38.89(4)°, 41.51(4)° and 80.40(6)°. The dihedral angles between the central planar Cu₂O₂ ring and each of the phenyl rings are of 32.25°. The crystal lattice is stabilized by hydrogen bonding interactions between the coordinated water hydrogens and both the nitro and ketone groups in adjacent units (see Fig. 1).

The normal dissociation constants of the **1** ligand were determined, by pH-metric titration, as pK₁ = 6.35 ± 0.04 and pK₂ = 10.22 ± 0.01 (for details, see Supplementary information Tables S1 and S5). The ability to abstract a proton from various groups in tautomeric forms of related ligands was evaluated previously [5,6] and it was considered that pK₁ concerns the proton abstraction from an –OH group in the *ortho* position to the hydrazo moiety in the aromatic ring of the molecule, while pK₂ refers to the deprotonation of the hydrazone group itself (=N–NH–) (see Scheme 1, hydrazo form). The thermodynamic parameters of the dissociation process of **1** were determined by studying the

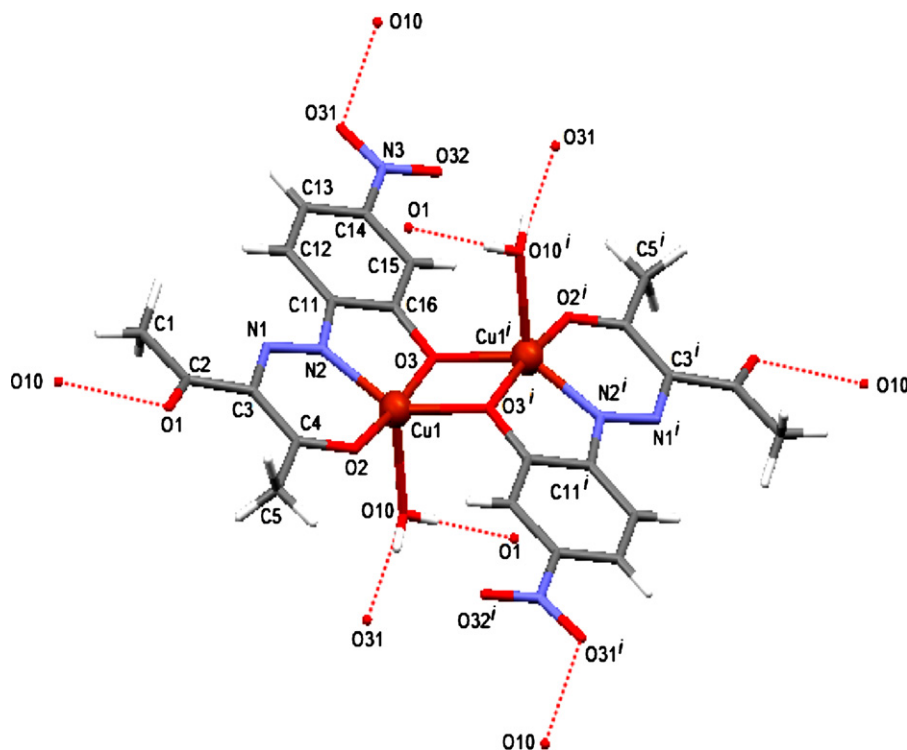


Fig. 1. Molecular structure of **2** with atomic numbering scheme and intermolecular hydrogen bonding interactions (dotted lines). D–H...A [$d(D\cdots A)$ Å; $\angle(DHA)^\circ$]: O10–H10A...O31ⁱⁱ [2.842(2)Å, 170.00°]; O10–H10B...O1ⁱⁱⁱ [2.705(2)Å, 178.00°]. Translation of symmetry code to equivalent positions: (i) 1 – x, 1 – y, 1 – z; (ii) 1 + x, y, –1 + z and (iii) x, 1 + y, z.

dependence of the dissociation constants with the temperature (Table S5). The analysis of these values reveals that the acidity of the compound grows with an increase of the temperature and that the dissociation process is not spontaneous (positive ΔG°) and is endothermic (positive ΔH°).

Based on the experimental data and calculated values (for details, see Supplementary information, Table S6), we can conclude that: (i) the maximum value of the function of formation of \bar{n} is two, meaning that the Cu:H₂L ratio in the complexes is 2:2 [56–58]. (ii) With increase of temperature the stepwise stability constants decrease. (iii) The metal complex titration curves are shifted to down side of the ligand titration curves along the pH axis, indicating proton release upon complex formation (the large decrease in pH for the metal titration curves relative to those of ligand titration indicates the formation of strong metal complexes). (iv) The negative values of ΔG° show that complex formation is spontaneous [14–16,59,60] and is mainly contributed by the enthalpy factor (the process is exothermic and favourable at low temperatures) [61]. (v) The positive change of the entropy contribution conceivably is caused by the release of water molecules and formation of a complex with a lower charge as compared to the initial ions, as well as by a lower solvation of the obtained complexes [56], although it may also depend on the ligand configuration (entropy of tautomeric equilibrium).

Both metal ion coordination and proton elimination occur for complex formation (Scheme 3) and thus the overall conductivity of the systems increases due to the higher proton mobility. Comparison of the stability constants of the complexes (Table S6b) and conductivity studies (see Supplementary information, Fig. S1) show that the formed complex is stable in solution. It can also be seen

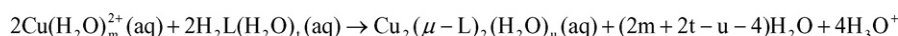
from Fig. S1 that the conductivities decrease after the equivalence point, what can be associated with protonation of free L²⁻, HL⁻ or H₂L [15,62].

3.2. Catalytic activity of the dicopper complex **2**

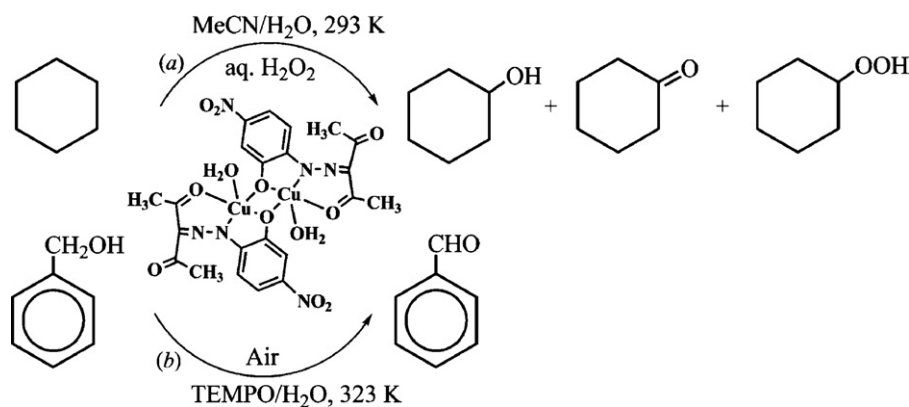
The oxidations of cyclohexane and benzyl alcohol (Scheme 4) were chosen as model reactions to test the catalytic potential of the synthesized binuclear copper compound **2** for oxidations of alkanes and alcohols.

This complex exhibits a good catalytic activity in the peroxidative oxidation of cyclohexane by aqueous H₂O₂, under mild conditions, to afford cyclohexanol (CyOH), cyclohexanone and cyclohexyl hydroperoxide (CyOOH) (Scheme 4a, Tables 2 and 3). The total yield, in a single batch, reaches 27%, for a substrate to catalyst molar ratio of 50, which is comparable with those obtained for other mono- and multinuclear copper(II) complexes with N,O-ligands [55,63–65]. However, the turnover number (TON) values (up to 17 moles of products per mole of catalyst, for a single batch) of our catalyst are not so high as those achieved by other multicopper triethanolamine complexes [28,55]. Nevertheless, the activity of our catalyst is much higher than that of a simple copper(II) salt such as Cu(NO₃)₂ which, under similar conditions, almost does not show any catalytic activity (TON of 1.4, Table 2, run 9).

The GC analyses (Table 2) were performed with and without triphenylphosphine (reducer of CyOOH to CyOH) in order to estimate the yields of cyclohexyl hydroperoxide (CyOOH) in the final reaction mixture, according to a method developed by Shul'pin [53,54]. Hence, CyOOH produced along the reaction is, at the end, still present in a considerable amount (3–4% yield) that does not



Scheme 3. Complexation of copper(II) with H₂L (**1**).



Scheme 4. Oxidations of cyclohexane and benzyl alcohol using **2** as a catalyst.

Table 2
Peroxidative oxidation of cyclohexane to cyclohexanol and cyclohexanone^a.

Entry	Cu catalyst	$n(\text{C}_6\text{H}_{12})/n(\text{Cat})$	Yield ^b of products, %			TON ^c
			Alcohol	Ketone	Total ^d	
1	2	320	1.6	3.4	5.0	16.0
2	2	200	2.2	5.1	7.3	14.6
3	2	100	6.0	10.2	16.2	16.2
4	2	50	7.8	18.8	26.6	13.3
5 ^e	2	320	3.5	1.7	5.2	16.6
6 ^e	2	200	3.8	3.8	7.6	15.2
7 ^e	2	100	7.7	8.6	16.3	16.3
8 ^e	2	50	9.8	16.8	26.6	13.3
9 ^f	$\text{Cu}(\text{NO}_3)_2$	25	1.6	3.8	5.4	1.4

^a Selected data; reaction conditions: C_6H_{12} (1 mmol), MeCN 4 mL, $n(\text{HNO}_3)/n(\text{Cat}) = 10$, H_2O_2 (10.0 mmol added as an aqueous 30% solution), 6 h reaction time, 298 K.

^b Moles of product/100 moles of C_6H_{12} (alcohol = cyclohexanol and ketone = cyclohexanone).

^c Overall TON values (moles of products/mole of catalyst).

^d Cyclohexanol + cyclohexanone.

^e GC analysis performed upon addition of PPh_3 (conversion of CyOOH into cyclohexanol prior to GC analyses).

^f For comparative purposes, $\text{Cu}(\text{NO}_3)_2$ was used as the catalyst (25 μmol), C_6H_{12} (0.63 mmol), MeCN 3 mL, other conditions as in footnote a.

vary appreciably with the $n(\text{C}_6\text{H}_{12})/n(\text{Cat})$ molar ratio (Table 3). However, the yields of both cyclohexanol and cyclohexanone are enhanced upon decreasing that ratio (*i.e.* increasing the catalyst amount), while the TON tends to a slight decrease (Table 3).

The ketone (cyclohexanone) always predominates over the alcohol (cyclohexanol) which, at the highest $n(\text{C}_6\text{H}_{12})/n(\text{Cat})$ molar ratio is not present in the final reaction medium in a significant amount (Table 3). The measured amount of cyclohexanol is then essentially derived upon decomposition of CyOOH in the GC or upon its reduction by PPh_3 (when adding this reagent to the final reaction solution) [53,54]. The catalyst is stable under the reaction conditions and soluble in the acetonitrile–diethyl ether mixture, and can be isolated in a crystalline form at the end of the process via evaporation of the organic phase. Thus, for run 4 (Table 2), *ca.* 51% of the catalyst was recovered and could be reused.

When the reaction was performed in the presence of a radical trap, a dramatic fall of the catalytic activity was observed

(Table 4). This occurred for either a C-centred radical scavenger (such as CBrCl_3 [66] or $(\text{CH}_2)_3(\text{CMe}_2)_2\text{NO}$ (TEMPO) [67]) or an O-centred radical trap (Ph_2NH [66]), indicating that the reaction proceeds mainly via radical paths involving both C- and O-centred radicals, as for other multi-copper systems [28,30,55,63,65]. Hence, H-abstraction from cyclohexane conceivably by the hydroxyl radical HO^\bullet (formed by metal-assisted decomposition of H_2O_2) leads to the cyclohexyl radical Cy^\bullet , and, although the detailed mechanistic pathway is still to be established, it can possibly proceed, as suggested in other cases, through reaction of Cy^\bullet with O_2 to give the organoperoxy CyOO^\bullet , or with a metal-hydroperoxy species to yield cyclohexyl hydroperoxide (CyOOH) [31,39,68–72]. The conversions of CyOO^\bullet and CyOOH into the products can also be metal-assisted, conceivably involving dismutation of CyOO^\bullet to both cyclohexanol (CyOH) and cyclohexanone with O_2 , or homolytic decomposition of CyOOH to CyOO^\bullet (upon O–H bond cleavage) and the alcoxyl CyO^\bullet (upon O–O bond rupture). CyOH could

Table 3
Estimated amounts of cyclohexanol, cyclohexanone and cyclohexyl hydroperoxide^a, formed upon peroxidative oxidation of cyclohexane^b.

Entry	$n(\text{C}_6\text{H}_{12})/n(\text{Cat})$	Yield ^b of products, %			Alcohol/ketone	TON
		Alcohol	Ketone	CyOOH		
1	320	0	1.6	3.5	0	16.3
2	200	0.7	3.6	2.9	0.2	14.4
3	100	4.3	8.6	3.3	0.5	16.2
4	50	5.8	16.8	4.1	0.35	13.4

^a Estimated (values before GC analysis) according to Shul'pin's method [53,54] based on the analytical values (Table 2) measured in the absence of PPh_3 and after addition of this phosphine to the final reaction solution, considering that (i) in the GC spectrometer CyOOH decomposes to $1/2$ cyclohexanol + $1/2$ cyclohexanone, and (ii) $\text{CyOOH} + \text{PPh}_3 \rightarrow \text{cyclohexanol} + \text{OPPh}_3$.

^b See footnotes a, b and d of Table 2.

Table 4Effects of radical traps on the peroxidative oxidation of cyclohexane to cyclohexanol and cyclohexanone^a.

Entry	$n(\text{rad. trap})/n(\text{C}_6\text{H}_{12})$	Radical trap ^b	Yield of products, %			TON ^c	Yield drop owing to radical trap ^d , %
			Alcohol	Ketone	Total ^e		
1	2.5	CBrCl ₃	0.4	0.8	1.2	1.2	93
2	2.5	TEMPO	3.2	1.8	5.0	5.0	69
3	2.5	Ph ₂ NH	1.9	6.0	7.9	7.9	51
4 ^f	0	No radical trap	6.0	10.2	16.2	16.2	–

^a Selected data; reaction conditions: C₆H₁₂ (1 mmol), catalyst precursor (10 μmol), MeCN 4 mL, HNO₃ (0.10 mmol), H₂O₂ (10 mmol, added as an aqueous 30% solution), 6 h reaction time, 25 °C.

^b Radical trap (2.5 mmol).

^c Overall TON (moles of products/mole of catalyst).

^d $[1 - (\text{total yield with radical trap}/\text{total yield without radical trap})] \times 100$.

^e Cyclohexanol + cyclohexanone.

^f Entry 3 of Table 2.

Table 5TEMPO-mediated aerobic oxidation of selected alcohols by air^a.

Entry	Cu compound	Substrate	Product	Time [h]	Yield ^b [%]
1	2	Benzyl alcohol	Benzaldehyde	6	45
2	Cu(NO ₃) ₂	Benzyl alcohol	Benzaldehyde	6	20
3	2	Benzyl alcohol	Benzaldehyde	22	99
4	2	Benzyl alcohol	Benzaldehyde	22	2 ^c
5	Cu(NO ₃) ₂ + H ₂ L (1:1)	Benzyl alcohol	Benzaldehyde	22	95
6	Cu(NO ₃) ₂ + H ₂ L (1:2)	Benzyl alcohol	Benzaldehyde	22	62
7	2	4-Methylbenzyl alcohol	4-Methylbenzaldehyde	22	91
8	2	Cinnamyl alcohol	Cinnamaldehyde	22	34
9	2	1-Phenylethanol	Acetophenone	22	5
10	2	1-Heptanol	1-Heptanal	22	<1

^a Conditions: 3 mmol of the substrate, 1 mol% of **2**, 5 mol% of TEMPO, 10 mL of 0.1 M K₂CO₃ aqueous solution, 1 atm of air, 323 K.

^b Yields based on GC analyses, selectivities in all cases >97%.

^c Reaction in the absence of TEMPO.

also be derived upon H-abstraction, by CyO•, from cyclohexane [36,53–55,73–77].

The combination of the TEMPO radical with copper complexes has been reported as an interesting and efficient catalytic system for the selective aerobic oxidation of alcohols [42–46,78–83], particularly in aqueous media [41,84–87]. In the current work we have tested the catalytic activity of **2** for the aerobic oxidation of alcohols in aqueous solutions mediated by TEMPO (Scheme 4b, Table 5). When benzyl alcohol (3 mmol) was allowed to react with air (1 atm) in the presence of **2** (1 mol%) and TEMPO (5 mol%) in 0.1 M K₂CO₃ aqueous solution, for 6 h at 323 K, benzaldehyde (45% yield) was obtained (Table 5, entry 1); the prolongation of the reaction time to 22 h gives 99% of benzaldehyde (entry 3). When the reaction was performed under the same experimental conditions, but with Cu(NO₃)₂ instead of **2**, only 20% yield of benzaldehyde was achieved (entry 2). Practically no oxidation of benzyl alcohol was observed in the absence of TEMPO (2%, entry 4).

As previously reported [86,87], copper catalysts for alcohol oxidation can be prepared *in situ*, by mixing the ligand and the metal salt in the reaction medium. This possibility was also examined, using the combination of copper nitrate and the free ligand (**1**) in 1:1 and 1:2 molar ratios (entries 5 and 6). These experiments revealed nearly the same activity for the Cu/H₂L 1:1 ratio (95% of benzaldehyde yield) as for the pre-synthesized complex (99%). **2** was also found to be an active catalyst for the oxidation of a substituted benzylic alcohol (4-methylbenzyl alcohol is oxidized to the corresponding aldehyde with 91% yield, entry 7). Oxidation of cinnamyl alcohol leads to cinnamaldehyde in a moderate yield (34%, entry 8), while secondary alcohols (such a 1-phenylethanol) were barely reactive, as well as simple aliphatic alcohols (such a 1-heptanol) (entries 9 and 10, respectively). This kind of chemoselectivity of the present system towards primary benzylic alcohols shares similarities to previously reported ones [41,46,79,80,86], and thus we can assume that the plausible mechanism for this

system is that of the galactose oxidase type, known for copper complexes with N,N- or N,O-ligands. This mechanism involves coordination of the alcohol, followed by copper-centred oxidative dehydrogenation of the alcohol, where the H-abstraction from the α-carbon atom by TEMPO is the rate-determining step of the reaction [79,80,82].

4. Final remarks

This work shows that a new azoderivative of pentane-2,4-dione, *i.e.* 3-(2-hydroxy-4-nitrophenylhydrazo)pentane-2,4-dione (H₂L), displays a good coordination ability towards complex formation with copper(II), acting as a suitable ligand to this metal ion to form a good copper catalyst precursor for oxidations of alkanes and alcohols, thus extending for the first time the application of ADB ligands to these fields of current interest.

Based on the NMR results it was established that the free ligand is stabilized in the hydrazo form which is also preserved, in the solid state, in the new binuclear complex [Cu₂(H₂O)₂(μ-L)₂] (**2**) with Cu(II) coordination number of 5, as shown by X-rays. It was established that the dissociation process of H₂L is unspontaneous, endothermic and entropically unfavorable, while the complexation of copper(II) with H₂L is spontaneous, exothermic and entropically favourable.

The newly synthesized hydroxy-hydrazo-dione (H₂L) behaves (in the basic L²⁻ form) as a convenient N,O,O-ligand to Cu(II) to form complex **2**, that acts as a good catalyst for oxidation processes, particularly for the peroxidative oxidation, under mild conditions, of cyclohexane to the corresponding alcohol, ketone and organohydroperoxide (total yield up to 27% in a single batch, the catalyst being recyclable), as well as for selective oxidation of benzyl alcohol to benzaldehyde (up to 99% yield of benzaldehyde with >99% selectivity).

Hence, this study opens up the possibility to use azoderivatives of β -diketones for the design of metal complex catalysts for mild oxidation reactions, namely of the difficult to oxidize alkane substrates, a still unexplored (but promising as shown by this work) area of research for such a type of ligands. The study is being extended in our laboratory to other azoderivatives of β -diketones and transition metal ions; other catalytic applications of this type of complexes are also being attempted.

Acknowledgements

This work has been partially supported by the Foundation for Science and Technology (FCT), Portugal, and its PPCDT (FEDER funded) and “Science 2007” programs. K.T.M., P.J.F. and Y.Yu.K. express gratitude to the FCT for their post-doc and doctoral fellowships. The authors gratefully acknowledge the Portuguese NMR Network (IST-UTL Center) for providing access to the NMR facility.

Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at doi:10.1016/j.molcata.2009.11.006.

References

- [1] K.T. Mahmudov, R.A. Aliyeva, S.R. Gadjieva, F.M. Chyragov, *J. Anal. Chem.* 63 (2008) 435.
- [2] V. Bertolasi, P. Gilli, V. Ferretti, G. Gilli, K. Vaughan, *New J. Chem.* 23 (1999) 1261.
- [3] P. Gilli, V. Bertolasi, L. Pretto, A. Lycka, G. Gilli, *J. Am. Chem. Soc.* 124 (2002) 13554.
- [4] V. Bertolasi, V. Ferretti, P. Gilli, G. Gilli, Y.M. Issa, O.E. Sherif, *J. Chem. Soc. Perkin Trans. 2* (1993) 2223.
- [5] S.R. Gadjieva, T.M. Mursalov, K.T. Mahmudov, F.H. Pashaev, F.M. Chyragov, *J. Anal. Chem.* 61 (2006) 550.
- [6] R.A. Aliyeva, F.H. Pashaev, A.G. Gasanov, K.T. Mahmudov, *Methods Objects Chem. Anal.* 2 (2008) 167.
- [7] J. Sokolnicki, J. Legendziewicz, W. Amirhanov, V. Ovchinnikov, L. Macalik, J. Hanuza, *Spec. Chim. Acta part A* 55 (1999) 349.
- [8] E. Natividad, M. Castro, R. Burriel, L.A. Angurel, *J. Therm. Anal. Cal.* 84 (2006) 307.
- [9] M.R. Ganjali, P. Norouzi, S. Shirvani-Arani, *J. Anal. Chem.* 62 (2007) 312.
- [10] Z. Chen, F. Huang, Y. Wu, D. Gu, F. Gan, *Inorg. Chem. Commun.* 9 (2006) 21.
- [11] Z. Chen, Y. Wu, D. Gu, F. Gan, *Dyes Pigments* 76 (2008) 624.
- [12] H.B. Hassib, Y.M. Issa, W.S. Mohamed, *J. Therm. Anal. Cal.* 92 (2008) 775.
- [13] M.J. Jeong, J.H. Park, C. Lee, J.Y. Chang, *Org. Lett.* 8 (2006) 2221.
- [14] S.R. Gadjieva, T.M. Mursalov, K.T. Mahmudov, F.M. Chyragov, *Rus. J. Coord. Chem.* 32 (2006) 304.
- [15] S.R. Gadjieva, F.H. Pashaev, F.M. Chyragov, A.G. Gasanov, K.T. Mahmudov, *Rus. J. Inorg. Chem.* 52 (2007) 640.
- [16] S.R. Gadjieva, K.T. Mahmudov, F.H. Pashaev, A.G. Gasanov, F.M. Chyragov, *Rus. J. Coord. Chem.* 34 (2008) 534.
- [17] J. Marten, W. Seichter, E. Weber, *Z. Anorg. Allg. Chem.* 631 (2005) 869.
- [18] J. Marten, W. Seichter, E. Weber, U. Bohme, *J. Phys. Org. Chem.* 20 (2007) 716.
- [19] R.A. Aliyeva, F.M. Chyragov, K.T. Mahmudov, *J. Anal. Chem.* 60 (2005) 137.
- [20] S.R. Gadjieva, F.M. Chyragov, K.T. Mahmudov, *J. Anal. Chem.* 62 (2007) 1028.
- [21] R.L. Lieberman, A.C. Rosenzweig, *Nature* 434 (2005) 177.
- [22] S.I. Chan, V.C.-C. Wang, J.C.-H. Lai, S.S.-F. Yu, P.P.-Y. Chen, K.H.-C. Chen, C.-L. Chen, M.K. Chan, *Angew. Chem. Int. Ed.* 46 (2007) 1992.
- [23] A.E. Shilov, G.B. Shul'pin, *Chem. Rev.* 97 (1997) 2879.
- [24] G.B. Shul'pin, Oxidations of C–H compounds catalyzed by metal complexes, in: F.M. Beller, F.C. Bolm (Eds.), *Transition Metals for Organic Synthesis*, vol. 2, 2nd ed., Wiley–VC, Weinheim/New York, 2004, pp. 215–242.
- [25] T. Punniyamurthy, L. Rout, *Coord. Chem. Rev.* 252 (2008) 134.
- [26] M.M. Dias-Requejo, P.J. Perez, *Chem. Rev.* 108 (2008) 3379.
- [27] C.J. Elsevier, J. Reedijk, P.H. Walton, M.D. Ward, *J. Chem. Soc. Dalton Trans.* (2003) 1869.
- [28] A.M. Kirillov, M.N. Kopylovich, M.V. Kirillova, M. Haukka, M.F.C. Guedes da Silva, A.J.L. Pombeiro, *Angew. Chem. Int. Ed.* 44 (2005) 4345.
- [29] D.S. Nesterov, V.N. Kokozay, V.V. Dyakonenko, O.V. Shishkin, J. Jezierska, A. Ozarowski, A.M. Kirillov, M.N. Kopylovich, A.J.L. Pombeiro, *Chem. Commun.* 44 (2006) 4605.
- [30] C. Di Nicola, Y.Yu. Karabach, A.M. Kirillov, M. Monari, L. Pandolfo, C. Pettinari, A.J.L. Pombeiro, *Inorg. Chem.* 46 (2007) 221.
- [31] M.V. Kirillova, A.M. Kirillov, M.F.C. Guedes da Silva, A.J.L. Pombeiro, *Eur. J. Inorg. Chem.* 22 (2008) 3423.
- [32] K.R. Gruenwald, A.M. Kirillov, M. Haukka, J. Sanchiz, A.J.L. Pombeiro, *J. Chem. Soc. Dalton Trans.* (2009) 2109.
- [33] Y.Yu. Karabach, A.M. Kirillov, M. Haukka, J. Sanchiz, M.N. Kopylovich, A.J.L. Pombeiro, *Cryst. Growth Des.* 8 (2008) 4100.
- [34] A.M. Kirillov, Y.Yu. Karabach, M. Haukka, M.F.C. Guedes da Silva, J. Sanchiz, M.N. Kopylovich, A.J.L. Pombeiro, *Inorg. Chem.* 47 (2008) 162.
- [35] M.V. Kirillova, A.M. Kirillov, M.L. Kuznetsov, J.A.L. Silva, J.J.R. Frausto da Silva, A.J.L. Pombeiro, *Chem. Commun.* 17 (2009) 2353.
- [36] M.V. Kirillova, A.M. Kirillov, P.M. Reis, J.A.L. Silva, J.J.R. Frausto da Silva, A.J.L. Pombeiro, *J. Catal.* 248 (2007) 130.
- [37] E.C.B. Alegria, M.V. Kirillova, L.M.D.R.S. Martins, A.J.L. Pombeiro, *Appl. Catal. A: Gen.* 317 (2007) 43.
- [38] T.F.S. Silva, E.C.B.A. Alegria, L.M.D.R.S. Martins, A.J.L. Pombeiro, *Adv. Synth. Catal.* 350 (2008) 706.
- [39] S. Contaldi, C. Di Nicola, F. Garau, Y.Yu. Karabach, L.M.D.R.S. Martins, M. Monari, L. Pandolfo, C. Pettinari, A.J.L. Pombeiro, *J. Chem. Soc. Dalton Trans.* 25 (2009) 4928.
- [40] Ullmann's Encyclopedia of Industrial Chemistry, 6th ed., Wiley–VCH, Weinheim, 2002.
- [41] P.J. Figiel, A.M. Kirillov, Y.Yu. Karabach, M.N. Kopylovich, A.J.L. Pombeiro, *J. Mol. Cat. A. Chem.* 305 (2009) 178.
- [42] T. Vogler, A. Studer, *Synth. Stuttgart* (2008) 1979–1993.
- [43] M.V.N. De Souza, *Mini-Rev. Org. Chem.* 3 (2006) 155.
- [44] R.A. Sheldon, *J. Mol. Catal. A: Chem.* 251 (2006) 200.
- [45] R.A. Sheldon, I.W.C.E. Arends, *Adv. Synth. Catal.* 346 (2004) 1051.
- [46] F. Minisci, F. Recupero, G.F. Pedulli, M. Lucarini, *J. Mol. Catal. A: Chem.* 204–205 (2003) 63.
- [47] R.G. Bates, *Determination of pH: Theory and Practice*, Wiley, New York, 1973.
- [48] F.R. Japp, F. Klingemann, *Liebigs Ann. Chem.* 247 (1888) 190.
- [49] Bruker, APEX2 & SAINT Bruker, AXS Inc., Madison, Wisconsin, USA, 2004.
- [50] G.M. Sheldrick, *Acta Crystallogr. Sect. A* 46 (1990) 467.
- [51] G.M. Sheldrick, *Acta Crystallogr. Sect. A* 64 (2008) 112.
- [52] L.J. Farrugia, *J. Appl. Crystallogr.* 32 (1999) 837.
- [53] G.B. Shul'pin, *J. Mol. Catal. A: Chem.* 189 (2002) 39.
- [54] G.B. Shul'pin, *Comptes Rendus Chimie* 6 (2003) 163.
- [55] A.M. Kirillov, M.N. Kopylovich, M.V. Kirillova, Y.Yu. Karabach, M. Haukka, M.F.C. Guedes da Silva, A.J.L. Pombeiro, *Adv. Synth. Catal.* 348 (2006) 159.
- [56] N.M. Dyatlova, V.Ya. Temkina, I.D. Kolpakova, *Complexones, Khimiya*, Moscow, 1970.
- [57] J. Bjerrum, *Metal Amine Formation in Aqueous Solution: Theory of the Reversible Step Reactions*, P. Haase & Son, Copenhagen, 1957.
- [58] A. Albert, E. Serjeant, *Ionization Constants*, Methuen, London, 1962.
- [59] P.W. Atkins, J. Paula, *Physical Chemistry*, 7th ed., Oxford University Press, 2002.
- [60] L.M. Batuner, E.M. Pozin, *Mathematical Methods in Chemical Technique*, Khim. Lit, Leningrad, 1963.
- [61] A.G. Grechin, H.-J. Buschmann, E. Schollmeyer, *J. Solution Chem.* 34 (2005) 1095.
- [62] T.A. Khudyakova, A.P. Kreshkov, *Theory and Practice of Conductometric Analysis*, Khimiya, Moscow, 1976.
- [63] C. Di Nicola, F. Garau, Y.Yu. Karabach, L.M.D.R.S. Martins, M. Monari, L. Pandolfo, C. Pettinari, A.J.L. Pombeiro, *Eur. J. Inorg. Chem.* 5 (2009) 666.
- [64] Y.Yu. Karabach, A.M. Kirillov, M.F.C. Guedes da Silva, M.N. Kopylovich, A.J.L. Pombeiro, *Cryst. Growth Des.* 6 (2006) 2200.
- [65] Y.Yu. Karabach, A.M. Kirillov, M. Haukka, M.N. Kopylovich, A.J.L. Pombeiro, *J. Inorg. Biochem.* 102 (2008) 1190.
- [66] L.M. Slaughter, J.P. Collman, T.A. Eberspacher, J.I. Brauman, *Inorg. Chem.* 43 (2004) 5198.
- [67] A.J.L. Beckwith, V.W. Bowry, K.U. Ingold, *J. Am. Chem. Soc.* 114 (1992) 4983.
- [68] A.M. Kirillov, M. Haukka, M.F.C. Guedes da Silva, A.J.L. Pombeiro, *Eur. J. Inorg. Chem.* 11 (2005) 2071.
- [69] G.B. Shul'pin, Y.N. Kozlov, G.V. Nizova, G. Suss-Fink, S. Stanislas, A. Kitaygorodskiy, V.S. Kulikova, *J. Chem. Soc. Perkin Trans. 2* (2001) 1351.
- [70] G.B. Shul'pin, *J. Mol. Catal. A: Chem.* 227 (2005) 247.
- [71] Y.N. Kozlov, V.B. Romakh, A. Kitaygorodskiy, P. Buglyo, G. Suss-Fink, G.B. Shul'pin, *J. Phys. Chem. A* 111 (2007) 7736.
- [72] M.L. Kuznetsov, A.J.L. Pombeiro, *Inorg. Chem.* 48 (2009) 307.
- [73] M. Costas, M.P. Mehn, M.P. Jensen, L. Que Jr., *J. Chem. Rev.* 104 (2004) 939.
- [74] M. Costas, K. Chen, L. Que Jr., *Coord. Chem. Rev.* 200–202 (2000) 517.
- [75] G.V. Nizova, B. Krebs, G. Suss-Fink, S. Schindler, L. Westerheide, L.G. Cuervo, G.B. Shul'pin, *Tetrahedron* 58 (2002) 9231.
- [76] G. Suss-Fink, L. Gonzalez, G.B. Shul'pin, *Appl. Catal. A: Gen.* 217 (2001) 111.
- [77] G.B. Shul'pin, H. Stoeckli-Evans, D. Mandelli, Y.N. Kozlov, A.T. Vallina, C.B. Voitiski, R.S. Jimenez, W.A. Carvalho, *J. Mol. Catal. A: Chem.* 219 (2004) 255.
- [78] S. Striegler, *Tetrahedron* 62 (2006) 9109.
- [79] P. Gamez, I.W.C.E. Arends, R.A. Sheldon, *J. Reedijk, Adv. Synth. Catal.* 346 (2004) 805.
- [80] P. Gamez, I.W.C.E. Arends, J. Reedijk, R.A. Sheldon, *Chem. Commun.* 19 (2003) 2414.
- [81] A. Dijkstra, I.W.C.E. Arends, R.A. Sheldon, *Org. Biomol. Chem.* 1 (2003) 3232.
- [82] J.S. Uber, Y. Vogels, D. van den Helder, I. Mutikainen, U. Turpeinen, W.T. Fu, O. Roubeau, P. Gamez, J. Reedijk, *Eur. J. Inorg. Chem.* 26 (2007) 4197.
- [83] L. Lin, J. Liuyan, W. Yunyang, *Catal. Commun.* 9 (2008) 1379.
- [84] R. Hu, M. Lei, H. Wei, Y. Wang, *Chin. J. Chem.* 27 (2009) 587.
- [85] M. Zhu, B. Li, P. He, X. Wei, Y. Yuan, *Tetrahedron* 64 (2008) 9239.
- [86] P.J. Figiel, M. Leskelä, T. Repo, *Adv. Synth. Catal.* 349 (2007) 1173.
- [87] H. Korpi, P.J. Figiel, E. Lankinen, P. Ryan, M. Leskelä, T. Repo, *Eur. J. Inorg. Chem.* 17 (2007) 2465.