



# Supported Catalysts

# Chiral Copper(II) Bis(oxazoline) Complexes Directly Coordinated to Amine-Functionalized Phenylene/Biphenylene Periodic Mesoporous Organosilicas as Heterogeneous Catalysts

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**Abstract:** Copper(II) complexes with commercial chiral bis(oxazoline)s were for the first time directly coordinated onto aminemodified mesoporous phenylene and biphenylene silicas. All final materials maintained the 2D ordered mesoporous structure. The copper metal coordinates directly to the amine groups within the walls of the materials. The materials were tested as asymmetric heterogeneous catalysts in the kinetic resolution of hydrobenzoin. They were active, selective, and enantioselective in this reaction. The material containing the (S)-(-)-2,2'-isopropylidene-bis(4-phenyl-2-oxazoline) (Me<sub>2</sub>PhBox) ligand, the best ligand in the homogeneous phase, presented the highest enantioselectivity of all the materials in the first cycle (73 %). The 2,2'-methylenebis[(4*S*)-4-phenyl-2-oxazoline] (PhBox) ligand rendered the catalyst more stable, independent of the anion or organic moiety in the periodic mesoporous organosilica material; this catalyst was reused over five cycles without any significant loss of catalytic activity or enantioselectivity. This type of ligand plays an important role in the stability of the corresponding copper(II) complex upon immobilization and in the robustness of the heterogeneous catalyst upon reuse.

## Introduction

Asymmetric catalysis is unique in the sense that a minute quantity of chiral catalyst is able to generate large amounts of enantiomerically pure compounds that are vital for many applications. There is a wide range of synthetic catalysts based on a diverse class of chiral organic ligands that can achieve excellent levels of enantioselectivity for many different types of reactions.<sup>[1]</sup> Bis(oxazoline)s are among this class of privileged ligands.<sup>[2,3]</sup> They are bidentate organic ligands with a N<sub>2</sub> coordination sphere and are able to coordinate several types of transition metals (Figure 1). The copper(II) complexes are the most used catalysts for several reactions such as the asymmetric cyclopropanation of alkenes, Diels–Alder cycloaddition, kinetic resolution of 1,2-diols, and so on.<sup>[3–5]</sup>

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Figure 1. Copper(II) complexes with bis(oxazoline) ligands; OTf = trifluoro-methylsulfonyl.

However, these catalysts work in the homogeneous phase and are difficult to separate at the end of a reaction, which hinders their recycling. This constitutes a major drawback in homogeneous asymmetric catalysis, especially given that most of the chiral ligands used are costly. A number of strategies to make this type of catalyst recyclable have been designed.<sup>[4,6]</sup> The most popular is immobilization of the homogeneous catalyst onto the surface of a porous material (e.g., zeolites, clays, ordered mesoporous silicas, carbon materials).<sup>[4,6]</sup> Different methodologies have been adopted as well, such as encapsulation, incipient wet impregnation, electrostatic interactions, and covalent attachment.<sup>[4,6–8]</sup> The use of simple and leaching-effective immobilization strategies is highly desirable to maintain the reusability and economical feasibility of the heterogeneous



catalyst. Because the majority of homogeneous catalysts are transition-metal complexes, they can potentially be directly coordinated onto the surface of a conveniently functionalized porous material.

Periodic mesoporous organosilicas (PMOs),<sup>[9-11]</sup> prepared for the first time in 1999, are interesting materials, because they possess high specific surface areas and pore volumes, a narrow pore-size distribution, and an alternating hydrophobic-hydrophilic character. Moreover, PMOs are interesting materials, as they may act as "channel ligands" by binding transition metals. In 2002, the preparation of PMOs with aromatic bridges with phenylene<sup>[12]</sup> (Ph) and biphenylene<sup>[13]</sup> (Bph) moieties was reported, and the synthesis of these materials was remarkable owing to the presence of crystal-like walls. Additionally, the aromaticity of these bridges allowed easy incorporation of amine functionalities into the framework of these PMOs to give rise to NH<sub>2</sub>PhPMO and NH<sub>2</sub>BphPMO through the use of simple electrophilic substitution organic reactions.<sup>[14,15]</sup> The coordination of copper complexes to the primer functional amine group in the framework of these materials is a step to be explored. Herein, we describe the direct coordination of copper(II) complexes with bis(oxazoline) ligands onto amine-modified phenyleneand biphenylene-bridged PMOs (i.e., NH<sub>2</sub>PhPMO and NH<sub>2</sub>BphPMO). The materials were tested as heterogeneous catalysts in the kinetic resolution of hydrobenzoin.

### **Results and Discussion**

#### Characterization

Figure 1 depicts the copper(II) complexes with bis(oxazoline) ligands immobilized in the periodic amino-functionalized mesoporous phenylene- and biphenylene-bridged PMOs, containing 1.82 and 2.61 mmol g<sup>-1</sup> of amine groups, respectively (Table 1),<sup>[14,15]</sup> to form CuMe<sub>2</sub>PhBox(OTf)<sub>2</sub>@NH<sub>2</sub>PhPMO, CuPhCl<sub>2</sub>@NH<sub>2</sub>PhPMO, and CuPhBox(OTf)<sub>2</sub>@NH<sub>2</sub>BphPMO. The materials were characterized by elemental analysis (C, N, and H) and copper inductively coupled plasma atomic emission spectroscopy (Cu ICP-AES); the results are compiled in Table 1. From the increase in the nitrogen content, it can be concluded that the copper(II) complexes (Figure 1) were introduced at the surface of the amino-modified mesoporous organosilicas. Given that each PhBox molecule possesses two nitrogen atoms, this increase in nitrogen content corresponds to 57, 368, and 94 µmol g<sup>-1</sup> of bis(oxazoline) ligand in CuMe<sub>2</sub>PhBox-(OTf)<sub>2</sub>@NH<sub>2</sub>PhPMO, CuPhCl<sub>2</sub>@NH<sub>2</sub>PhPMO, and CuPhBox-(OTf)<sub>2</sub>@NH<sub>2</sub>BphPMO, respectively. Analysis of these materials by

Table 1. Elemental analysis and copper ICP-AES results.

The X band electron paramagnetic resonance (EPR) spectra of the copper(II) complexes immobilized on the amine-modified organosilicas at 120 K are shown in Figure 2. The spectra are typical of magnetically diluted copper(II) species. The hyperfine structure from the coupling of the free electron with the  $Cu^{II}$  nucleus (I = 3/2) can be clearly seen in the case of the CuPhBox(OTf)<sub>2</sub>@NH<sub>2</sub>BphPMO material. The CuMe<sub>2</sub>PhBox-(OTf)2@NH2PhPMO and CuPhCl2@NH2PhPMO materials possess higher copper contents (Table 1) and broadening of the hyperfine structure is observed, which is not completely resolved in the latter case. Nevertheless, the results of the simulation of the spectra by using the WinEPR software are compiled in Table 2, together with parameters from the free copper(II) salts and complexes with related bis(oxazoline) ligands found in the literature.<sup>[1]</sup> The spectra are axial or almost axial with  $A_7$  higher than the corresponding free copper(II) salts, which is indicative of the presence of nitrogen in the coordination sphere. Furthermore, the  $A_7$  values are high in the case of the CuMe<sub>2</sub>PhBox-(OTf)<sub>2</sub>@NH<sub>2</sub>PhPMO and CuPhBox(OTf)<sub>2</sub>@NH<sub>2</sub>BphPMO materials and are typical of square-planar structures. The  $A_z$  value for the CuPhCl<sub>2</sub>@NH<sub>2</sub>PhPMO material is lower, which is indicative of tetrahedral distortions. Nevertheless, the value is higher than that for CuCl<sub>2</sub>, which indicates the presence of nitrogen in the

Sample	C	H	N	Cu	N	Box	Cu	Cu/Box
	[%]	[%]	[%]	[%]	[mmol g ']	[µmol g ']	[µmol g ']	
NH <sub>2</sub> phPMO	34.22	2.66	2.55		1.82			
CuMe <sub>2</sub> PhBox(OTf) <sub>2</sub> @NH <sub>2</sub> PhPMO	34.40	2.85	2.71	2.20	1.94	57	347	6.1
CuPhBoxCl <sub>2</sub> @NH <sub>2</sub> PhPMO	36.85	3.31	3.58	3.87	2.56	368	610	1.7
NH <sub>2</sub> BphPMO	48.39	3.40	3.66		2.61			
CuPhBox(OTf)2@NH2BphPMO	44.16	3.74	3.92	1.17	2.80	94	185	2.0
Cu(OTf) <sub>2</sub> @NH <sub>2</sub> BphPMO				0.92			145	





Table 2. EPR parameters obtained b	simulation for the copper(II) complexes coordinate	ed onto amine-modified mesoporous organosilicas at 120 K.

Sample	g <sub>x</sub>	g <sub>y</sub>	<i>g</i> <sub>z</sub>	A <sub>x</sub> <sup>[b]</sup>	A <sub>y</sub> <sup>[b]</sup>	$A_z^{[b]}$	Ref.
Cu(OTf) <sub>2</sub> <sup>[a]</sup>	2.083	2.083	2.412	4.4	4.4	134.6	[1]
CuCl <sub>2</sub> <sup>[a]</sup>	2.061	2.061	2.316	18.3	18.3	152.7	[1]
$CuMe_{2}PhBox(OTf)_{2}(H_{2}O)_{2}^{[a]}$	2.064	2.073	2.313	5.0	4.8	169.0	[1]
CuMe <sub>2</sub> PhBoxCl <sub>2</sub> <sup>[a]</sup>	2.057	2.057	2.280	11.0	11.0	132.0	[1]
CuMe <sub>2</sub> PhBox(OTf) <sub>2</sub> @NH <sub>2</sub> PhPMO	2.083	2.083	2.300	[c]	[c]	182	this work
CuPhBoxCl <sub>2</sub> @NH <sub>2</sub> PhPMO	2.090	2.090	2.316	[c]	[c]	162	this work
CuPhBox(OTf)2@NH2BphPMO	2.078	2.078	2.270	[c]	[c]	185	this work
Cu(OTf) <sub>2</sub> @NH <sub>2</sub> BphPMO	2.080	2.080	2.300	[c]	[c]	170	this work

[a] In frozen THF/CH<sub>2</sub>Cl<sub>2</sub> solution at 140 K. [b] Values  $\times 10^{-4}$  cm<sup>-1</sup>. [c] Not simulated owing to larger linewidths in the solid-state EPR spectra.

coordination sphere. It is also noteworthy that the  $A_z$  value for the CuMe<sub>2</sub>PhBox(OTf)<sub>2</sub>@NH<sub>2</sub>PhPMO material is higher than that for the free complex in THF/CH<sub>2</sub>Cl<sub>2</sub> solution (1:1). This may be due to a change in the geometry of the coordination sphere from distorted octahedral to square planar<sup>[1]</sup> and/or coordination to the nitrogen atom of the amine-modified mesoporous NH<sub>2</sub>PhPMO. The  $g_z$  values of the copper(II) complexes immobilized on the amine-modified mesoporous organosilicas are similar and lower than the value for the corresponding copper(II) salts, which is consistent with the incorporation of nitrogen into their coordination spheres.



Figure 2. X-band EPR spectra of the copper(II) complexes immobilized on the amine-modified organosilicas at 120 K.

The amine-modified materials are also able to coordinate copper(II) salts directly. As an example, the NH<sub>2</sub>BphPMO material was able to coordinate 145 µmol g<sup>-1</sup> of copper(II) triflate (Table 1) from a methanol solution containing 1.15 mmol of copper(II) salt per gram of material. The EPR spectrum of the resulting Cu(OTf)<sub>2</sub>@NH<sub>2</sub>BphPMO material is depicted in Figure S1 (Supporting Information) and the corresponding parameters are shown in Table 2. The spectrum is also typical of a copper(II) magnetically diluted species with lower  $g_z$  and higher  $A_z$  values than the free copper(II) triflate (Table 2). This is consistent with the incorporation of nitrogen into the copper(II) coordination sphere. Relative to that shown by the CuPhBox(OTf)<sub>2</sub>@NH<sub>2</sub>BphPMO material, Cu(OTf)<sub>2</sub>@NH<sub>2</sub>BphPMO

shows higher values of  $g_z$  and lower  $A_{zr}$  and this indicates that the former has more nitrogen incorporated in its coordination sphere.

The FTIR attenuated total reflectance (ATR) spectra of the parent amine-modified mesoporous organosilicas and the coordinated copper(II) complexes are depicted in Figure 3. The amine-modified NH<sub>2</sub>PhPMO and NH<sub>2</sub>BphPMO materials possess a typical N–H stretching vibration at  $\tilde{v} \approx 3380 \text{ cm}^{-1}$  and a N–H bending vibration at  $\tilde{v} = 1625$  and 1608 cm<sup>-1</sup>. The materials with the coordinated copper(II) complexes present spectra that are more complex with additional bands: C-H stretching vibrations at  $\tilde{v}$  = 2915 and 2853 cm<sup>-1</sup>, C=N stretching vibrations between  $\tilde{v}$  =1654 and 1660 cm<sup>-1</sup>, a shoulder for the parent material resulting from N-H bending vibration, and a S=O stretching vibration at  $\tilde{v} = 638 \text{ cm}^{-1}$  for materials in which copper(II) triflate was used. Thus, the presence of these additional bands from both the copper(II) salt and the bis(oxazoline) ligand further proves the presence of copper(II) complexes at the surface of the amine-modified mesoporous organosilicas.

Figure 4 presents the powder X-ray diffraction (PXRD) data of NH<sub>2</sub>PhPMO (Figure 4, a) and NH<sub>2</sub>BphPMO (Figure 4, b) before and after copper coordination to evaluate the structural order of the prepared materials. The PXRD patterns of NH<sub>2</sub>PhPMO and NH<sub>2</sub>BphPMO present characteristic low-angle diffraction peaks at d = 4.65 and 4.75 nm, respectively. Additionally, molecularscale periodicity along the wall is observed through the presence of medium-range reflections at d = 0.76 nm for  $NH_2PhPMO$  and d = 1.20 nm for  $NH_2BphPMO$ . Thus, both pristine materials possess meso- and molecular-scale periodicities. Upon coordination of copper to the amine functionalities of  $NH_2PhPMO$ , the 100 reflection is maintained at d = 4.65 nm, whereas the coordination of CuPhBox(OTf)<sub>2</sub> to NH<sub>2</sub>BphPMO leads to a slight increase from d = 4.75 to 4.80 nm. Both CuMe<sub>2</sub>PhBox(OTf)<sub>2</sub>@NH<sub>2</sub>PhPMO and CuPhboxCl<sub>2</sub>@NH<sub>2</sub>PhPMO presents peaks in the medium-scattering angle range at d =0.76 nm, whereas CuPhBox(OTf)<sub>2</sub>@NH<sub>2</sub>BphPMO processes peaks related to the molecular scale at d = 1.18 nm.

The mesoporosity of the prepared materials is also evidenced by nitrogen adsorption–desorption isotherms acquired at –196 °C (Figure S2) through the observation of type IV isotherms (IUPAC classification) characteristic of mesoporous materials. A reduction in the values of  $S_{BET}$ ,  $V_p$ , and  $d_p$  upon coordination of the copper ligand in the amine functionalities of NH<sub>2</sub>PhPMO and NH<sub>2</sub>BphPMO is observed (Figure S2 and





a)



Figure 3. (a) FTIR ATR spectra of the parent amine-modified mesoporous organosilicas and with the coordinated copper(II) complexes; (b) expansions of the 600-1000, 1250-1850, and 2500-4000 cm<sup>-1</sup> regions.



Figure 4. PXRD patterns of pristine and metal-functionalized NH<sub>2</sub>PhPMO and NH<sub>2</sub>BphPMO.

Table 3). The maxima in the pore-size distribution (PSD) curves (Figure S2 and Table 3) shift from 3.5 to 3.1 nm for NH<sub>2</sub>PhPMO and from 3.0 to 2.5 nm for NH<sub>2</sub>BphPMO upon coordination of CuPhBoxCl<sub>2</sub> and CuPhBox(OTf)<sub>2</sub> to the amine functionalities of the PMOs.

To corroborate the presence of copper in the materials and to assure the mesopore nature after Cu incorporation, transmission electron microscopy (TEM) observation and chemical analyses by energy-dispersive X-ray spectroscopy (EDS) were performed. Figure 5 (a) depicts the structure of CuMe<sub>2</sub>PhBox(OTf)<sub>2</sub>@NH<sub>2</sub>PhPMO along the [001] orientation, which presents the hexagonal pore array, and the corresponding fast-Fourier transform (FFT) in the inset, which was indexed by assuming a p6mm symmetry. A magnified TEM image perpendicular to the pores is also presented in the inset, which reveals the molecular-scale order. The corresponding EDS analysis is shown and confirms the Si, O, and C composition of the mesoporous material and, in addition, the presence of Cu anchored in the walls and uniformly distributed (inset in the EDS graphic). Figure 5 (b) exhibits a similar analysis acquired for CuPhBoxCl<sub>2</sub>@NH<sub>2</sub>PhPMO; first, a low-magnification image of the material is presented with the FFT (inset), which corresponds to the particle marked by a white dashed rectangle orientated along [001]. A micrograph perpendicular to the pores clearly reveals the good crystallinity of the sample with an interatomic distance of 0.77 nm, which corresponds to the molecular periodicity of the walls. The FFT, shown in the inset, presents two types of spots named "a" that can be attributed to the mesoscale and "b" at a larger distance to the central spot that corre-





#### Table 3. Physical properties of the prepared materials.

Sample	d <sub>100<sup>[a]</sup> [nm]</sub>	<i>а</i> <sup>[b]</sup> [nm]	S <sub>BET</sub> <sup>[c]</sup> [m <sup>2</sup> g <sup>-1</sup> ]	<i>V</i> <sub>P</sub> <sup>[d]</sup> [cm <sup>3</sup> g <sup>-1</sup> ]	d <sub>P</sub> <sup>[e]</sup> [nm]	b <sup>[f]</sup> [nm]
NH <sub>2</sub> PhPMO	4.65	5.36	631	0.84	3.5	1.82
CuMe <sub>2</sub> PhBox(OTf) <sub>2</sub> @NH <sub>2</sub> PhPMO	4.65	5.36	436	0.55	3.2	2.19
CuPhBoxCl <sub>2</sub> @NH <sub>2</sub> PhPMO	4.65	5.36	313	0.45	3.1	2.25
NH <sub>2</sub> BphPMO	4.75	5.48	533	0.54	3.0	2.46
CuPhBox(OTf) <sub>2</sub> @NH <sub>2</sub> BphPMO	4.80	5.54	522	0.44	2.5	3.00

[a] Spacing of the 100 reflection. [b] Unit cell parameter calculated as  $(2d_{100}/\sqrt{3})$ . [c] BET surface area. [d] Pore volume. [e] Pore width obtained from the BJH method with the corrected Kelvin equation, that is, KJS–BJH method at the maximum of pore-size distribution calculated on the basis of adsorption data. [f] Pore wall thickness calculated as  $(2d_{100}/\sqrt{3} - d_P)$ , in which the first term is the unit cell parameter.



Figure 5. TEM images of (a)  $CuMe_2PhBox(OTf)_2@NH_2PhPMO$ , (b)  $CuPhBoxCl_2@NH_2PhPMO$ , and (c)  $CuPhBox(OTf)_2@NH_2BphPMO$ . The EDS and inset figures show the presence of Cu and the uniform distribution along the particles.

sponds to the molecular scale. The chemical analysis also corroborates the presence of Cu incorporated in the material and the homogeneous distribution.

Scanning transmission electron microscopy (STEM) coupled with a high angle annular dark field detector (HAADF) was employed to characterize CuPhBox(OTf)<sub>2</sub>@NH<sub>2</sub>BphPMO (Figure 5,





c). Although clear order is not observed in this sample, both a mesostructure and a molecular structure can be identified. In this case, the interatomic distances are 1.17 nm. EDS analysis corroborates the presence of copper in the material.

The solid-state <sup>13</sup>C cross polarization magic angle spinning (CP MAS) NMR spectra of the NH<sub>2</sub>PhPMO and NH<sub>2</sub>BphPMO materials before and after copper coordination are shown in Figure S3. NH<sub>2</sub>PhPMO shows resonances at  $\delta$ = 120.6, 123.5, 133.5, and 150.3 ppm assigned to the  $sp^2$  carbon atoms of the aminefunctionalized phenylene bridge of the PMO. Note that the resonance at  $\delta$ = 150.3 ppm corresponds to the carbon atom of the phenylene group linked to the amine functionality.<sup>[14,17]</sup> Coordination of the copper ligands to the amine group of NH<sub>2</sub>PhPMO leads to enormous differences in the <sup>13</sup>C NMR spectra. As Cu<sup>II</sup> has a paramagnetic nucleus, the carbon nuclei close to it are not visible in the <sup>13</sup>C CP MAS NMR spectra. In this way, the carbon signals related to both the bis(oxazoline) ligands and the amine-functionalized phenylene group are absent. The <sup>13</sup>C CP MAS NMR spectra of CuMe<sub>2</sub>PhBox(OTf)<sub>2</sub>@NH<sub>2</sub>PhPMO and CuPhBoxCl<sub>2</sub>@NH<sub>2</sub>PhPMO only display a small amount of noncoordinated carbon atoms. For example, the signal at  $\delta =$ 150.2 ppm almost disappears in both materials, which corroborates the coordination of the copper ligands to the amine phenylene bridge of the PMO material. The intense resonance at  $\delta = 133.5$  ppm also corresponds to the sp<sup>2</sup> carbon atoms of the phenylene moieties from the 1,4-bis(triethoxylsilyl)benzene precursor that are not aminated during the amination process.<sup>[14,17]</sup> Other small resonances in the spectrum between  $\delta$ = 10 and 75 ppm may correspond to residual carbon atoms of the alkyl chain of the surfactant. The <sup>13</sup>C CP MAS NMR spectrum of NH<sub>2</sub>BphPMO presents five resonances at  $\delta$ = 126.1, 130.4, 135.2, 140.0, and 147.7 ppm that are assigned to biphenylene moleties functionalized with amine groups. The signal at  $\delta =$ 147.7 ppm is assigned to the sp<sup>2</sup> carbon atom directly linked to the NH<sub>2</sub> group.<sup>[15]</sup> Once more, this signal disappears upon coordination of CuPhBox(OTf)<sub>2</sub> to the amine group of NH<sub>2</sub>BphPMO, as expected. The presence of resonances at  $\delta$ = 130.0, 130.2, 135.2, and 140.5 ppm are assigned to the biphenylene moieties that are not aminated during the amination reaction.

Figure S4 shows the <sup>29</sup>Si MAS and CP MAS NMR spectra of NH<sub>2</sub>PhPMO and CuMe<sub>2</sub>PhBox(OTf)<sub>2</sub>@NH<sub>2</sub>PhPMO. The parent NH<sub>2</sub>PhPMO exhibits signals at ca.  $\delta$ = –59, –71, and –80 ppm assigned to T<sup>1</sup>, T<sup>2</sup>, and T<sup>3</sup> [T<sup>m</sup> = RSi(OSi)<sup>m</sup>(OH)<sup>3-m</sup>] organosiliceous species, respectively, as described in the literature.<sup>[14,17]</sup> Coordination of CuMe<sub>2</sub>PhBox(OTf)<sub>2</sub> to the NH<sub>2</sub>PhPMO material leads to differences in the <sup>29</sup>Si MAS and CP MAS NMR spectra. The T<sup>1</sup> signal almost disappears and the intensity of the T<sup>2</sup> resonance suffers a decrease with respect to the intensity of the T<sup>3</sup> sites. As mentioned before, Cu<sup>II</sup> is a paramagnetic nucleus and its presence may affect the signals of the diamagnetic nuclei just by being in the immediate vicinity. In this way, the intensities of all the signals in the spectra are reduced, as only the silicon atoms away from the Cu<sup>II</sup> center give rise to a signal. This is supported by a higher level of noise specific to the CP/ MAS spectra after functionalization of the amine groups of the materials. Moreover, it is possible to enhance the condensation

of free silanols during the functionalization reactions, which reduces the intensities of the  $T^1$  and  $T^2$  signals.

Thermogravimetric analysis (TGA) of NH<sub>2</sub>PhPMO and NH<sub>2</sub>BphPMO before and after copper coordination (Figure S5) revealed a first weight loss below 100 °C owing to desorption of physisorbed water. The NH<sub>2</sub>PhPMO material has thermal stability up to 360 °C. Above this value, decomposition of the amine groups takes place, and above 500 °C, decomposition of the phenylene organic mojeties occurs. The thermal stability decreases upon introduction of the CuMe<sub>2</sub>PhBox(OTf)<sub>2</sub> and CuPhBoxCl<sub>2</sub> copper ligands to NH<sub>2</sub>PhPMO. For both materials, CuMe<sub>2</sub>PhBox(OTf)<sub>2</sub>@NH<sub>2</sub>PhPMO and CuPhBoxCl<sub>2</sub>@NH<sub>2</sub>PhPMO, decomposition of the bis(oxazoline) ligands starts at 135 °C, which is followed by degradation of the triflate anion, in the case of CuMe<sub>2</sub>PhBox(OTf)<sub>2</sub>@NH<sub>2</sub>PhPMO. Finally, the decomposition of the NH<sub>2</sub>PhPMO material starts above 300 °C for CuMe<sub>2</sub>PhBox(OTf)<sub>2</sub>@NH<sub>2</sub>PhPMO and above 400 °C for CuPh-BoxCl<sub>2</sub>@NH<sub>2</sub>PhPMO. TGA of NH<sub>2</sub>BphPMO revealed a weight loss above 225 °C, which corresponds to cleavage of the amine bond. Decomposition of this PMO materials starts above 450 °C. Coordination of CuPhBox(OTf)<sub>2</sub> to NH<sub>2</sub>BphPMO leads to a weight loss up to 200 °C, which corresponds to decomposition of the bis(oxazoline) ligands followed by degradation of the triflate anion and decomposition of the PMO material above 300 °C. Note that this temperature degradation is inferior to that achieved for the Cu(OTf)2@NH2BphPMO material (above 350 °C), and this is due to the presence of the organic bis(oxazoline) ligand.

#### **Catalytic Experiments**

The amine-modified mesoporous organosilicas with the coordinated copper(II) complexes were tested as heterogeneous catalysts in the kinetic resolution of hydrobenzoin. The results of the catalytic experiments and the recycling experiments of the catalysts are compiled in Table 4. Taking into consideration that in kinetic resolution the maximum product yield that can be obtained is 50 %, it can be seen that all the materials are active, selective, and enantioselective in the monobenzoylation of hydrobenzoin (Figure 6). The material containing the Me<sub>2</sub>PhBox ligand, the best ligand in the homogeneous phase (Table 4), presented the highest enantioselectivity of all the materials in the first cycle (73 %). However, upon reuse, the enantioselectivity dropped drastically, which indicates that there was consecutive leaching of the ligand into the solution. This material contains the lowest amount of ligand, and thus the constant for the formation of the complex between copper(II) and the bis(oxazoline) ligand must play an important role in the stability of the complex,[16] especially if coordinated to the amine groups of the material. On the other hand, the materials containing the PhBox ligand presented lower enantioselectivities, but the catalysts were robust upon recycling over five cycles. This indicates that the CuPhBox complex with either chloride or triflate counteranions is more stable even if further coordinated to amine groups. The material containing the highest amount of ligand and copper, that is, CuPhBoxCl<sub>2</sub>@NH<sub>2</sub>PhPMO, is more active and enantioselective than CuPhBox-





Table 4. Kinetic resolution of hydrobenzoin by the copper(II) complexes with bis(oxazoline) ligands coordinated to the amine-modified mesoporous organosilicas.<sup>[a]</sup>

Sample	Time [h]	Run	Cu <sup>[b]</sup> [mol-%]	Ligand <sup>[b]</sup> [mol-%]	Yield <sup>[c]</sup> [%]	<i>ee</i> <sup>[d]</sup> [%]	S <sup>[e]</sup>	TON <sup>[f]</sup>
CuCl <sub>2</sub> •2H <sub>2</sub> O	2	1	5.5		38	0.1	1	7
without catalyst	24				21	0		
$CuCl_2 + (S,S)$ -PhBox	2	1	5.4	4.8	42	79	15	8
$[Cu(OTf)_2] + (S,S)-PhBox$	24		1.0	1.0	46	85	27	46
$[Cu(OTf)_2] + (S,S)-Me_2PhBox$	24		1.0	1.0	47	99	581	47
CuPhBoxCl <sub>2</sub> @NH <sub>2</sub> PhPMO	24	1	5.2	2.1	42	57	5	8
CuPhBoxCl <sub>2</sub> @NH <sub>2</sub> PhPMO	24	2	4.6	1.8	40	57	5	9
CuPhBoxCl <sub>2</sub> @NH <sub>2</sub> PhPMO	24	3	4.4	1.7	43	53	5	10
CuPhBoxCl <sub>2</sub> @NH <sub>2</sub> PhPMO	24	4	3.9	1.5	41	44	3	11
CuPhBoxCl <sub>2</sub> @NH <sub>2</sub> PhPMO	24	5	3.5	1.4	39	47	4	11
CuMe <sub>2</sub> PhBox(OTf) <sub>2</sub> @NH <sub>2</sub> PhPMO		1	2.9	0.5	42	73	11	15
CuMe <sub>2</sub> PhBox(OTf) <sub>2</sub> @NH <sub>2</sub> PhPMO		2	2.8	0.5	40	12	1	15
CuMe <sub>2</sub> PhBox(OTf) <sub>2</sub> @NH <sub>2</sub> PhPMO		3	2.6	0.4	35	2	1	14
CuPhBox(OTf)2@NH2BphPMO	24	1	1.5	0.8	32	43	3.0	21
CuPhBox(OTf)2@NH2BphPMO	24	2	1.5	0.7	30	47	3.4	20
CuPhBox(OTf)2@NH2BphPMO	24	3	1.4	0.7	31	43	3.0	22
CuPhBox(OTf)2@NH2BphPMO	24	4	1.3	0.7	29	42	2.9	22
CuPhBox(OTf) <sub>2</sub> @NH <sub>2</sub> BphPMO	24	5	1.3	0.7	27	44	3.0	21

[a] Reactions were performed for 24 h at 0 °C by using (*R*,*R*)-hydrobenzoin (0.48 mmol), (*S*,*S*)-hydrobenzoin (0.48 mmol), DIPEA (1.00 mmol), Cu (1.0 mol-%), and benzoyl chloride (0.50 mmol) in of CH<sub>2</sub>Cl<sub>2</sub> (5.0 mL). [b] Percentage of copper and ligand in the catalyst in relation to hydrobenzoin (see Table 1); for the recycling experiments, corrected for the weight of heterogeneous catalyst loss. [c] Yield of the isolated monobenzoylated product (Figure 6). [d] Enantiomeric excess of the monobenzoylated product, determined by HPLC. [e] Selectivity (*S*) = ln[1 – yield (1 + *ee*)]/ln[1 – yield (1 – *ee*)]. [f] Turnover number (TON) = mol of isolated monobenzoylated product/mol of Cu.

(OTf)<sub>2</sub>@NH<sub>2</sub>BphPMO. However, after the third cycle, the enantioselectivity of the former catalyst dropped, whereas the latter one remained the same. Relative to the enantioselectivities obtained for the homogeneous phase reaction with the free complexes, the enantioselectivities obtained for the heterogeneous phase were always lower. As the amine-modified mesoporous organosilicas with the coordinated copper(II) complexes possess higher amounts of copper than the bis(oxazoline) ligand, the decrease in the enantioselectivity can be partially explained by racemization through non-enantioselective monobenzoylation by the copper(II) centers not coordinated to the bis(oxazoline) ligand. Nevertheless, in comparison to control experiments run with the copper(II) salt and without catalyst, the reactions present enantioselectivity supporting the presence of bis(oxazoline) ligands in the coordination sphere of the coordinated copper(II) complexes.



Figure 6. Kinetic resolution of hydrobenzoin; DIPEA = N,N-diisopropylethylamine.

With the use of a more complex immobilization strategy by functionalization of the PhBox bis(oxazoline) bridge and by grafting onto the surface ordered mesoporous silicas and their carbon replicas, more enantioselective heterogeneous catalysts could be obtained in the kinetic resolution of hydrobenzoin.<sup>[18]</sup> The amount of copper(II) coordinated to the material was considerably lower than the amount of bis(oxazoline), which must be essential to attain high enantioselectivities.

# Conclusions

Three copper(II) complexes with commercial bis(oxazoline) ligands were immobilized onto amine-modified mesoporous organosilicas for the first time by direct coordination onto the amino groups. Partial decoordination of the bis(oxazoline) ligands occurred upon immobilization onto the periodic mesoporous organosilica surface amino groups, which resulted in lower amounts of ligand than copper on the materials. The materials were active, selective, and enantioselective heterogeneous catalysts for the kinetic resolution of hydrobenzoin. In two cases, the materials were reused over five cycles without any significant loss of catalytic activity or enantioselectivity. The enantioselectivities were, however, lower than those in the homogeneous phase owing to partial racemization of the product by non-enantioselective pathways. The bis(oxazoline) ligand and the corresponding constant of formation for the copper(II) complex seem to play important roles in the immobilization yields of the copper(II) bis(oxazoline) complexes (Figure 1) and in the robustness of the heterogeneous catalysts upon reuse. Steric constrains related to the size of the ligands (Me<sub>2</sub>PhBox larger than PhBox) and the curvature typical for mesoporous materials cannot be ruled out.

#### **Experimental Section**

**Materials:** Copper(II) trifluoromethanesulfonate {copper(II) triflate,  $[Cu(OTf)_2]$ , 98 %}, 2,2'-methylenebis[(45)-4-phenyl-2-oxazoline] (PhBox, 97 %), (S)-(-)-2,2'-isopropylidene-bis(4-phenyl-2-oxazoline) (Me<sub>2</sub>PhBox, 97 %), dry tetrahydrofuran (THF,  $\geq$ 99.9 %), (*R*,*R*)-1,2-diphenyl-1,2-ethanediol (99 %), (*S*,*S*)-1,2-diphenyl-1,2-ethanediol (99 %), *N*,*N*'-diisopropylethylamine (DIPEA,  $\geq$ 99 %), and potassium bromide (FTIR grade,  $\geq$ 99 %) were purchased from Aldrich and were





used as received. Ethanol (p.a.) and methanol (p.a.) were from Riedel-de Haën. Dichloromethane was purchased from Romil and was HPLC grade.

#### Immobilization of the Copper(II) Complexes onto the Amine-Modified Mesoporous Organosilicas

**CuMe<sub>2</sub>PhBox(OTf)<sub>2</sub>@NH<sub>2</sub>PhPMO:** A methanol solution (40 mL) containing Me<sub>2</sub>PhBox (0.162 mmol) and copper(II) trifluoromethanesulfonate (0.143 mmol) was stirred for 2 h (Figure 1). Then, NH<sub>2</sub>PhPMO (0.1730 g, synthetized according to the literature<sup>[14]</sup>), previously dried at 120 °C, was added, and the mixture was heated at reflux for 48 h. The material was filtered, washed, and heated at reflux for 3 h in fresh methanol (40 mL) to remove physisorbed copper(II) complexes. Finally, the material was filtered and dried at 120 °C for 6 h. The material acquired a green color.

**CuPhBoxCl<sub>2</sub>@NH<sub>2</sub>PhPMO:** A methanol solution (40 mL) containing PhBox (0.210 mmol) and copper(II) chloride (0.215 mmol) was stirred for 18 h (Figure 1). Then, NH<sub>2</sub>PhPMO (0.2322 g, prepared according to the literature<sup>[14]</sup>), previously dried at 120 °C, was added, and the mixture was heated at reflux for 72 h. The material was filtered, washed, and heated at reflux in fresh methanol (40 mL) for 3 h to remove physisorbed copper(II) complexes. Finally, the material was filtered and dried at 120 °C for 6 h. The material acquired a green color.

**CuPhBox(OTf)**<sub>2</sub>@**NH**<sub>2</sub>**BphPMO:** A methanol solution (40 mL) containing PhBox (0.203 mmol) and copper(II) trifluoromethanesulfonate (0.209 mmol) was stirred for 5 h (Figure 1). Then, NH<sub>2</sub>BphPMO (0.1730 g, prepared according to the literature<sup>[15]</sup>) was added, and the mixture was heated at reflux for 48 h. The material was filtered, washed, and heated at reflux in fresh methanol (40 mL) for 6 h to remove physisorbed copper(II) complexes. Finally, the material was filtered and dried at 120 °C for 6 h. The material acquired a green color.

Physicochemical Characterization: Elemental analysis (C, H, and N) was done by using a TruSpec 630-200-200 CNHS Analyzer at University of Aveiro. ICP-AES analysis was performed at the University of Vigo (Spain), and EPR analysis at 120 K was performed at University of Santiago de Compostela (Spain). FTIR spectroscopy was performed with a FTIR Bruker Tensor 27 instrument with a Golden Gate ATR (Attenuated Total Reflectance). PMO powders were dehydrated at 110 °C overnight before FTIR analysis. Powder X-ray diffraction (PXRD) data were recorder with a Rigaku Geigerflex D Max-C Series diffractometer by using Cu- $K_{\alpha}$  radiation. Samples were step scanned in 0.02°  $2\theta$  steps with a counting time of 20 s per step. Nitrogen adsorption-desorption isotherms were collected at -196 °C by using a Gemini V 2.00 instrument model 2380. The PMO materials were dehydrated overnight at 120 °C to an ultimate pressure of 1024 mbar and then cooled to room temperature preceding the adsorption. <sup>13</sup>C NMR, <sup>29</sup>Si NMR, and <sup>15</sup>N NMR spectra were acquired by using a double resonance MAS probe on a Bruker Avance III 400 spectrometer operating at 9.4 T. <sup>13</sup>C CP MAS NMR spectra were acquired by employing a 4 µs <sup>1</sup>H 90° pulse; a contact time of 3 ms; a spinning rate of 8, 9, 10, or 12 kHz; and a recycle delay (RD) of 5 s. <sup>29</sup>Si MAS NMR spectra were gathered by using 40° flip angle pulses, a spinning rate of 5.0 kHz, and a RD of 60 s. <sup>29</sup>Si CP MAS NMR spectra were performed with 4 µs <sup>1</sup>H 90° pulses, a CT of 8 ms, a spinning rate of 5 kHz, and a RD of 5 s. Tetramethylsilane was used as reference for the chemical shifts in the <sup>13</sup>C NMR and <sup>29</sup>Si NMR spectra. Thermogravimetric analysis (TGA) was performed with a Shimadzu TGA-50 instrument with a program rate of 5 °C min<sup>-1</sup> in air. For electron microscopy observations, the samples were crushed by using a mortar and pestle and were dispersed in

ethanol. A few drops of the suspension were then placed onto holey carbon nickel microgrids. Transmission electron microscopy (TEM) was performed with a Tecnai F30 operated at 300 kV. The microscope, which allowed a spatial resolution of 0.19 nm, was equipped with an EDS (EDAX) detector for chemical analysis, a Gatan bottom-entry CCD 2K  $\times$  2K camera, STEM module, and a Gatan Tridiem energy filter for spectroscopic measurements.

Catalysis Experiments: All the catalytic reactions of the prepared materials were performed in batch reactors at atmospheric pressure and with constant stirring. Kinetic resolution of 1,2-diphenylethane-1,2-diol (Figure 6) was performed at 0 °C by using (R,R)-1,2-diphenylethane-1,2-diol (0.48 mmol), (S,S)-1,2-diphenylethane-1,2-diol (0.48 mmol), DIPEA (170 µL, 1.00 mmol), heterogeneous catalyst (1.0 mol-% Cu), and benzoyl chloride (58 µL, 0.50 mmol) in CH<sub>2</sub>Cl<sub>2</sub> (5.00 mL).<sup>[5,18]</sup> The mixture was stirred for 24 h, and after filtration of the heterogeneous catalyst, the solvent was evaporated from the filtrate and the monobenzoylated product (Figure 6) was isolated by column chromatography (silica gel, *n*-hexane/ethyl acetate, 3:1). The yields were calculated on the basis of the 1,2-diol.<sup>[5,18]</sup> The enantiomeric excess of the monobenzoylated product was determined by HPLC at  $\lambda$ = 254 nm by using a Chiralcel OD column (250 mm  $\times$  4.6 ID, 5  $\mu$ m) and *n*-hexane/2-propanol (9:1) as the eluent. The retention times of the enantiomers of the (R)-monobenzoylated and (S)-monobenzoylated products were identified by comparison with those of a racemic monobenzoylated product.<sup>[5,18]</sup> The reaction selectivity (S) was calculated on the basis of the yield of the isolated monobenzoylated product and the respective enantiomeric excess by using the formula:  $\ln[1 - yield (1 + ee)]/\ln[1 - yield (1 + ee)]$ yield (1 - ee)]. The isolated materials at the end of the reactions were washed extensively with the appropriate solvent, dried under vacuum, and reused in another cycle under the same experimental conditions. Control experiments were also performed by using the same experimental procedure in the homogeneous phase with equimolar quantities of [Cu(OTf)<sub>2</sub>] and either PhBox or Me<sub>2</sub>PhBox to compare with the heterogeneous ones.

**Supporting Information** (see footnote on the first page of this article): HPLC chromatograms of racemic and enantioenriched 2-hydroxy-1,2-diphenylethyl benzoate, <sup>29</sup>Si MAS and <sup>29</sup>Si CP MAS NMR spectra, nitrogen adsorption-desorption isotherms collected at –196 °C, STEM-HAADF images with EDS analysis, XRD, and thermo-gravimetry.

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