

Bis(oxazoline)–Copper Complexes, Supported by Electrostatic Interactions, as Heterogeneous Catalysts for Enantioselective Cyclopropanation Reactions: Influence of the Anionic Support

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Several bis(oxazoline)–copper complexes have been supported by cation exchange in nafion and nafion–silica nanocomposite. The catalytic performance of these solids and that of the materials prepared with laponite clay have been compared in the benchmark cyclopropanation reaction of styrene with ethyl diazoacetate at room temperature in 1,2-dichloroethane. The results depend on the nature of both the chiral auxiliary and the support. Nafion-type supports are better than laponite for the complex between Cu(II) and 2,2'-isopropylidene-[(4*R*)-4-phenyl-2-oxazoline] because of their weaker electrostatic interaction with the complex, and the nafion–silica nanocomposite is the best support due to its high surface area. In this case the enantioselectivities (58% ee in the *trans*-cyclopropanes and 47% ee in the *cis*-cyclopropanes) are similar to those obtained in the homogeneous phase and the catalyst is recoverable and retains almost the same catalytic performance. However, this is not the case for the other two Cu–bis(oxazoline) complexes. For example, the complex between Cu(II) and 2,2'-isopropylidene-[(4*S*)-4-*tert*-butyl-2-oxazoline] leads to good results (69% ee in the *trans*-cyclopropanes and 64% ee in the *cis*-cyclopropanes) when supported on laponite, but it is the worst catalyst when exchanged in sulfonic supports, in spite of being the best catalyst in the homogeneous phase. This effect might only be explained by an interaction between a support and ligand which must have a steric nature. © 1999 Academic Press

INTRODUCTION

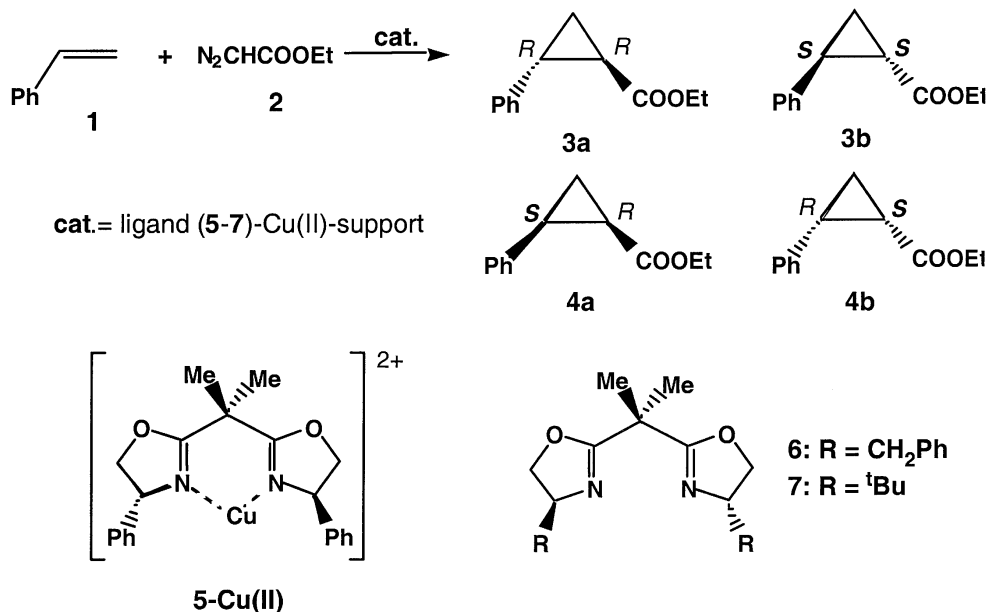
Enantioselective synthesis promoted by chiral catalysts is a topic of known importance in chemical research (1). Within the field of enantioselective catalysis, the development of heterogeneous catalysts able to promote enantioselective organic reactions is an area of growing interest due to the inherent advantages of heterogeneous-to-homogeneous catalysts (2).

One of the strategies most frequently used to prepare chiral heterogeneous catalysts is the immobilization of chiral metal complexes. However, the attachment of a homogeneous catalyst onto a support often leads to changes in its catalytic properties.

Heterogenization through a covalently bound ligand, which is attached to the support by a bifunctional linker, is the most important strategy for the heterogenization of metal complexes. The linking of the chiral auxiliary to the support modifies the conformational preferences of the reactant–catalyst intermediates, and unfortunately, this modification often leads to a reduction in the asymmetric induction.

Immobilization without covalent bonds frequently avoids the chemical modification of the chiral auxiliary, which may reduce the conformational differences between the homogeneous and the heterogeneous system. There are several strategies for the immobilization of homogeneous catalysts without a covalent bond. The complex can be encapsulated within the pores of a zeolite (3) or embedded into a mesoporous silicate (4). The chiral complex can also be immobilized by occlusion in a polydimethylsiloxane membrane (5). Another strategy involves the use of a thin layer of a suitable solvent containing the homogeneous catalyst, supported onto a solid with high surface area (6). It is also possible to immobilize a cationic or anionic complex by ion pairing with an anionic or cationic solid. Thus, clays with cation-exchange capacity (7) and anionic resins (8) have been used to support chiral cationic complexes.

Let us consider electrostatic attachment between the chiral complex and the support. It must be expected that the nature of the support will influence the results of the reaction. However, comparisons between different supports are not frequently carried out. We therefore considered it to be of interest to compare two different sulfonic solids, nafion (an organic polymer) and nafion–silica (an organic–inorganic nanocomposite), as supports for cationic copper–bis(oxazoline) complexes, with laponite (a lamellar clay). We have already shown that copper–bis(oxazoline) complexes can be immobilized onto clays (9). The choice of the chiral complexes was based on the versatile character of bis(oxazolines) as chiral auxiliaries in enantioselective catalysis, given that their complexes with several cations



SCHEME 1

promote different enantioselective organic reactions (10), cyclopropanation being one of the most interesting from a synthetic point of view (11). The different supported catalysts were tested in the benchmark cyclopropanation reaction of styrene with ethyl diazoacetate (Scheme 1).

EXPERIMENTAL

2,2'-Isopropylidenebis[(4*R*)-4-phenyl-2-oxazoline] (**5**) and 2,2'-isopropylidenebis[(4*S*)-4-benzyl-2-oxazoline] (**6**) were obtained from (*R*)-phenylglycinol and (*S*)-phenylalaninol following a previously described method (12). 2,2'-Isopropylidenebis[(4*S*)-4-*tert*-butyl-2-oxazoline] (**7**) was purchased from Aldrich. Laponite was obtained from Laporte Adsorbents and nafion from Fluka. The solvents were purchased from Scharlau and purified and dried by standard procedures.

Preparation of the Nafion-Silica Nanocomposite

The high surface area nafion-silica nanocomposite was prepared using a slight modification of a previously described method (13). A brief description is as follows. In a typical procedure, 200 g of a 10 wt% silica-containing solution, made by diluting a sodium silicate solution, was added to 100 g of a 3 wt% nafion-containing solution. The two solutions were mixed for 5–10 min; 3.5 M HCl, approximately 52 g, was then added rapidly to adjust the pH to 7. By using this approach, the system gels in about 10–15 s. The gel was dried at 90°C overnight and re-acidified by repeated washing with 25% HNO₃.

The typical surface area, pore volume, and pore diameter are 180 m² g⁻¹, 1.05 cm³ g⁻¹, and 140 Å, respectively. The

particle size is typically 1–3 nm. The loading of the nafion resin within the silica, determined by both TGA and measurement of the number of acid sites by titration, is about 13 wt%. The solid typically contains 0.15 meq g⁻¹ of acid sites. This material is also thermally stable to at least 250°C and is chemically very stable; for instance, it can be recycled by boiling in HNO₃.

Preparation of Laponite-Exchanged Catalysts

To a solution of bis(oxazoline) (1 mmol) in methanol (20 ml) was added 1 mmol of Cu(OTf)₂. Laponite (1 g) was slowly added to the above blue solution and the suspension was stirred at room temperature for 24 h. The solid was filtered off, thoroughly washed with methanol and then with dichloromethane, and dried under air before use.

Preparation of Nafion- and Nafion-Silica-Exchanged Catalysts

Before exchange with the chiral catalyst, both solids were transformed into their sodium forms by passing a solution of NaCl (2 M) through a column of the solid until a neutral pH was obtained. The solids were then washed with deionized water and dried under vacuum at 110°C for 20 h, in the case of nafion, or at 150°C for 4 h, in the case of nafion-silica.

To a solution of bis(oxazoline) (2 mmol) in methanol (20 ml) was added 2 mmol of Cu(OTf)₂. To this blue solution was added the corresponding support (3 g), and the suspension was stirred at room temperature for 24 h. The solid was filtered off, thoroughly washed with methanol, and then washed with dichloromethane. Before use, the

catalysts were dried under vacuum and the nafion-silica was also ground using a mortar and pestle.

Characterization of the Catalysts

Copper analyses were carried out by plasma emission spectroscopy on a Perkin-Elmer Plasma 40 emission spectrometer. Nitrogen analyses were carried out on a Perkin-Elmer 2400 elemental analyzer. Step-scanned X-ray diffraction patterns of oriented samples were collected at room temperature from 3° in 2 θ up to 60°, using a D-max Rigaku system with rotating anode. The diffractometer was operated at 40 kV and 80 mA, and the CuK α radiation was selected using a graphite monochromator. Transmission FTIR spectra of self-supported wafers evacuated (<10⁻⁴ Torr) at 50°C were taken with a Mattson Genesis Series FTIR. Diffuse reflectance IR spectra were taken with a Mattson Research Series FTIR.

Cyclopropanation Reactions

The reactions were carried out in a batch-type glass round-bottomed flask. To a suspension of the corresponding supported catalyst (150 mg of laponite catalyst, 500 mg of nafion catalyst, or 300 mg of nafion-silica catalyst) in a solution of styrene (**1**) (5 mmol) and *n*-decane (100 mg) in the corresponding solvent (5 ml, see Tables 2, 4 and 5) was added ethyl diazoacetate (**2**) (2.5 mmol) in the same solvent (0.5 ml), under an argon atmosphere, for 2 h using a syringe pump. The reaction was monitored by gas chromatography, and after consumption of the diazoacetate, a second portion of this reagent was added in the same way. The reactions with nafion-supported catalysts were carried out at 60°C. After the reaction, the catalyst was filtered off, washed with the same solvent, and dried. The recovered catalysts were reused following the same method.

The results of the reactions were determined by gas chromatography; FID from Hewlett-Packard 5890II; cross-linked methyl silicone column, 25 m \times 0.2 mm \times 0.33 μ m; helium as the carrier gas, 20 psi; injector temperature, 230°C; detector temperature, 250°C; oven temperature program, 70°C (3 min), 15°C min⁻¹ to 200°C (5 min); retention times, ethyl diazoacetate (**2**) 4.28 min, styrene (**1**) 5.03 min, *n*-decane 6.93 min, diethyl fumarate 8.73 min, diethyl maleate 9.04 min, *cis*-cyclopropanes (**4**) 11.84 min, and *trans*-cyclopropanes (**3**) 12.35 min.

The asymmetric inductions of the reactions were also determined by gas chromatography: FID from Hewlett-Packard 5890II, Cyclodex B column: 30 m \times 0.25 mm \times 0.25 μ m; helium as the carrier gas, 20 psi; injector temperature, 230°C; detector temperature, 250°C; oven temperature program, 125°C isotherm; retention times, (1*S*,2*R*)-cyclopropane (**4b**) 28.9 min, (1*R*,2*S*)-cyclopropane (**4a**) 29.8 min, (1*R*,2*R*)-cyclopropane (**3a**) 34.3 min, and (1*S*,2*S*)-cyclopropane (**3b**) 34.9 min. The peaks were assigned to the corresponding enantiomers by comparison with previ-

ously described results. The *cis* and *trans* stereochemistry was assigned by comparison of the peak ratios with those obtained with the nonchiral column.

The cyclopropanes were purified by column chromatography on silica gel and their structures confirmed by ¹H-NMR spectroscopy.

RESULTS AND DISCUSSION

Preparation and Characterization of the Catalysts

In the liquid phase, the counterion of a cationic complex is crucial for its catalytic activity and the enantioselectivity of the reaction (14). The results obtained with clays (9) indicate that this is probably also the situation with solid supports, where the counterion is a solid with anionic sites. Given that triflate is one of the anions of choice in homogeneously catalyzed reactions, an analogous organic polymer such as nafion was chosen, as an alternative for laponite. However nafion has a very low surface area, so another sulfonic solid was chosen, namely, a nafion-silica nanocomposite, produced using an *in situ* sol-gel technique in which soluble silica precursors are mixed with a nanometer-sized colloidal dispersion of nafion in a polar solvent. The silica network forms via the aggregation of nanometer-sized silica particles, formed from condensing siloxanes, and as the gel is dried, the nafion resin particles become entrapped and highly dispersed throughout this network. This material can therefore be described as a nanocomposite, in which the nafion is dispersed at the nanometer level within the silica. This situation essentially increases the surface area of the nafion by several orders of magnitude compared to the pure polymer. In the case of the pure polymer, some acid sites remain buried and are essentially inaccessible, whereas within the composite they are accessible via pores in the range of 10–20 nm. As a consequence, this new microstructure shows greater catalytic activity, compared to nafion, for a number of acid-catalyzed reactions (13). It was thought to be interesting to test whether, in spite of its lower cation-exchange capacity with regard to nafion, this material also showed advantageous properties when used as a support for cationic chiral catalysts due to its better accessibility to the catalytic sites (15).

H-forms of nafion and nafion-silica were exchanged on a column with NaCl until a neutral pH was obtained. The exchange of the two solids with the complex formed by 2,2'-isopropylidene-[(4*R*)-4-phenyl-2-oxazoline] (**5**) and Cu(II) triflate was carried out in methanol for 24 h. Attempts to carry out the exchange by other methods, namely, in another solvent (nitroethane) or with the complex of CuCl₂, led to solids with a lower copper content, lower catalytic activity, and lower enantioselectivity. The solids obtained were characterized by different methods and the analyses are shown in Table 1.

TABLE 1
Analysis of the Supported Cu(II)-5 Complexes

Support	Cu (mmol g ⁻¹)		Surface area (m ² g ⁻¹)
	As-prepared	After 1 run	
Laponite	0.28	0.25	225
Nafion	0.22	0.23	<0.02 ^a
Nafion-silica	0.05	0.05	84

^aReference 11.

The copper content changes from one support to another and it is lowest in the nafion-silica nanocomposite, a fact that is in agreement with the lower concentration of anionic sites in this support. In the case of laponite, the nitrogen content was in good agreement with the ratio N/Cu of the complex. However, the nitrogen content of the catalysts on nafion-type supports is too low to be reproducible.

IR spectroscopy was used to confirm the structure of the complex exchanged in the support in each case. The laponite catalyst was pressed as a self-supported wafer and the transmission spectrum under vacuum was recorded (Fig. 1). An intense band corresponding to the C=N double bond was observed at 1640 cm⁻¹, shifted with respect to its position in the complexes with triflate (1660 cm⁻¹) and chloride (1655 cm⁻¹). The different nature of the anion accounts for this shift. Nafion beads were pressed directly and the spectrum showed a band at 1662 cm⁻¹, close to the position in the complex with triflate. Nafion-silica did not form self-supported wafers, and in this case, the diffuse reflectance spectrum in the open air was recorded (Fig. 2). The presence of a band at 1660 cm⁻¹, together with the water band at 1630 cm⁻¹, is in good agreement with the spectrum of the triflate complex. Further confirmation of the structure of the complex resulted from the enantioselectivity obtained in the catalytic tests, which will be discussed in the following section.

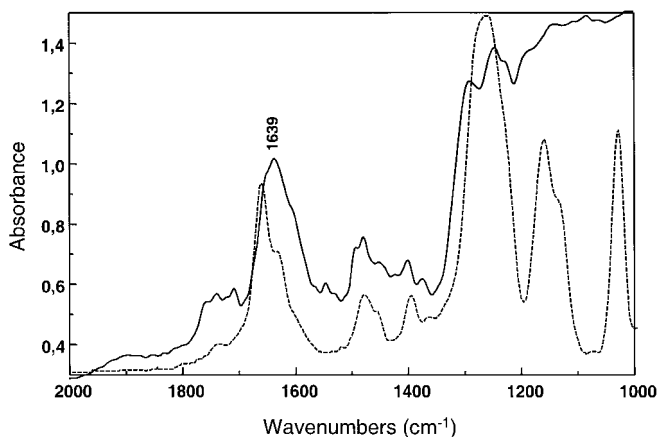


FIG. 1. Comparison of the IR absorption spectra of the 5-Cu(II) complex exchanged in laponite (continuous line) and in solution (dashed line).

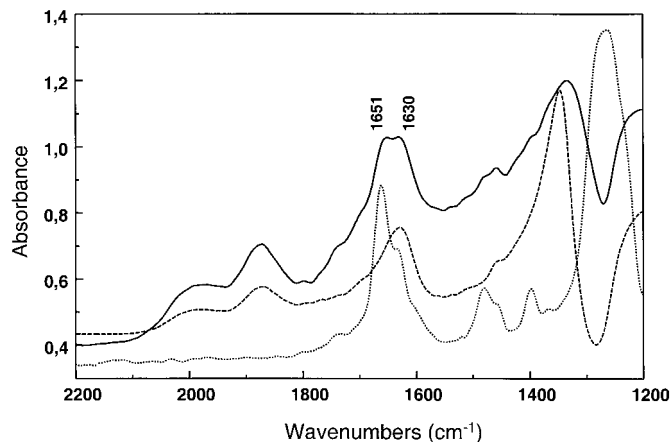


FIG. 2. Comparison of the IR spectra of the 5-Cu(II) complex exchanged in nafion-silica (continuous line) and in solution (dotted line), with that of the nafion-silica support (dashed line).

The laponite catalyst showed an increased basal spacing, from 16 to 17.7 Å, indicating the intercalation of the complex, at least in part, between the silicate sheets. The same expanded basal spacing was observed in the recovered catalyst.

Catalytic Tests

The three solids were tested as catalysts in the benchmark reaction of styrene (**1**) with ethyl diazoacetate (**2**) (Scheme 1). The results obtained are gathered in Table 2. As can be seen, all the catalysts promote the reaction with enantioselectivity, a fact that confirms the stability of the complex after the exchange. However, the catalytic activity changes from one support to another. It has been described (14) that the nature of the anion has a decisive influence on the catalytic activity of the homogeneous copper-bis(oxazoline) complexes, and that the best results are obtained with anions of low basicity, such as triflate. A comparison between laponite and nafion-silica shows that the solid bearing the anionic centers of lower basicity, i.e., nafion-silica, is more active, in spite of its lower surface area and the lower amount of copper present in the reaction (0.3% in the case of nafion-silica and 0.84% in laponite). The extremely low surface area of nafion justifies its lower catalytic activity, in spite of the fact that it bears the same anion as nafion-silica and contains a larger amount of copper (2.64%). This lower activity made it necessary to carry out the reaction at higher temperature (60°C).

The support also has a noticeable influence on the *trans/cis* (**3/4**) selectivity and a minor *trans* preference is observed with the laponite catalyst. An increase in the amount of *cis* product had already been described with clays exchanged with Cu(II) (**16**) and was explained in terms of the dimensionality of the clay and the isolation of the catalytic sites. Given that neither nafion nor nafion-silica

TABLE 2

Results Obtained From the Reaction of Styrene (**1**) with Ethyl Diazoacetate (**2**) Promoted by Supported Cu(II)-5 Complexes

Support	Styrene/Cu	Solvent	<i>T</i> (°C)	<i>t</i> (h)	Conv. 1 ^a	Select. 1 ^a	Select. 2 ^a	3/4 ^a	% ee 3 ^b	% ee 4 ^b
—	10	CH ₂ Cl ₂	25	5	49	67	33	2.1	60	51
Laponite	119	CH ₂ Cl ₂	25	21	40	76	31	1.2	43	6
Laponite ^c	133	CH ₂ Cl ₂	25	24	38	74	28	1.2	41	13
Nafion	45	DCE ^d	60	9	52	71	37	2.0	59	45
Nafion ^c	44	DCE	60	9	50	75	33	1.9	58	47
Nafion-silica	333	DCE	25	9	38	70	27	1.9	57	46
Nafion-silica ^c	333	DCE	25	9	42	64	27	1.9	56	45

^aDetermined by gas chromatography.^bDetermined by gas chromatography with a chiral column. **3b** and **4b** are the major enantiomers.^cRecovered catalyst.^d1,2-Dichloroethane.

show this behavior, the involvement of site isolation can be discounted. The stability of the cyclopropanes in the reaction conditions discards the decomposition of the *trans* isomer as the reason for this behavior.

The use of a nafion-type support, with lower basicity than laponite, leads to enantioselectivities very similar to the values obtained in the analogous homogeneous system and higher than those obtained with laponite. The presence of the support does not modify the direction of the asymmetric induction, and the major enantiomers obtained are the same under both homogeneous and heterogeneous conditions. In these cases, as in the homogeneous reaction, enantioselectivities in both *cis*- and *trans*-cyclopropanes are very similar. These results show that the extremely low enantioselectivity in the *cis* product obtained with laponite is an anomalous behavior, not observed either with other supports or, as it is shown below, with other chiral auxiliaries. Consequently, it must be related to this particular couple of support and bis(oxazoline) and its influence on the relative energy of the four diastereomeric transition states. However, we cannot offer any explanation for this special behavior.

To confirm the heterogeneous nature of these reactions, the catalysts were separated by filtration and an additional amount of ethyl diazoacetate was added to the liquid phase under the same reaction conditions. The amount of cyclopropanes did not increase, showing that no homogeneous reaction occurs. Copper analyses of the recovered catalysts show that leaching does not take place under the reaction conditions. Furthermore, the recovered catalysts have the same catalytic activity and lead to the same *trans/cis* and enantioselectivities.

Application to Other Bis(oxazoline) Ligands

The results obtained show the advantages of using anionic supports of low basicity and high surface area. We therefore attempted to apply this methodology with other bis(oxazoline) ligands, namely, those bearing different

groups, benzyl (**6**) (obtained from (*S*)-phenylalaninol) and *tert*-butyl (**7**) (from (*S*)-*tert*-leucinol). The catalysts were obtained again by cation exchange of the bis(oxazoline)-Cu(II) triflate complexes in the Na forms of nafion and nafion-silica. The solids were analyzed (Table 3) and tested in the reaction of styrene (**1**) with ethyl diazoacetate (**2**), the results of which are gathered in Tables 4 and 5.

With the Cu(II)-**6** complex, laponite presented two main problems when it was used as a support, an important copper leaching (Table 3) and also an enantioselectivity lower than that in the homogeneous phase. Both problems are clearly overcome by the use of sulfonic supports. Copper analysis shows that leaching, if it exists, is very low. Moreover, an additional amount of ethyl diazoacetate was added to the filtrate after the heterogeneous reaction. As no reaction was detected, we can conclude that if some copper is lost, it is in an inactive form, so the reaction is truly heterogeneous. More likely, this decrease in the copper content can be due to the gain in weight because of the adsorption of by-products, already detected in the case of laponite (**9**). The enantioselectivity is higher than that obtained with laponite and only slightly lower than that observed in the homogeneous reaction. However, this enantioselectivity is lowered after recycling, as it also happened with laponite.

TABLE 3

Analysis of the Supported Cu(II)-6 and Cu(II)-7 Complexes

Support	Ligand	Cu (mmol g ⁻¹)	
		As-prepared	After 2 runs
Laponite	6	0.35	0.22 ^a
Nafion	6	0.25	0.22
Nafion-silica	6	0.05	0.03
Laponite	7	0.11	0.10 ^a
Nafion	7	0.28	0.28
Nafion-silica	7	0.07	0.03

^a Analysis after 1 run.

TABLE 4
Results Obtained from the Reaction of Styrene (1) with Ethyl Diazoacetate (2) Promoted by Supported Cu(II)-6 Complexes

Support	Styrene/Cu	Solvent	<i>T</i> (°C)	<i>t</i> (h)	Conv. 1	Select. 1	Select. 2	3/4	% ee 3^a	% ee 4^a
—	10	CH ₂ Cl ₂	25	7	69	85	58	2.1	59	53
Laponite	95	CH ₂ Cl ₂	25	22	38	66	25	1.0	24	19
Laponite ^b	151	CH ₂ Cl ₂	25	22	44	73	32	1.1	14	12
Nafion	40	DCE	60	24	50	54	27	1.5	44	44
Nafion ^b	45 ^c	DCE	60	24	45	59	27	1.5	34	34
Nafion-silica	333	DCE	25	21	47	71	34	1.6	49	49
Nafion-silica ^b	555 ^c	DCE	25	46	29	80	23	1.6	37	36

^a **3a** and **4a** are the major enantiomers.

^b Recovered catalyst.

^c Calculated on the basis of Cu analysis after the second reaction.

In spite of the fact that bis(oxazoline) **7** is the best ligand for the homogeneous catalytic reaction, the results with laponite were only good in the first reaction, 69% ee in the *trans* isomer, but the enantioselectivity was reduced to 43% ee with the recycled catalyst.

Whereas the loss of catalytic activity in a heterogeneous catalyst is normally explained by the leaching or the poisoning of the catalytic sites, the change in enantioselectivity must be explained by changes in these catalytic sites, and in particular, the generation of nonchiral sites seems to be a plausible explanation. The chiral ligand is not covalently bonded to the support but coordinated to the copper, and it can be substituted by other ligands with a better coordination ability or present in an amount enough to shift the equilibrium. In these reactions even the cyclopropanes or the diethyl fumarate and mainly the diethyl maleate and some heterocyclic by-products (**17**), obtained from the carbene intermediates, may play this role (Scheme 2). In fact, the presence of molecules bearing carbonyl groups can be detected by IR spectroscopy of the catalysts supported on laponite after one reaction (Figure 3), supporting our hypothesis. Thus, the stability of the chiral-supported catalyst

depends on both the electrostatic interaction of the cationic complex with the support and the strength of the ligand-copper interaction.

Furthermore, the cationic exchange used to obtain the catalyst is the result of a series of equilibria, and if the exchanged chiral complex has a very low stability, the solid contains a noticeable amount of nonchiral catalytic sites. Therefore, the use of nafion-type supports did not lead to good results with 2,2'-isopropylidene-[(4*S*)-4-*tert*-butyl-2-oxazoline] (**7**). In fact, with nafion, the enantioselectivity was nearly zero and only around 20% with nafion-silica. The high catalytic activity, as demonstrated by the short reaction times, agrees with the presence of nonchiral catalytic centers. To confirm this hypothesis, we carried out the analysis of the solution used in the exchange process with Cu-**7** after evaporation to dryness. The residue had more bis(oxazoline) than copper, as shown by nitrogen and copper analyses, whereas an equimolecular mixture had been used in the preparation of the complex. Thus, in nafion-silica exchanged with Cu-**7**, about 30% of the exchanged copper was in the form of a complex but 70% was free of the chiral ligand. When the same analysis

TABLE 5
Results Obtained from the Reaction of Styrene (1) with Ethyl Diazoacetate (2) Promoted by Supported Cu(II)-7 Complexes

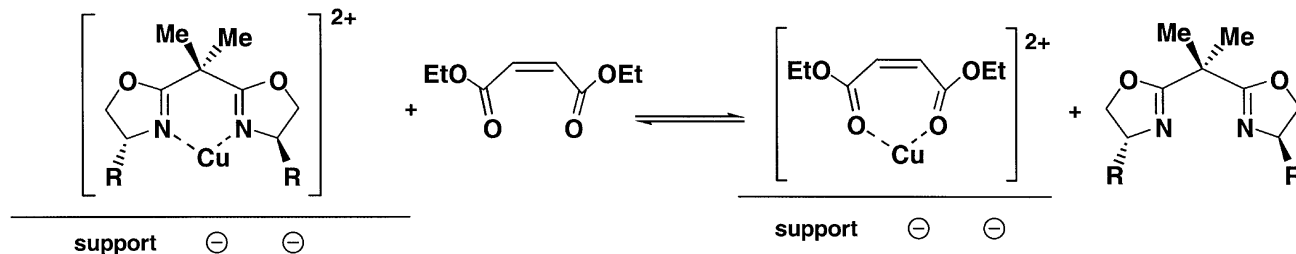
Support	Styrene/Cu	Solvent	<i>T</i> (°C)	<i>t</i> (h)	Conv. 1	Select. 1	Select. 2	3/4	% ee 3^a	% ee 4^a
—	10	CH ₂ Cl ₂	25	7	89	82	72	2.4	94	91
Laponite ^b	303	CH ₂ Cl ₂	25	39	37	82	30	1.8	69	64
Laponite ^c	333	CH ₂ Cl ₂	25	88	22	59	26	1.4	43	37
Nafion	36	DCE	60	9	34	77	26	1.7	5	7
Nafion ^c	36 ^d	DCE	60	9	34	68	23	1.7	5	6
Nafion-silica	238	DCE	25	2	41	76	31	1.5	23	19
Nafion-silica ^c	555 ^d	DCE	25	2	34	91	31	1.6	14	14

^a **3a** and **4a** are the major enantiomers.

^b Catalyst prepared in nitroethane with the complex between **7** and CuCl₂.

^c Recovered catalyst.

^d Calculated on the basis of Cu analysis after the second reaction.



SCHEME 2

was carried out with Cu-5, the results obtained were consistent within the experimental error with the absence of nonchiral catalytic sites. This result would explain the low enantioselectivity observed with Cu-7 exchanged in nafion-silica, which is not better if the solid is treated with a large excess of chiral ligand. The results obtained show that the formation and the recovery of the chiral catalysts depend on the nature of both the support and the chiral ligand.

This behavior must have its origin in the existence of a repulsive interaction between the ligand and support. Taken into account that the electrostatic nature of the complexes remains essentially constant, the interaction responsible for this result must be of a steric nature. If we look at the chiral ligands, the substituent in ligand 5 is a phenyl group of flat shape, whereas in ligand 6 the methylene group confers an angular shape and the *tert*-butyl group in ligand 7 has a globular shape. In the case of the phenyl group, the steric interactions between the chiral auxiliary and the supports are weak enough to obtain stable and recoverable catalysts.

In the case of the benzyl group, the steric interaction must be weak because of the fairly good results in the first reaction, showing that most of the catalytic species introduced in the exchange process are chiral. However, this interaction is strong enough to let part of the ligand go loose during the reaction. When the ligand bears a globular substituent,

the steric interactions must be greatly increased, so in the exchange process the noncomplexed metal is favorably exchanged despite its low concentration. Consequently, the enantioselectivity is lower than that in the homogeneous phase in the first reaction, and when possible, it is reduced after recovery. So the role of the support is not only electrostatic but also steric, and nafion gives rise to stronger steric interactions.

CONCLUSIONS

The results obtained in the benchmark cyclopropanation reaction of styrene with ethyl diazoacetate show that it is possible to support chiral copper-bis(oxazoline) complexes by electrostatic interaction with anionic supports. The catalytic performance of the supported catalysts depends on the nature of both the chiral auxiliary and the support. The use of supports bearing weakly basic anionic centers leads to better results, as it also happens under homogeneous conditions, but only with ligands whose steric interaction with the support is low. The complex formed by 2,2'-isopropylidene-[(4*R*)-4-phenyl-2-oxazoline] (5) and Cu(II) supported on nafion-type solids affords the best enantioselectivities described to date for heterogeneous chiral cyclopropanation reactions with a recyclable catalyst (58% ee in the *trans*-cyclopropanes and 47% ee in the *cis*-cyclopropanes). However, when the chiral ligand has important steric requirements, as in the case of 2,2'-isopropylidene-[(4*S*)-4-benzyl-2-oxazoline] (6) and 2,2'-isopropylidene-[(4*S*)-4-*tert*-butyl-2-oxazoline] (7), the basicity of the support is less important. In these cases, the steric interactions between the chiral auxiliary and the support reduce the stability of the supported chiral complexes, so that nonchiral catalytic sites are formed in the preparation of the catalyst or during the reaction, leading to low enantioselectivities in the reactions promoted by the recovered and, in some cases, by the freshly prepared catalysts.

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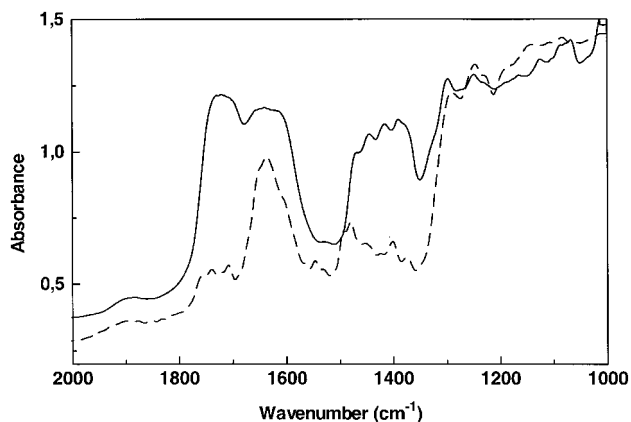


FIG. 3. Comparison of the IR spectra of the 6-Cu(II) complex exchanged in laponite as-prepared (dotted line) and after a catalytic run (continuous line).

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