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Catalysis

Mixed-Ligand Mandelato-Phosphine Copper(I) Complexes as Active Catalysts in Carbene Transfer Reactions

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Two mixed ligand copper(I) complexes, [Cu(PPh$_3$)$_3$(κ-O-mand)] (**CuP3M**) and [Cu(PPh$_3$)$_2$(κ^2-O,O′-mand)] (**CuP2M**) (mand = DL-mandelate) were synthesized and fully characterized. The different coordination modes of the α-hydroxycarboxylate ligand in **CuP2M** and **CuP3M** are clearly demonstrated by infrared spectroscopy, with the asymmetric $\nu_{C=O}$ stretching being observed at 1626 (**CuP3M**) and 1593 (**CuP2M**) cm^{-1}, respectively. Solution NMR studies (^{1}H, ^{31}P{^{1}H}), elemental and X-ray structure analyses confirmed the nature of the synthesized compounds. Complexes **CuP2M** and **CuP3M** were active in carbene transfer reactions towards unsaturated bonds, using ethyl diazoacetate ($N_2CHCOOEt$, EDA) as carbene source. Indeed, they promoted the *trans*-diastereoselective cyclopropanation of terminal and internal olefins under mild reaction conditions and low catalyst loading (1 % mol).

Introduction

α-Hydroxycarboxylates are among the most widespread classes of compounds in nature, having significant roles in many biochemical processes, like in the Krebs cycle,[1] just to name one. Moreover, they can mimic more complex ligands in coordination compounds, such as siderophores, many of which contain the α-hydroxycarboxylate group.[2] Indeed, by possessing both a hydroxylic and a carboxylate group, they display a wide range of coordination modes,[3] starting with the most common κ^2-O,O″, in which both groups are chelating a metal center, forming a highly stable five-membered ring.[4] Also, they can lead to the formation of supramolecular structures, thanks to the presence of both a hydrogen bond donor (OH) and an acceptor group (COO$^-$), thus having the possibility to create an extended arrangements through relatively strong intermolecular H-bonding interactions. The κ^2-O,O″ mode is more commonly encountered in mixed ligand complexes, either with monodentate ligands (NH$_3$,[5] H$_2$O,[6] py,[7] imidazole[8]) or with *N,N′* bidentate ancillary ligands like phenanthrolines,[9,10] 2,2′-bipyridines[11] or 2,2′-dipyridylamine.[12]

Less common, if the hydroxyl group is not involved in the coordination, two different possibilities can be considered: in the κ^2-O,O′ mode, the carboxylic moiety acts as a bidentate ligand,[13] while κ-O indicates the coordination via only one oxygen atom of the carboxylic functionality (Figure 1).[14]

On the other hand, molecules containing a cyclopropane moiety represent a very important class of compounds, present in many natural[15,16] and pharmaceutical species, despite their high restrain energy (27.5 kcal mol^{-1}) due to the strained three-membered ring. They possess many interesting biological activities, like superior olfactory impact with respect to other standard species used in fragrance chemistry[17] or their role in the biosynthesis of terpenoids.[16] Moreover, they represent a fundamental building block in organic synthesis,[18] as in the total synthesis of (−)-6-epi-Ophiobolin N or Piperarborenine B.

Among the most convenient methods for the preparation of cyclopropane rings, transition-metal-catalyzed transfer reactions of carbenes to unsaturated organic compounds are one of the most efficient way, exploiting diazo compounds as

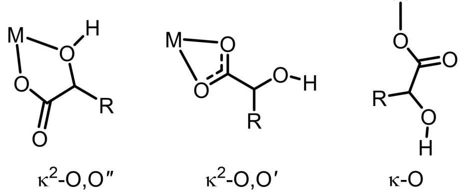

Figure 1. Possible coordination modes to a single metal center for monoanionic α-hydroxycarboxylates.

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carbene sources,[19] especially diazo acetates[20] because of their relatively higher stability and safety among the diazo compounds. These reactions are usually promoted by several metals, like rhodium,[21] ruthenium,[22] gold,[23] or copper,[24,25] the latter representing a very valid choice because of its low-cost. Le Maux and Simonneaux showed the remarkable activity of copper-based bisoxazoline complexes,[26] whereas Pereira studied the properties of tris(pyrazolyl)borate[27] copper(I) complexes in the functionalization of O–H bonds. Copper(I)-phosphine complexes have also been used in the chemoselective insertion into N–H bonds.[28]

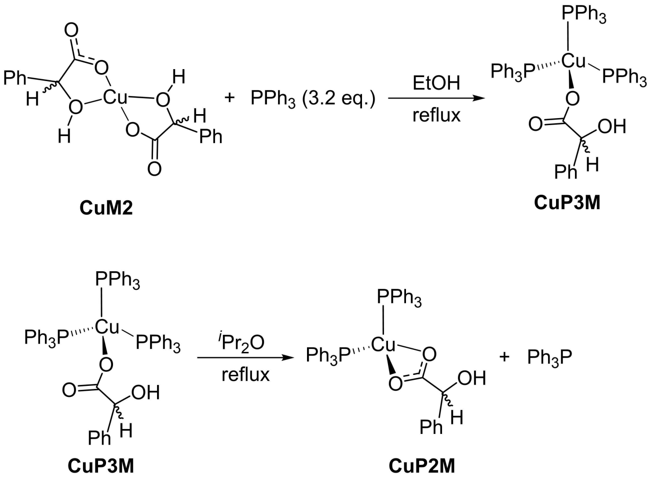
Among our research group, a lot of efforts have been devoted in the past years in the study of copper catalyst in the cyclopropanation of alkenes via carbene transfer,[29–31] with a particular focus on complexes containing α-hydroxycarboxylate ligands. In fact, we reported on mixed ligand copper(I) complexes containing a lactate ion, $[Cu(PPh_3)_2(\kappa^2\text{-O,O}''\text{-lact})]$[32] (**CuP2L**) and $[Cu_2(\mu\text{-dppm})_2(\kappa\text{-O-lact})(\mu\text{-}\kappa\text{-O-lact})]$ (**CudppmL**)[33] (lact = L-(+)-lactate). In particular, compound **CuP2L** demonstrated high activity in catalytic carbene transfer reactions in the presence of diazoacetates.[34] To further explore the chemistry of copper compounds bearing α-hydroxycarboxylates, we now report the synthesis, the characterization, and the catalytic properties of new copper(I) coordination compounds bearing a mandelate ligand.

Results and Discussion

Syntheses and characterization

The starting copper(II) mandelate compound $[Cu(\kappa^2\text{-O,O}''\text{-mand})_2]$ has been prepared via acid-base reaction between $Cu(OH)_2$ and DL-mandelic acid, in ethanol at room temperature. In the course of the reaction (3 days), the color of the suspension slowly changed from deep blue ($Cu(OH)_2$) to light blue ($[Cu(\kappa^2\text{-O,O}''\text{-mand})_2]$). In the Infrared spectrum (ATR), the broad medium-intensity band at about 3100 cm^{-1} is attributed to ν(OH), whereas the $\nu(COO)_{asym}$ stretching is found at 1578 cm^{-1}; a broad band at 2600 cm^{-1} is indicative of strong O–H···O hydrogen bonds involving mandelate ions.

After treatment of $[Cu(\kappa^2\text{-O,O}''\text{-mand})_2]$ with a slight excess of PPh_3 in refluxing ethanol, the expected reduction of the Cu(II) center occurs and complex $[Cu(PPh_3)_3(\kappa\text{-O-mand})]$ (**CuP3M**) is formed (Scheme 1). Worthy of note, the same reaction performed on the analogous copper(II) lactate derivative[32] led to the formation of $[Cu(PPh_3)_2(\kappa^2\text{-O,O}''\text{-lact})]$ (**CuP2L**), with a different final Cu:PPh$_3$ ratio. The 1:3 Cu:PPh$_3$ ratio in **CuP3M** was determined from elemental and ^1H NMR analyses. In the ^1H NMR spectrum of **CuP3M** ($CDCl_3$, 25 °C) the signals due to CH (4.99 ppm) and the aromatic protons are clearly visible in a 1:50 proportion. The resonance at 4.99 ppm appears as a doublet ($^3J_{HH} = 4.5$ Hz) due to the coupling with O–H, the latter also emerging as a doublet at 4.37 ppm ($^3J_{HH} = 4.5$ Hz). Isotopic exchange with D_2O confirmed these assignments (Figure S1). Besides aromatic carbons, the ^{13}C NMR spectrum ($CDCl_3$, 25 °C) shows a signal at 74.5 ppm (*C*H) and a downshifted resonance at 177.9 ppm attributed to the carboxylic carbon (Figure S2). Finally, the three phosphorous atoms generate a sharp singlet at −3.28 ppm in the $^{31}P\{^1H\}$ NMR (Figure S3), confirming a symmetrical environment.



Scheme 1. Synthesis of complexes $[Cu(PPh_3)_3(\kappa\text{-O-mand})]$ (**CuP3M**) and $[Cu(PPh_3)_2(\kappa^2\text{-O,O}'\text{-mand})]$ (**CuP2M**).

The infrared spectrum of **CuP3M** (Figure S4) is characterized by a sharp band at 1093 cm^{-1} correlated to coordinated PPh$_3$ and two intense stretching at 1626 cm^{-1} ($\nu(COO)_{asym}$) and 1349 cm^{-1} ($\nu(COO)_{sym}$) assigned to the carboxylate. Such frequencies lead to a Δν (asym-sym) of 277 cm^{-1}, in accordance with a monodentate (κ-O) mandelate.[35] The medium intensity band at 3362 cm^{-1} is associated to the OH group of mandelate ion, not involved in hydrogen bonds.

With the aim of synthesizing a bis-diphenylphosphine mandelate complex, analogous to $[Cu(PPh_3)_2(\kappa^2\text{-O,O}''\text{-lact})]$ (**CuP2L**),[32] **CuP3M** was gently refluxed in isopropyl ether, to promote PPh$_3$ dissociation. Repeated washings done by replacing the solvent with fresh aliquots, allowed to isolate a new copper(I) derivative formulated as $[Cu(PPh_3)_2(\kappa^2\text{-O,O}'\text{-mand})]$ (**CuP2M**). The ^1H NMR spectrum of **CuP2M** ($CDCl_3$, 25 °C) shows the signals attributed to C*H* (4.99 ppm), OH (4.38 ppm) and the aromatic protons (7.19-7.50 ppm) in a 1:1:35 ratio (Figure S5). In the $^{13}C\{^1H\}$ NMR (Figure S6), resonances at 74.4 ppm (*C*H) and 178.1 ppm (*C*OO) are observed, whereas the $^{31}P\{^1H\}$ NMR (Figure S7) shows a sharp singlet at −2.34 ppm. The κ^2-O,O′ coordination for mandelate was postulated according to infrared data, in particular by the frequencies at 1593 cm^{-1} (νCOO_{asym}) and 1351 cm^{-1} (νCOO_{sym}) attributable to the carboxylate.[36] Again, the free OH group of mandelate ion produces a medium intensity band at 3342 cm^{-1} (Figure S8).

X-ray structural investigation

The coordination mode of mandelate in **CuP2M** was eventually confirmed by single crystal X-ray structure analysis. Several attempts to grow single crystals of **CuP3M** suitable for X-ray investigation were unsuccessful, always leading to crystals with poor-quality data. However, two of these attempts led to interesting X-ray crystal structures of **CuP2M** and a related derivative. By layering diethyl ether on a dichloromethane solution of [Cu(PPh$_3$)$_3$(κ-O-mand)] (**CuP3M**), crystals representative of [Cu(PPh$_3$)$_2$(κ^2-O,O′-mand)] (**CuP2M**) were obtained (Figure 2). Reasonably, a PPh$_3$ molecule dissociates from **CuP3M** in solution during the crystallization process, and the vacant coordination site is occupied by a second oxygen atom from the mandelate anion, which then switches its coordination from κ-O to κ^2-O,O′. The infrared spectrum of grinded crystals (Figure S9) is identical to that of **CuP2M** (νCOO$_{asym}$ at 1593 cm^{-1}), thus confirming the κ^2-O,O′ binding mode.

In [Cu(PPh$_3$)$_2$(κ^2-O,O′-mand)] (**CuP2M**), the copper center shows a tetrahedral geometry (τ = 0.82[37]) with a P$_2$O$_2$ surrounding. Cu–P1 and Cu–P2 distances measure respectively 2.2363(8) and 2.2500(8) Å, whereas a higher discrepancy is observed between Cu–O1 (2.131(2)) and Cu–O2 (2.365(3)) distances (Table 1). The κ^2-O,O′ coordination of mandelate obviously imposes a very acute O1-Cu–O2 angle of 56.84(9)°, while P1-Cu–P2 measures 130.05(3)°. In the crystal packing, two close molecules are linked by intermolecular O–H···O hydrogen bond (2.57(1) Å) via the non-coordinated hydroxy groups of two neighboring mandelates. Later, in a different crystallization attempt, compound [Cu(PPh$_3$)$_3$(κ-O-mand)] (**CuP3M**) was dissolved in hot isopropanol and the solution was slowly cooled to room temperature, leading to the formation of white crystals of a new species, which was identified as [Cu(PPh$_3$)$_2$(κ-O-mand)(^{i}PrOH)] (**CuP2M-^{i}PrOH**) (Figure 2). Again, dissociation of one PPh$_3$ molecule from **CuP3M** occurred, with now isopropanol occupying the vacant coordination site and mandelate thus keeping its κ-O mode. The coordination of the solvent molecule is favored by the formation of an intramolecular O–H···O hydrogen bond (2.687(3) Å) with the non-coordinated oxygen atom of mandelate (Figure 2, Table 1). Again, the copper center has a tetrahedral geometry (τ = 0.84), with Cu–P bond lengths very similar to those observed in **CuP2M** (Cu–P1 = 2.2432(6) Å, Cu–P2 = 2.2601(6) Å). As expected, the Cu–O distances are quite dissimilar in **CuP2M-^{i}PrOH**, measuring respectively 2.0564(15) Å (Cu–O1, κ-O-mand) and 2.454(2) Å (Cu–O4, isopropanol).

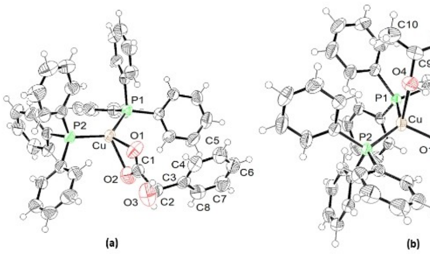


Figure 2. ORTEP representations of (a) [Cu(PPh$_3$)$_2$(κ^2-O,O′-mand)] (**CuP2M**) and (b) [Cu(PPh$_3$)$_2$(κ-O-mand)(^{i}PrOH)] (**CuP2M-^{i}PrOH**) at 50% probability level ellipsoids.

Table 1. Selected bond distances (Å) and angles (°) in **CuP2M** and **CuP2M-^{i}PrOH**.

Distances (Å) [Cu(PPh$_3$)$_2$(κ^2-O,O′-mand)] (**CuP2M**)		Angles (°)	
Cu–P(1)	2.2363(8)	P(1)–Cu–P(2)	130.05(3)
Cu–P(2)	2.2500(8)	O(1)–Cu–O(2)	56.84(9)
Cu–O(1)	2.131(3)	P(1)–Cu–O(1)	113.80(8)
Cu–O(2)	2.365(3)	P(1)–Cu–O(2)	111.01(8)
C(1)–O(1)	1.243(4)	P(2)–Cu–O(1)	109.84(7)
C(1)–O(2)	1.213(4)	P(2)–Cu–O(2)	112.57(7)
		O(1)–C(1)–O(2)	122.2(3)
[Cu(PPh$_3$)$_2$(κ-O-mand)(^{i}PrOH)] (**CuP2M-^{i}PrOH**)			
Cu–P(1)	2.2432(6)	P(1)–Cu–P(2)	126.70(2)
Cu–P(2)	2.2601(6)	O(1)–Cu–O(4)	94.28(7)
Cu–O(1)	2.0564(15)	P(1)–Cu–O(1)	115.24(5)
Cu–O(4)	2.454(2)	P(1)–Cu–O(4)	100.29(5)
C(1)–O(1)	1.255(3)	P(2)–Cu–O(1)	111.15(5)
C(1)–O(2)	1.211(3)	P(2)–Cu–O(4)	101.00(5)
O(4)–H–O(2)	2.687(3)	O(1)-C(1)-O(2)	127.10(2)

TD-DFT calculations were performed on **CuP2M** and **CuP2M-bis**. The calculations showed that the two coordination modes lead to species easily interconvertible, the difference in ΔG$_{form}$ being 1.6 kcal/mol (Figure 3). The same situation is observed for the analogous complexes bearing the lactate anion, [Cu(PPh$_3$)$_2$(κ^2-O,O′-lact)] (**CuP2L**) and Cu(PPh$_3$)$_2$(κ^2-O,O″-lact)] (**CuP2L-bis**), which are equienergetic (Δ(ΔG) = 0.7 kcal/mol) (Figure 3). Thus, the specific coordination mode observed in the X-ray crystal structure analysis (κ^2-O,O′ for mandelate and κ^2-O,O″ for lactate) can be rationalized by the stability imposed by packing phenomena.

Catalytic carbene transfer reactions

Complexes **CuP3M** and **CuP2M** are both active pre-catalysts in carbene transfer reactions, using ethyl diazoacetate (EDA) as a carbene source. Indeed, addition of ethyl diazoacetate to a solution of the olefin and the catalyst (1% mol) led under mild conditions to the conversion of the substrate into the corresponding cyclopropane derivatives with high yields (Table 2). Like previous studies,[34] the catalytic runs were performed in dichloromethane, at room temperature. As known, side products deriving from EDA self-coupling (i.e., diethyl maleate and diethyl fumarate) can also be generated. To lessen their formation, an excess of olefin was employed, so that in a typical run the catalyst:EDA:olefin molar ratio was

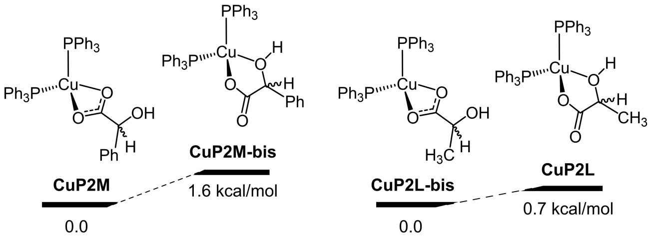


Figure 3. Differences in ΔG$_{form}$ (kcal/mol) calculated for bis-phosphine α-hydroxycarboxylate copper(I) complexes bearing mandelate or lactate either in a κ-O,O′ or a κ-O,O″ coordination mode.

Table 2. Olefin cyclopropanation by ethyl diazoacetate (EDA) decomposition catalyzed by **CuP3M** and **CuP2M**.[a]

Olefin	Entry	Catalyst	*cis* + *trans* (%)[b]	*cis*:*trans* ratio[c]
Styrene	1	**CuP3M**	80	25:75
Styrene	2	**CuP2M**	79	36:64
α-Methylstyrene	3	**CuP3M**	90	42:58
α-Methylstyrene	4	**CuP2M**	90	43:57
1-hexene	5	**CuP3M**	68	28:72
1-hexene	6	**CuP2M**	58	31:69
1,1-Diphenylethylene	7	**CuP3M**	85	–
1,1-Diphenylethylene	8	**CuP2M**	89	–
Ethyl vinyl ether	9	**CuP3M**	87	24:76
Ethyl vinyl ether	10	**CuP2M**	80	27:73
2-Vinylpyridine	11	**CuP3M**	<5	–
2-Vinylpyridine	12	**CuP2M**	<5	–
Cyclohexene	13	**CuP3M**	76	4:96[d]
Cyclohexene	14	**CuP2M**	72	5:95[d]
4-Phenyl-3-buten-2-one	15	**CuP3M**	<5	–
4-Phenyl-3-buten-2-one	16	**CuP2M**	<5	–
2,5-Dimethyl-2,4-hexadiene	17	**CuP3M**	75	34:66
2,5-Dimethyl-2,4-hexadiene	18	**CuP2M**	90	34:66

[a] Reactions conditions: catalyst/EDA/olefin = 1/100/250; CH_2Cl_2 (8 mL), 20 °C. [b] Yields were determined by GC-MS analysis of the bulk, as the ratio of products peak area: (*cis* + *trans*) + (diethyl maleate + diethyl fumarate) = 100 %, after complete EDA consumption (> 99 % in all runs) monitored by disappearance of $\nu_{N\equiv N}$ in infrared spectroscopy. [c] Determined by GC-MS analysis of the bulk. [d] In this specific case, the diastereoselectivity is referred to *exo*:*endo* ratio.

1:100:250, and EDA was added dropwise over a half-hour period to the olefin-catalyst solution.

Both complexes showed high activity in the cyclopropanation of activated terminal olefins (Table 2, entries 1–10), with yields of conversion $\geq$80 %, except in the case of 1-hexene (58–68 %).

Compounds **CuP3M** and **CuP2M** were not active in the presence of non-activated alkenes like 2-vinyl pyridine (entries 11–12).

The same trend was observed with internal olefins: cyclohexene was converted in the corresponding cyclopropanes in good yields (entries 13–14), whereas the electron poor *trans*-benzylideneacetone gave the desired products with unsatisfactorily yields (entries 15–16). Finally, one diene was also employed as substrate, 2,5-dimethyl-2,4-hexadiene (DMHD), showing a conversion into the corresponding chrysantemate ethyl esters in high yields (up to 90 %, entry 18). Overall, the yields in cyclopropane products are comparable to those reported for the analogous copper(I)-lactate species [Cu-$(PPh_3)_2$(κ^2-O,O''-lact)] (**CuP2L**).[34] Diastereoselectivities were comparable to previous publications as well: a 25:75 to 30:70 *cis/trans* ratio was recorded in the catalytic cyclopropanation of internal olefins, with the exception of α-methylstyrene which was converted with a lower *trans* diastereoselectivity (ca. 40:60, entries 3–4). Both complexes showed a remarkable diastereoselectivity in the cyclopropanation of cyclohexene (entry 6), where a 4:96 *exo*:*endo* ratio was achieved. Analogously with what observed for mono-olefins, when complexes **CuP3M** and **CuP2M** were used as catalysts in the conversion of conjugated di-olefins into the corresponding cyclopropanes (entries 17–18), the *trans* isomer was again the major product. Worthy of note, the nearly identical catalytic activity of **CuP3M** and **CuP2M** could be ascribed to the dissociation of one PPh_3 molecule from **CuP3M**, as previously discussed.

Competitive experiments

Some competitive experiments were then performed using alternatively styrene, α-methyl styrene and diphenylethylene as substrates, and compound **CuP2M** as catalyst (Scheme 2). To maintain the same molar ratio between copper and olefins, the latter were added both in a 1:250 Cu:olefin ratio. As reported in Table 3, the overall yields were in the range 73–81 %, the remaining 19–27 % being represented by the expected fumarate and maleate side products. When less bulky substituents are present (i.e., H or Me), electronic effects predominate: the electron donor methyl group in α-methyl styrene favors nucleophilic attack of the olefin towards the electrophilic [Cu=CHCOOEt] carbene supposed as active intermediate. On the contrary, in the presence of bulkier substituents (i.e., Ph) the cyclopropane derived from diphenylethylene was always detected in lower yields, reasonably due to the higher steric hindrance of the phenyl substituent.

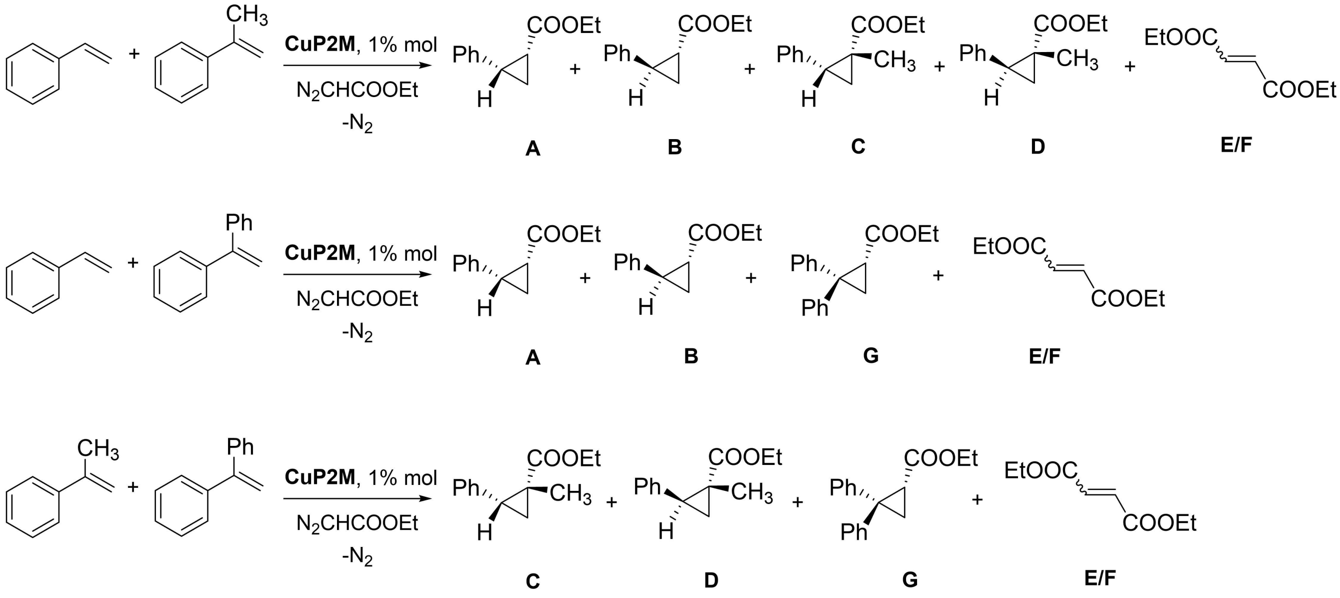
Conclusion

Herein we reported the synthesis of two mixed-ligand copper(I) complexes, [Cu$(PPh_3)_3$(κ-O-mand)] (**CuP3M**) and [Cu$(PPh_3)_2$(κ^2-O,O'-mand)] (**CuP2M**) (mand = mandelate), which were characterized via infrared, ^1H, $^{13}C\{^1H\}$ and $^{31}P\{^1H\}$ NMR spectroscopy as well as by single-crystal X-ray structure analysis. The mandelate ion exhibited two different coordination modes, confirming the adaptability of the mandelate ligand in the presence of other coordinating species (i.e., solvent molecules). The catalytic activity of the two complexes (catalyst loading = 1 mol-%) in carbene transfer reactions to olefins was evaluated under mild conditions using ethyl diazoacetate as a carbene source. Low yields were recorded for olefins bearing electron withdrawing substituents, suggesting poor interaction with the electrophilic

Table 3. Competitive experiments performed using styrene, α-methyl styrene and diphenylethylene as substrates and **CuP2M** as catalyst.[a]

Run	**A + B**[b]	**C + D**[b]	**G**[b]	**E + F**[b]
1	24 % (A:B = 27:73)[c]	57 % (C:D = 42:58)[c]	–	19 %
2	41 % (A:B = 24:76)[c]	–	32 %	27 %
3	–	54 % (C:D = 43:57)[c]	24 %	22 %

[a] Reactions conditions: catalyst/EDA/olefin1 + olefin2 = 1/100/250 + 250; CH_2Cl_2 (8 mL), 20 °C. [b] Yields were determined by GC-MS analysis of the bulk, after complete EDA consumption (> 99 % in all runs) monitored by disappearance of $\nu_{N\equiv N}$ in infrared spectroscopy. [c] Determined by GC-MS analysis of the bulk.



Scheme 2. Competitive cyclopropanation reactions performed using Styrene, α-Methylstyrene and 1,1-Diphenyl ethylene as substrates and **CuP2M** as catalyst.

[Cu=CHCOOEt] carbene intermediate. However, in the case of internal activated olefins, compounds **CuP3M** and **CuP2M** showed remarkably high selectivity towards the formation of *trans* isomers.

Experimental Section

General remarks

All reactions involving copper(I) species were carried out under purified nitrogen using standard Schlenk techniques. Solvents were dried and distilled according to standard procedures prior to use. NMR spectra were recorded with an AVANCE 400 Bruker spectrometer at 400 MHz for ^1H NMR, 100 MHz for $^{13}C\{^1H\}$ and 162 MHz for $^{31}P\{^1H\}$ NMR. Chemical shifts are given as δ values in ppm relative to residual solvent peaks as the internal reference (for ^1H and ^{13}C NMR) and to external H_3PO_4 (85 %) (for ^{31}P NMR). *J* values are given in Hz. Elemental analyses were obtained with a Perkin-Elmer CHN Analyzer 2400 Series II. Infrared Spectra (ATR) were acquired on a Thermo Scientific™ Nicolet™ iS20 FTIR Spectrometer with a 1 cm^{-1} resolution. Quantitative analyses of products in the catalytic runs were performed on a Finnigan Trace GC with a DB-5MS UI capillary column (30 m, 0.25 mm) equipped with a Finnigan Trace Mass Spectrometer. All chemicals were of reagent grade quality, were purchased commercially (Carlo Erba, TCI Chemicals, Fluorochem) and used as received.

Syntheses

Synthesis of [Cu(κ^2-O,O″-mand)$_2$] (CuM2)

In a 250 mL flask, $Cu(OH)_2$ (2.44 g, 25 mmol) was suspended in 60 mL of ethanol. To the suspension, DL-mandelic acid (9.51 g, 62.5 mmol) in 40 mL of ethanol was added. The resulting light blue suspension was stirred at room temperature for 3 days. After complete reaction of $Cu(OH)_2$, the suspension was filtered and the light blue solid was washed with ethanol (50 mL) and diethylether (50 mL). Yield: 8.69 g (95 %). IR (nujol, ν/cm^{-1}): 3064 br (OH), 1578 s. Anal. Calc. for $C_{16}H_{14}CuO_6$ requires: C, 52.53; H, 3.86. Found: C, 52.69; H, 3.97.

Synthesis of [Cu(PPh$_3$)$_3$(κ-O-mand)] (CuP3M)

In a two-necked 100 mL flask, 2.90 g (11.07 mmol) of PPh_3 were suspended in 30 mL of deoxygenated ethanol, and the suspension was heated at gentle reflux for 1 hour to ensure complete dissolution of PPh_3. Then, [Cu(κ^2-O,O″-mand)$_2$ (1.27 g, 3.47 mmol) was slowly added and the suspension was heated at reflux for 5 h. This led to the formation of a clear, colorless solution, which was evaporated to dryness. The white residue was suspended in deoxygenated diethylether (40 mL), and the solid was filtered, thoroughly washed with diethylether and dried in vacuo. **CuP3M** is highly stable in the solid state and can be stored under air for several weeks. Yield: 2.90 g (83 %). IR (nujol, ν/cm^{-1}): 3362 m (OH), 1626 s (COO). Anal. Calc. for $C_{62}H_{52}CuO_3P_3$ requires: C, 74.35; H, 5.23. Found: C, 74.29; H, 5.19. ^1H NMR (400 MHz, $CDCl_3$, 25 °C): $\delta = 4.37$ (d, $J_{H,H} = 4.5$ Hz, 1H, O*H*), 4.99 (d, $J_{H,H} = 4.5$ Hz, 1H, C*H*), 7.23-7.50 (m, 50H, ArH). $^{13}C\{^1H\}$ NMR (100 MHz, $CDCl_3$, 25 °C): 74.52 (*C*H), 126.75 (Ph), 126.77 (Ph), 128.01 (Ph), 128.57 (d, $J_{PC} = 8.0$ Hz, PPh_3-CH^{meta}), 129.50 (s, PPh_3-CH^{para}), 133.77 (d, $J_{PC} = 16.0$ Hz, PPh_3-CH^{ortho}), 133.86 (d, $J_{PC} = 18.8$ Hz, PPh_3-C^{ipso}), 142.28 (Ph), 177.87 (s, *C*OO). $^{31}P\{^1H\}$ NMR (162 MHz, $CDCl_3$, 25 °C): $\delta = -3.28$.

Synthesis of [Cu(PPh$_3$)$_2$(κ^2-O,O″-mand)] (CuP2M)

[Cu(PPh$_3$)$_3$(κ-O-mand)] (**CuP3M**) (2.0 g, 2.99 mmol) was suspended in isopropyl ether (20 mL), and the suspension was heated at gentle reflux for 2 h. Then the suspension was cooled to room temperature and decanted. The solvent was removed and replaced with fresh deoxygenated isopropyl ether (20 mL), and the suspension further heated at reflux for 2 h. The same procedure was repeated three times, after which the white solid was filtered, washed with isopropyl ether (10 mL) and dried in vacuo. Yield:

1.88 g (85 %). IR (nujol, ν/cm^{-1}): 3442 m (OH), 1593 s (COO). Anal. Calc. for $C_{44}H_{37}CuO_3P_2$ requires: C, 71.49; H, 5.04. Found: C, 71.34; H, 5.18. ^{1}H NMR (400 MHz, $CDCl_3$, 25 °C): δ = 4.37 (s, O*H*), 4.99 (s, C*H*), 7.22-7.50 (m, 35H, ArH). ^{13}C{^{1}H} NMR (100 MHz, $CDCl_3$, 25 °C): 74.45 (*C*H), 126.75 (Ph), 126.80 (Ph), 128.04 (Ph), 128.66 (d, J_{PC} = 8.1 Hz, PPh_3-CH^{meta}), 129.91 (s, PPh_3-CH^{para}), 133.74 (d, J_{PC} = 14.3 Hz, PPh_3-CH^{ortho}), 132.30 (d, J_{PC} = 31.6 Hz, PPh_3-C^{ipso}), 142.16 (Ph), 178.08 (s, *C*OO). ^{31}P{^{1}H} NMR (162 MHz, $CDCl_3$, 25 °C): δ = −2.34.

General procedure for olefin cyclopropanation reactions

In a standard experiment, to a solution of catalyst (0.015 mmol) and olefin (3.75 mmol) in dichloromethane (8 ml) at room temperature and under inert atmosphere, ethyl diazoacetate (EDA) (160 μL, 1.50 mmol) was added dropwise over a period of 30 minutes. The consumption of EDA was monitored by infrared spectroscopy ($\nu_{N\equiv N}$, 2109 cm^{-1}). After disappearance of EDA, yields and diastereoselectivity (*trans*:*cis* ratio) were determined by GC-MS analysis of the crude. In selected cases, products were isolated after removal of the solvent and purified by column chromatography (dichloromethane:hexane = 6 : 4). Their collected analytical data were in agreement to those reported in the literature.[29]

Computational details

All calculations were carried out at the density functional (DFT) level of theory with the ADF2021.102[38] program package employing the dispersion-corrected PBE functional PBE–D3.[39] C, H, O and P atoms were described through the TZ2P basis sets [triple-ζ Slater-type orbitals (STOs) plus two polarization functions]; the QZ4P basis set (quadruple-ζ STO plus four polarization functions) was used for the Cu atoms. Vibrational analysis was carried out in order to confirm stationary points and obtain thermodynamic data. Restricted formalism, no-frozen-core approximation (all-electron) and no-symmetry constrains were used in all calculations. Solvent effects were simulated employing the conductor-like continuum solvent model (COSMO)[40] as implemented in the ADF suite.

Single-crystal X-ray structure analysis

Crystals of **CuP2M** and **CuP2M-^{i}PrOH** were mounted on a Stoe Image Plate Diffraction system equipped with a ϕ circle goniometer, using Mo–Kα graphite monochromated radiation (λ = 0.71073 Å) with ϕ range 0–200°. The structure was solved by direct methods using the program SHELXS,[41] while refinement and all further calculations were carried out using SHELXL.[42] The H-atoms were included in calculated positions and treated as riding atoms using the SHELXL default parameters. The non-H atoms were refined anisotropically, using weighted full-matrix least-square on F^2. Crystallographic details are summarized in Table S1. Figure 2 was drawn with ORTEP–32.[43] Worthy of note, in compound **Cu2PM** the OH group is disordered over two equivalent positions, with 50 % occupancies, due to the racemic mixture of mandelate.

CCDC-2169011 (**CuP2 M**) and 2169012 (**CuP2 M-^{i}PrOH**) contain the supplementary crystallographic data for this paper. These data can be obtained free of charge via www.ccdc.cam.ac.uk/data request/cif, by e-mailing data request@ccdc.cam.ac.uk, or by contacting The Cambridge Crystallographic Data Centre, 12, Union Road, Cambridge CB2 1EZ, UK; fax: + 44 1223 336033.

Supporting Information Summary

infrared and ^{1}H, ^{13}C{^{1}H} and ^{31}P{^{1}H} NMR spectra of complexes **CuP3M** and **CuP2M**; crystallographic data for **CuP2M** and **CuP2M-^{i}PrOH**.

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Conflict of Interest

The authors declare no conflict of interest.

Data Availability Statement

The data that support the findings of this study are available from the corresponding author upon reasonable request.

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