

Reactivity of Copper Complexes with Bispiperidine and Bisquinoline Ligands

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Abstract: Copper complexes with the ligands bispiperidine (BP) or bisquinoline (BQ) were investigated. A dinuclear carbonato bridged copper(II) complex as well as a dinuclear copper(I) complex with BP as ligand were structurally characterized. The reaction of a copper(I) BP complex investigated by low temperature stopped-flow techniques showed the very fast formation of a bis- μ -oxido copper intermediate leading to an intramolecular ligand hydroxylation. However, substrates such as e. g. benzyl alcohol could be oxidized as well with this complex. In contrast, no intermediates could be spectroscopically observed when BQ or derivatives of this ligand were used. Instead complex reaction behaviour was observed when copper(II) chloride was reacted with BQ as a ligand in air or under inert conditions. Several crystal structures helped to establish a mechanism for these reactions. An interesting reaction product obtained that way was a new coordination polymer.

Introduction

Copper is a ubiquitous used element in nature and as trace element indispensable for bacteria, plants, animals and humans.^[1] Especially for the redox processing of molecular dioxygen, copper ions are used in the active sites of important biologically active metalloproteins^[2] (only a few examples are given in the references), such as hemocyanin,^[3] tyrosinase^[4,5,6] and methane monooxygenase.^[7–9] To fully understand the interactions of dioxygen with copper metalloproteins it is an important area of research to study the reactivity of copper(I) complexes with dioxygen under controlled conditions.^[6–8,10,11–17] The goal of utilization copper-dioxygen complexes as catalytical and selective oxidizing agents under ambient conditions is relevant for organic synthesis in lab scale as well as a large scale in industry.^[5,6,11–13,15-18]

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Different ligands have been applied to optimize these reactions by modifications of type and number of donor atoms, chelate ring sizes, sterically hindrance and electronic properties.^[12,16,17,19] In that regard, different bidentate ligand systems proved to be promising.^[16] Their copper-complexes can be useful for selective hydroxylation reactions.^[20] ^[21] In the past Schönecker et al. had demonstrated that attaching such a simple unit to a steroid system could be applied in synthetic chemistry of complex organic molecules.^[22] More recently this approach had been optimized by Baran and co-workers who could very efficiently make use of these compounds for selective C-H oxidation reactions.^[23] Stack and co-workers applied very simple diamine ligands that allowed to study binding of dioxygen in great detail.^[24–26] Modification of such ligands with guanidine groups allowed the selective oxidation of organic substrates.^[19]

Due to these successful applications, we thought it might be useful to apply a different set of bidentate ligands based on either a bispiperidine or a bisquinoline system (Scheme 1: a with n = 2 and b). These new ligands are close analogues of bisoxazolines (Scheme 1, c), well known C_2 -symmetric *N*-heterocyclic ligand systems. The latter were introduced by Masamune^[27] and optimized by Evans^[28] and now have proven very successful in asymmetric transformations.^[29]





We were interested in similar methylene-bridged five membered and six membered *N*-heterocycles as new ligands for transition metal catalysis and copper-dioxygen complexes, which were constructed by linking a CH_2 -unit with two aliphatic *N*-heterocycles such as piperidine. In comparison to the bisoxazoline-nitrogen the bispiperidine-nitrogen is a better donor, due to its hybridization. Thus, different complexation behavior of these ligands might be expected. Furthermore, by varying the substituents attached to the nitrogen, the electronic and steric properties of these ligands can be modified. In that regard, as an extension of the bispiperidine system, we furthermore became

interested in the sterically more demanding aromatic *C*-bridged bisquinoline system (Scheme 1). So far, these ligands have not been reported as ligands for copper complexes. However, a modified ligand based on the methylene-bridged bisquinoline core was used as ligand in a palladium(II) complex that could be applied for ethylene polymerization.^[30] Herein, we now report the reactivity of copper complexes with ligands of type a (n = 2) and b (Scheme 1).

Results and Discussion

Synthesis, characterization and reactivity of copper complexes with the ligand BP

Synthesis of the ligand (bis-2-piperidyl-)methane (= BP, Scheme 1: n = 2, $R^1 = R^2 = R^3 = H$ *rac* and *meso*) has been described elsewhere.^[31] BP was obtained and used as a bidentate ligand in both diastereomeric forms. However, in regard to the reactivity of the according copper complexes described below no difference in reaction behavior towards dioxygen was observed.

When reacting BP with copper(II) chloride in a stoichiometric ratio in methanol it was expected that $[Cu(BP)Cl_2]$ would form. From the reaction mixture (with BP_{meso}) a few crystals were obtained that could be structurally characterized. Due to the small number of crystals obtained no further characterization could be carried out. In contrast to our expectations it turned out that a binuclear complex with the two copper ions bridged by a carbonate anion had formed. The molecular structure of this complex is shown in Figure 1. Crystallographic data are reported in Table 1 and in supporting information.



Figure 1: Molecular structure of [Cu₂(BP_{meso})₂(CO₃)Cl₂] (1).

The bridging carbonate ligand in [Cu₂(BP_{meso})₂(CO₃)Cl₂] (1) is not an unusual feature and has been described previously e. g. by Sorrell and co-workers.^[32] The copper(II) complex with the ligand BP_{meso} obviously picked up carbon dioxide from air during the crystallization process. A little bit surprising is the fact that carbonate is coordinated instead of two more chloride ions. Chloride anions usually are good ligands in comparison with a carbonate anion. Both copper(II) ions are coordinated by five donor atoms. Interestingly the coordination geometry of the two copper(II) ions is different. According to the τ -parameter established by Addison^[33] ($\tau = 0$ represents an ideal square While the reaction of copper(II) chloride with BP_{meso} did lead to a complex in which the copper(II) cation was coordinated to both nitrogen atoms of one BP_{meso} ligand this was different for the reaction with copper(I) salts [Cu(CH₃CN)₄]^{*}. According to Scheme 2 a dinuclear copper(I) BP_{meso} complex formed in which two copper(I) ions are coordinated to a nitrogen donor atom of each ligand



Scheme 2: Reaction of $[Cu(CH_3CN)_4]OTf$ with BP_{meso} in THF at room temperature under inert conditions.

For the stoichiometric reaction with triflate as anion and the BP_{meso} ligand in THF crystals could be obtained (after many attempts) and the molecular structure of $[Cu(BP_{meso})]_2(OTf)_2$ (2) is shown in Figure 2.



Figure 2: Molecular structure of $[Cu(BP_{meso})]_2(OTf)_2$ (2). Triflate anions are not shown for clarity.

Obviously the BP_{meso} ligand did not act as a chelating ligand as expected to form $[Cu(BP)(CH_3CN)_X]OTf$ (with X = 1 or 2). Instead a more unusual linear copper(I) complex system crystallized where one piperidine ring system had flipped around of about 180° to avoid the *syn-pentane* interaction thus leading to the observed molecular structure.^[34] Unfortunately, for the copper complex with the *rac* configured BP ligand no crystals could be

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obtained under the same conditions. The BP_{rac} ligand should act most likely as a normal chelating ligand because in this configuration no *syn-pentane* interactions exist.

The reaction of $[Cu(BP)]_2(OTf)_2$ (meso and rac) with dioxygen has been investigated in THF using low temperature stopped-flow techniques. The complex was obtained in situ prior to the reaction by mixing the copper(I) salt solution (under argon) with the ligand solution (under dioxygen) in the syringes of the stopped-flow unit. When the reaction was performed an unstable reaction intermediate was detected spectroscopically (Figure 3).



Figure 3: Time resolved UV-Vis spectra of the low temperature stopped flow measurement of the reaction of $[Cu(BP)]_2OTf_2$ (c = $0.5 \cdot 10^{-4} \text{ mol/L}$) with dioxygen (c = $3.95 \cdot 10^{-3} \text{ mol/L}$) in THF at -80.0 °C (overall reaction time: 0.75 s). The inset shows the absorbance versus time trace at 394 nm.

This intermediate complex was not stable over time and decomposed quite fast especially at higher temperatures. As already mentioned above no difference was observed in reactivity if BP_{meso} or BP_{rac} were used as ligands.

Due to its instability the intermediate complex could not be isolated and structurally characterized. However, the spectral features, 390 nm and a second absorbance band close to 300 nm (limitation of the detector did not allow to measure UV data at lower wavelengths) clearly indicated that this intermediate was a bis- μ -oxido copper complex. The UV-vis data fit well with previous investigations on the formation of bis- μ -oxido copper complexes.^[13,19,20,35,36] This is surprising in so far that it would have been expected that a bis- μ -oxido unit would not be stable in the presence of amine hydrogen atoms. Usually amines used previously in these studies have been fully alkylated.^[19,24–26]

The fast formation reaction can be followed spectroscopically. An absorbance vs. time trace is shown as an inset in Figure 3. The data could be fitted with one exponential function leading to: k_{obs} = 34 s⁻¹. The rate law derives from the fact that in a first reaction

step the copper(I) complex reacts with dioxygen to form a mononuclear copper superoxido complex. The reaction can be described according to the following equation (L = BP):

$$[Cu(L)]^+ + O_2 \xrightarrow{k_1} [Cu(L)O_2]^+$$

Using excess of dioxygen (pseudo first order conditions) leads to the simplified rate law:

$$v = k_{obs} \times c([Cu(BP)]^{+})$$
 with $k_{obs} = k_1 \times [O_2]$

Concurrent reactions are much faster and thus do not allow observation of this intermediate. Therefore, only formation of the bis- μ -oxido complex can be observed. Most recently this has been supported for a related complex in a detailed computational study.^[35] In contrast to previous investigations on the formation of bis- μ -oxido complexes the reaction described here is much faster. Therefore, no detailed kinetic investigations could be performed.

Warming the solution did lead to a color change from a deep blue to a purple color and a purple colored solid could be obtained. Efforts to obtain crystals from a reaction were perchlorate as an anion (**2** with perchlorate instead of triflate) was used, failed. However, when the solid was recrystallized from hot methanol (a further color change to a green color was observed) crystals were obtained and the molecular structure of this complex is shown in Figure 4. Crystallographic data are reported in Table 1 and supporting information.



Figure 4: Molecular structure of $[Cu_2(BP_{rac})_2(OMe)_2]CIO_4)_2$ (3). Perchlorate anions are not shown for clarity.

From the molecular structure of $[(BP_{rac})Cu(OMe)_2Cu(BP)](CIO_4)_2$ (3) it is clear that now each copper(II) ion is again coordinated to one BP ligand with the two complex units bridged by two methoxy groups. While the copper(I) ions have been oxidized to copper(II) ions no effects on the ligand were observed. There is nothing unusual about this compound and more than a 100 crystal structures for copper complexes bridged by two methoxy groups are reported in the Cambridge Crystallographic Data Base (only a few examples for this complex type are given in the references).^[37–39] In principle these complexes are observed if no ligand hydroxylation takes place. Depending on the solvent

FULL PAPER

formation of bis- μ -hydroxido copper complexes can occur and has been observed previously. $^{[37,39]}$

In contrast when the same sample was recrystallized from cold methanol two sets of crystals were isolated that could be structurally characterized. One set was identified as the same complex 3, as obtained from hot methanol described above. However, additionally the molecular structure from crystals of the second set showed that ligand oxidation had occurred. The molecular structure of the dinuclear complex $[(OMeBP_{rac}O)_2Cu_2](ClO_4)_2 \quad (4)$ is presented in Figure 5. Crystallographic data are reported in Table 1 and supporting information.



Figure 5: Molecular structure of $[(OMeBP_{rac}O)_2Cu_2](CIO_4)_2$ (4). Anions are not shown for clarity.

It is obvious that a ligand hydroxylation of the ligand BP had occurred in the 5-position. Furthermore, in the final product each ligand contains an additional OMe group in the 6-position of the piperidine ring. From the overall results we suggest a reaction mechanism according to Scheme 3.

Because we did not observe a difference in reaction behavior using either BP_{meso} or BP_{rac} we think that the mononuclear copper complex [Cu(BP]⁺ is present in solution (Scheme 3; most likely with one or two acetonitrile molecules coordinated as additional ligands) and reacts with dioxygen to form a binuclear bis-u-oxido copper complex, [(BP)Cu(O)₂Cu(BP)]²⁺ (Scheme 3). No further intermediates prior to the formation of this complex could be detected. However, as discussed above, this is not surprising and has been described previously for a guanidine/amine copper system.^[35] The bis-µ-oxido copper complex then undergoes intramolecular ligand hydroxylation leading to the binuclear product (Scheme 3) in which the two copper ions are bridged through a hydroxide anion and the deprotonated alcohol group of the hydroxylated ligand. Due to the chemical oxidation reaction only one ligand molecule can be hydroxylated leading to a maximum yield of 50 %, well known for related systems.^[20,40] However, during recrystallization from methanol a rearrangement took place leading to the observation that the bis-methoxido bridged binuclear copper complex 3 (Scheme 3) could be isolated and structurally characterized.

The second product in Scheme 3 was not isolated. Instead some crystals of complex **4** were obtained and were structurally characterized (Figure 5). Obviously further oxidation took place leading to this complex. Reactions of this type are well known and have been described in general for different metal complexes by Constable.^[41] In more detail this has been reported previously for a related copper complex.^[42] A simplified mechanism for this reaction is presented in Scheme 4 (instead of the binuclear complex from Scheme 3 only half of the complex unit is used and without the OH group of the ligand coordinated). In the end this well-known mechanism explains why complex **4** was obtained as a final reaction product.



Scheme 3: Postulated mechanism for the reaction of copper(I) BP complexes with dioxygen and concurrent reactions.

Due to the finding that ligand hydroxylation was observed during the reaction of the copper(I) complex with the ligand BP it seemed to be interesting to furthermore test its potential for substrate oxidation reactions (Scheme 5 and Table 1). As shown by Stack and co-workers $^{\left[43\right] }$ a copper(I) complex with a derivative of an ethylene diamine ligand could be used together with dioxygen to oxidize different compounds such as e.g. 3,5-di-tert-butylcatechol to the respective quinone (>95 % yield). Furthermore, good yields were achieved when benzyl alcohol was oxidized to benzaldehyde (80 %) and benzylamine to benzonitrile (70 %). Karlin and co-workers^[44] demonstrated that a copper(I) complex with a tetradentate anisole containing polypyridylamine ligand could be applied for the oxidation of toluene to benzaldehyde in about 40 % yield with respect to the toluene. The oxidation of toluene to benzaldehyde is a four-electron process. But since the oxidizing agent, the bis-µ-oxido copper complex, only provides

FULL PAPER

two electrons, the yield was about 80 % with respect to the oxidizing agent.



Scheme 4: Mechanism of the formation of the methoxylated hemiaminalether **4** (Figure 5).

To test for the reactivity of the copper BP complex system the corresponding copper(I) triflate complex was prepared in situ in a glove box. A stoichiometric amount of different substrates according to Scheme 5 was added. The reaction mixture was then transferred out of the glovebox, cooled to -80 °C and subsequently O₂ was bubbled through the solution for 10 minutes. For comparison with previous work yield were referred to the copper complex neglecting possible oxidation by excess oxygen. The results of the oxidation experiments showed that no reaction was observed when catechol or toluene were used as substrates. In the case of 3,5-di-tert-butylcatechol a moderate yield of 49 % of 3,5-di-tert-butyl-1,2-quinone determined via GC-MS was obtained. Benzaldehyde was formed in 41 % yield when benzyl alcohol was used as a substrate. Most likely some benzaldehyde was further oxidized but could not be detected with GC-MS so that the total conversion cannot be specified. The effect of double oxidation of the substrate was observed when cyclohexene was used as substrate. Two oxidized compounds could be detected and analyzed as cyclohex-2-ene-1-ol (16 %) and cyclohex-2-ene-1-one (31 %). The observed allyl alcohol can be regarded as an intermediate that had been further oxidized to the corresponding unsaturated ketone. For this oxidation process again four electrons are needed. The $[Cu_2(BP)_2(O)_2]^{2+}$ complex provides two electrons for oxidation reactions. Therefore, two equivalents of the oxidizing agent are needed for the reaction of cyclohexene to the corresponding ketone. In summary the total conversion of the oxidizing agent was 78 % for cyclohexene as the substrate. The same electron counting is valid for the oxidation of benzylamine to benzonitrile Here the best conversion could be observed with 84 % with respect to the $[Cu_2(BP)_2(O)_2]^{2+}$ complex.



Scheme 5: Application of the $[Cu_2(BP)_2(O)_2]^{2+}$ complex as oxidizing agent in oxidizing experiments with various substrates.

Table 1: Results of the application of the $[Cu_2(BP)_2(O)_2]^{2+}$ complex in oxidizing experiments with various substrates.

| substrate | product | Yield ^[a] |
|------------------------|----------------------------|----------------------|
| Benzylalcohol | Benzaldehyde | 41 % |
| Benzylamine | Benzonitrile | 84 % |
| Cyclohexene | Cyclohex-2-ene-1-ol | 16 % |
| | Cyclohex-2-ene-1-one | 31 % |
| Catechol | o-Quinone | 0 % |
| 3,5-Di-t-butylcatechol | 3,5-Di-t-butyl-1,2-quinone | 49 % |
| Toluene | Benzylalcohol | 0 % |
| [a] based on GC-MS | | |

Synthesis, characterization and reactivity of copper complexes with the bisquinoline ligand and derivatives.

In our attempts to obtain a copper(II) complex with a bisquinoline ligand (BQ, b with $R^1 = R^2 = H$ in Scheme 1) CuCl₂ x H₂O was

FULL PAPER

reacted with BQ in a 1:1 ratio in methanol. During this reaction, the color of the solution changed to a deep red color and after 60 minutes another color change to a green color was observed. We assume that at the beginning of this reaction the copper(II) complex [Cu(BQ)Cl₂] (5) had formed (this assumption is supported by the molecular structure for [Cu(DMBQ)Cl₂] described below, Figure 12). However, no copper complex could be crystallized from this solution. Instead, after decomplexation of the copper ions with aqueous ammonia and extraction with dichloromethane, crystals could be obtained after addition of pentane. The molecular structure of one of these crystals is shown in Figure 6. Crystallographic data are reported in Table 1 and supporting information.



Figure 6: Molecular structure of bisquinolineketone.

The molecular structure clearly showed that the ligand BQ was oxidized at the bridging carbon to the according ketone (Scheme 6). At this carbon, a slight torsion could be observed leading to π stacking.



Scheme 6: Oxidation of BQ to the according bisquinoline ketone during complexation with $CuCl_2$ in methanol or dichloromethane and the presence of dioxygen from air.

This type of oxidation is a well-known reaction, quite typical for copper and iron complexes.^[41] It was reported previously for example by Sprecher and Zuberbühler (who worked with bis(1methyl-benzimidazol-2-yl)methane)^[45] or by Forlani et al.^[46]. A proposed mechanism for this reaction leading to a copper(II) complex (7) that could not be characterized either (and therefore product was demetalated to lead to the isolated bisquinolineketone) is presented in Scheme 7. In a first step the enamine formed from 5 can be deprotonated leading to two resonance structures that finally end up with a copper(I) ligand radical complex (6). Reactions of this type again are well known and have been described in general previously.^[41] Oxidation with dioxygen from air leads to copper(II) complex 7 and decomplexation finally to the crystallized bisquinoline ketone shown in Figure 6.

When the reaction was repeated under inert conditions, a few red crystals could be obtained that were structurally characterized. The molecular structure of this complex (9) is shown in Figure 7 and revealed that a binuclear copper complex had formed. Crystallographic data are reported in Table 1 and supporting information.



Scheme 7: Postulated mechanism for the oxidation of the bisquinoline ligand.

From the molecular structure, it is evident that this is not a Cu(II) complex anymore but instead a binuclear Cu(I) complex, bridged by two chloride ions, had formed. The geometry around the two copper(I) ions can be best described as a distorted tetrahedron. Furthermore, a hydroxyl function on the bridged carbon of each ligand can be observed (Figure 7a) In this redox reaction, Cu(II) was apparently reduced to Cu(I) and the bridging carbon atom was hydroxylated. However, the crystal structure analysis revealed that only 23% of the bridged carbon are substituted in this way. 37% are substituted with a chlorine atom (Figure 7b) and 40% do not show substitution at all. The hydroxy group is believed to originate from the water of the CuCl₂ x H₂O salt used (see proposed mechanism in Scheme 9.

After the hydroxylation reaction in the glove box the solution was transferred into air leading to a further reaction a second oxidation step takes place with the aid of oxygen from the air to form the bisquinoline ketone. When the previously obtained, red crystals were exposed to dioxygen, green crystalline leaflets were isolated and examined by X-ray crystallography, the molecular structure of this complex (**10**) is shown in Figure 8. Crystallographic data are reported in Table 1 and supporting information.

FULL PAPER



Figure 7: Molecular structure of the binuclear complexes formed under inert conditions a) $[Cu_2(BQOH)_2Cl_2]$ (9) and b) $[Cu_2(BQCI)_2Cl_2]$.



Figure 8: Molecular structure of the mononuclear copper(II) dichlorido methoxy bis chino-2-yl methanol complex (10) (solvent molecules omitted).

The molecular structure shows that the dinuclear Cu(I) complex (9) had been oxidized further to a mononuclear Cu(II) complex by atmospheric dioxygen. A further oxidation to the hemiacetal took place at the bridged carbon atom by introduction of a methoxy group. The methoxy group coordinates additionally to the Cu(II) ion whereby the Cu(II) is coordinated fivefold in a nearly quadratic pyramidal geometry.

In contrast if the reaction was carried out under inert gas conditions with anhydrous CuCl₂, no hydroxylation reaction was observed. However, still the bridging carbon atom was chemically activated during complexation of the ligand BQ with a copper(II)

ion to such an extent that it subsequently reacted with a second BQ ligand at the carbon bridge leading to an oxidative C-C coupling with the formation of a double bond. In addition to the oxidative coupling of the two ligands, the reduction of Cu(II) to Cu(I) was observed again. The oxidative coupled di-BQ ligand coordinates to one Cu(I) ion with each side. The copper ions are bridged by two chloride ions on the one side and the oxidative coupled di-BQ ligand on the other side thus forming a coordination polymer. Crystals could be obtained of this compound (11) and its molecular structure is presented in Figure 9. Crystallographic data are reported in Table 1 and supporting information.



Figure 9: Molecular structure of the linear chain of the coordination polymer $[Cu_2(di-BQ)Cl_2]_x$ (11) with the oxidative coupled bisquinoline as ligand (solvent molecules omitted).

One of the units with the bridging chloride anions is shown in scheme 8.



Scheme 8: Detail of the molecular structure of the $[Cu_2(di-BQ)Cl_2]_x$ complex (11) with focus on the oxidative coupled bisquinoline ligand.

From the overall findings a mechanism for this reaction can be proposed according to scheme 9. When no dioxygen is present one copper(II) unit still present in solution can further oxidise radical copper(I) complex **6** to complex **8** with a formal positive charge at the bridging carbon atom (alternatively, oxidation of the carbon radical by copper(II) chloride to the alkyl chloride is a possible side reaction leading to $[Cu_2(BQCI)_2Cl_2]$ shown in Figure 7b). Reaction with water then causes formation of the dimeric complex **9** that had been crystallized (Figure 7a). If this complex then is reacting with air in the presence of methanol the same oxidation steps occur as described above, finally leading to the hemiacetal complex **9** that again could be characterized structurally (Figure 8). If neither water and dioxygen are present

it is easy to imagine how complex **8** can react further leading to the observed copper(I) polymer **11** (Figure 9).



Scheme 9: Proposed mechanism for oxidation reactions.

While we have been fortunate with "crystal picking" to establish a reasonable mechanism for the complex reaction system we tried to get more insight into these reactions by studying the reaction of the copper(I) BQ complex with dioxygen using low temperature stopped-flow techniques. For that purpose and to compare the reaction with the copper BP complex described above we reacted dioxygen with the copper(I) complex prepared in situ by mixing stoichiometric amounts of BQ with [Cu(CH₃CN)₄]OTf in anhydrous THF solution under inert conditions. Time resolved UV-Vis spectra for this reaction are shown in supporting information. In contrast to our findings described above for the copper complex with BP as ligand we did not observe a bis-µoxido copper complex or any other reaction intermediate. The absorbance changes are a consequence of the oxidation of copper(I) to copper(II) and the formation of the bisquinoline ketone. After warming of the solution to room temperature the bisquinoline ketone as oxidized product could be detected by GC-MS.

Due to the fact that the bridging carbon atom in the BQ ligand obviously is very sensitive to oxidation it did not seem promising to use this ligand further in an effort to observe intermediate copper "dioxygen adduct" complexes. Therefore, in a first attempt to reduce the reactivity the carbon atom in BQ the fully methylated ligand DMBQ was synthesized (Scheme 10). This ligand could be obtained in a good yield and crystallographic data are reported in Table 1 and the molecular structure is reported in supporting information. Furthermore, it was possible to obtain a few crystals of the corresponding copper(II) complex [Cu(DMBQ)Cl₂]·1/4H₂O (12) and its molecular structure is presented in Figure 10. Crystallographic data are reported in Table 1 and supporting information. As described above the characterization of this complex supports formation of analogous copper(II) complex 5 prior to further reaction. Due to the missing hydrogen atom at the bridgehead carbon (so no deprotonation according to Scheme 7 can occur) this compound is stable towards oxidation reaction and therefore additionally supports the proposed mechanism presented in Scheme 7.

1. n-BuLi, -78 °C

3. *n*-BuLi, -78 °C 4. CH₃I, -78 °C → r.t.,

67 %

2. CH₃I, -78 °C \rightarrow r.t.

1. n-BuLi, THF, -78 °C

2. benzylbromide, THF -78 °C \rightarrow r.t., 87 %

cat. HCl, µw, 215 °C,

10 min, 52 %

Br

Br

Br

DMBQ

BnBQ

PyBQ

PicBQ



1. n-BuLi, THF, -78 °C

2. picolylbromide, THF,

-78 °C → r.t., 64 %

BQ

The copper(I) complex of the ligand DMBQ was subsequently prepared *in situ* by reaction of DMBQ with [Cu(CH₃CN)₄]OTf in anhydrous THF under inert conditions as well. The reaction of this complex solution with dioxygen was investigated in THF using low temperature stopped-flow techniques. No intermediates could be spectroscopically detected and only a slow oxidation reaction to a copper(II) complex was observed. Therefore, no further investigations were performed with this complex system.

With the introduction of a benzyl group at the bridged carbon of the BQ ligand the bidentate benzyl-BQ ligand (BnBQ, Scheme 10) was synthesized in an excellent yield. Unfortunately, for this system again no intermediate complex could be spectroscopically detected when the copper(I) complex of this ligand was reacted in situ with dioxygen. However, more interesting reactions were observed when $CuCl_2 \times H_2O$ was reacted with the BnBQ ligand in a dichloromethane/methanol mixture at room temperature. This reaction did lead to a green colored solution and green colored crystals could be isolated for structural characterization. The molecular structure of this complex (13) is shown in Figure 11. Crystallographic data are reported in Table 1 and supporting information.



Figure 10: Molecular structure of the [Cu(DMBQ)Cl₂] (12) complex.



hydroxylated at the bridging carbon atom had formed. The

reaction obviously follows the same pathway as described above

for the copper complexes with BQ as ligand in Scheme 9 and is

Scheme 11: Proposed mechanism of the oxidation of the BnBQ ligand.

Interestingly, when CuCl₂ x H_2O was added without methanol to a solution of BnBQ in dichloromethane a second set of green crystals could be isolated after a slightly longer reaction and cooling time. The molecular structure of this crystallized [Cu₂(BnBQ-O)₂Cl₂] compound (**13b**) is shown in Figure 12. Crystallographic data are reported in Table 1 and supporting information. Again, a dinuclear complex had formed. The newly introduced deprotonated alkoxy groups bridge both copper(II) ions, which are thus coordinated together with one chloride ion in a trigonal-bipyramidal geometry.

Clearly substitution of the bridging carbon atom with only one substituent does not reduce the oxidation sensitivity of this

Bn 13b



Figure 11: Molecular structure of the $[Cu_2(BnBQ-O)(CH_3OH)Cl_3]$ complex (13a) as reaction product of BnBQ in dichloromethane with $CuCl_2 \times H_2O$ dissolved in CH_3OH (co-crystallized solvent omitted).

The molecular structure shows that a dinuclear Cu(II) complex $[Cu_2(BnBQ-O)(CH_3OH)Cl_3]$ (13a) with a BnBQ ligand

FULL PAPER

position. Therefore, it is not surprising that no copper-dioxygen adduct species could be detected under controlled conditions even at low temperatures. For clarification a simplified picture of the hydroxylation reaction of the ligand BnBQ is shown in Scheme 11.



Figure 12: Molecular structure of the $[Cu_2(BnBQ-O)_2Cl_2]$ complex (13b) as reaction product of BnBQ with $CuCl_2\ x\ H_2O$ in dichloromethane.

Efforts to change the reactivity of the BQ ligands by introducing a third donor group thus leading to the tripodal ligands PyBQ and PicBQ (Scheme 10) were not really successful. While it was possible to prepare both ligands no crystals of either copper(I) or copper(II) complexes for structural characterization could be obtained. Furthermore, low temperature stopped flow investigations of the copper(I) complexes with these ligands prepared in situ showed no reactive intermediates that could be spectroscopically detected.

FULL PAPER

| Table 2. Crystallographic data from the X-ray diffraction studies | | | | | | | |
|---|---|--|--|--|---|---|--|
| | 1 | 2 | 3 | 4 | BQ-ketone | 9 | |
| Empirical Formula | $C_{23}H_{44}Cl_2Cu_2N_4O_3$ | $C_{12}H_{22}F_3N_2CuSO_3$ | $C_{12}H_{25}N_2O_5CICu$ | C ₁₂ H ₂₃ N ₂ O ₆ ClCu | C ₁₉ H ₁₂ N ₂ O | $\begin{array}{c} C_{38}H_{27,28}Cl_{2,72}N_4O_{0.53}\\ Cu_2 \end{array}$ | |
| M _r | 622.60 | 394.91 | 376.33 | 390.31 | 284.31 | 771.94 | |
| Temperature [K] | 223(2) | 190(2) | 190(2) | 190(2) | 223(2) | 193(2) | |
| Radiation used (λ [Å]) | Μο-Κ _α (0.71073) | Μο-Κ _α (0.71073) | Mo-K _α (0.71073) | Mo-K _α (0.71073) | Mo-K _α (0.71073) | Mo-K _α (0.71073) | |
| | | | | | | | |
| Crystal size [mm] | 0.30.0.20.0.10 | 0.30.0.10.0.07 | 0.15.0.12.0.08 | 0.75.0.40.0.20 | 0.35.0.25.0.15 | 0.40.0.24.0.08 | |
| Crystal system | triclinic | triclinic | monoclinic | monoclinic | orthorhombic | monoclinic | |
| Space group | ΡĪ | ΡĪ | P21/c | P2 ₁ /n | Pbca | P21/n | |
| a [Å] | 10.6637(3) | 9.0400(18) | 11.153(2) | 9.4490(19) | 21.5383(4) | 9.815(2) | |
| b [Å] | 11.4106(4) | 9.960(2) | 10.221(2) | 10.167(2) | 8.3878(2) | 9.952(2) | |
| c [Å] | 12.5781(4) | 10.040(2) | 14.974(3) | 16.178(3) | 31.0331(7) | 16.772(3) | |
| α [°] | 65.038(1) | 88.66(3) | 90 | 90 | 90 | 90 | |
| β [°] | 81.040(2) | 76.82(3) | 109.21(3) | 92.08(3) | 90 | 104.09(3) | |
| γ [°] | 85.034(1) | 67.78(3) | 90 | 90 | 90 | 90 | |
| V [Å ³] | 1370.22(8) | 812.8(3) | 1611.9(6) | 1553.2(5) | 5606.4(2) | 1589.0(6) | |
| z | 2 | 2 | 4 | 4 | 16 | 2 | |
| <i>F</i> (000) | 652 | 408 | 788 | 812 | 2368 | 784 | |
| ρ _{calcd.} [g⋅cm ⁻³] | 1.509 | 1.614 | 1.511 | 1.669 | 1.347 | 1.613 | |
| μ [mm ⁻¹] | 1.778 | 1.515 | 1.542 | 1.608 | 0.675 | 1.606 | |
| Total reflections | 14420 | 14603 | 12100 | 15831 | 35425 | 13683 | |
| Unique reflections | 4802 | 3573 | 2952 | 3402 | 4979 | 3833 | |
| R(int) | 0.035 | 0.03111 | 0.0832 | 0.0346 | 0.041 | 0.0842 | |
| Scan range θ [°] | 1.80 to 25.00 | 2.505 to 27.104 | 2.459 to 25.350 | 2.366 to 27.102 | 4.10 to 67.88 | 2.961 to 28.173 | |
| Completeness to θ_{max} [%] | 99.5 | 99.8 | 99.8 | 99.4 | 97.9 | 99.6 | |
| Index ranges | 0 ≤ <i>h</i> ≤ 12 -13 ≤ <i>k</i> ≤ 13 -14 ≤ <i>l</i> ≤ 14 | -11 ≤ h ≤ 11 -12 ≤ k ≤ 12 -12 ≤ l ≤ 12 | -13 ≤ h ≤ 12 -11 ≤ k ≤ 12 -17 ≤ l ≤ 18 | -12 ≤ h ≤ 8 -13 ≤ k ≤ 12 -19 ≤ l ≤ 20 | 0 ≤ <i>h</i> ≤ 25 0 ≤ <i>k</i> ≤ 9 -37 ≤ <i>l</i> ≤ 0 | -12 ≤ h ≤ 11 -13 ≤ k ≤ 13 -22 ≤ l ≤ 22 | |
| Data/restraints/parameters | 4802/0/323 | 3573/2/205 | 2952/2/197 | 3402/294/252 | 4979/0/397 | 3833/2/224 | |
| $R1^{[a][b]}_{,} wR2 \left[I > 4\sigma(I) \right]^{[c]}_{,}$ | 0.0276, 0.0664 | 0.0293, 0.0699 | 0.0576, 0.1118 | 0.0299, 0.0764 | 0.0405, 0.1005 | 0.0480, 0.1059 | |
| $R1^{[a][d]}_{,} wR2$ (all data) ^{[c][d]} | 0.0333, 0.0696 | 0.0369, 0.0726 | 0.1046, 0.1274 | 0.0355, 0.0795 | 0.0479, 0.1060 | 0.0889, 0.1215 | |
| Goodness-of-fit on F ^{2 [e]} | 1.035 | 1.040 | 1.050 | 1.064 | 1.007 | 0.911 | |
| Max./min. el. dens. [e.Å ⁻³] | 0.312, -0.362 | 0.289, -0.558 | 0.467, -0.346 | 0.319, -0.481 | 0.136, -0.173 | 0.620, -0.621 | |

^[a] $R1 = \sum ||F_o| - |F_c|| / \sum |F_o|$. ^[b] Denotes the value of the residual considering only the reflections with $l > 4\sigma(l)$. ^[c] $wR2 = \{\sum [w(F_o^2 - F_c^2)^2] / \sum [(F_o^2)^2]^{1/2}; w = 1/[\sigma^2(F_o^2) + (aP)^2 + bP], P = [max(F_o^2 or 0) + 2(F_c^2)]/3$. ^[d] Denotes the value of the residual considering all the reflections. ^[e] $S = [\sum w(F_o^2 - F_c^2)^2] / [(n - p)^{1/2}], n$: number of data, p: parameters used.

FULL PAPER

 Table 3. Crystallographic data from the X-ray diffraction studies, continued

| | 10 | 11 | DMBQ | 12 | 13a | 13b |
|--|---|---|---|---|---|--|
| Empirical Formula | $C_{22}H_{24}Cl_2N_2O_4Cu$ | $C_{40.8}H_{26.8}O_{0.7}Cl_2N_4Cu_2$ | $C_{21}H_{18}N_2$ | $C_{84}H_{74}Cl_8N_8Cu_4O$ | $C_{55}H_{48}Cl_8N_4O_4Cu_4$ | C ₂₆ H ₁₉ CIN ₂ CuO |
| M _r | 514.87 | 782.24 | 298.37 | 1749.27 | 1366.73 | 474.42 |
| Temperature [K] | 223(2) | 193(2) | 190(2) | 190(2) | 190(2) | 190(2) |
| Radiation used (λ [Å]) | Mo-K _α (0.71073) | Mo-K _α (0.71073) | Mo-K _α (0.71073) | Mo-K _α (0.71073) | Μο-Κ _α (0.71073) | Mo-K _α (0.71073) |
| | | | | | | |
| Crystal size [mm] | 0.25.0.25.0.06 | 0.20.0.10.0.05 | 0.56.0.08.0.07 | 0.36.0.33.0.20 | 0.46.0.30.0.26 | 0.30.0.10.0.08 |
| Crystal system | monoclinic | triclinic | monoclinic | orthorhombic | triclinic | trigonal |
| Space group | P2 ₁ /n | ΡĪ | P2 ₁ | Pnma | ΡĪ | R3 |
| a [Å] | 14.9211(3) | 10.981(2) | 9.4845(19) | 10.344(2) | 8.8410(18) | 32.209(11) |
| b [Å] | 9.5702(2) | 12.106(2) | 6.2235(12) | 17.330(4) | 9.0220(18) | 32.209(11) |
| c [Å] | 16.1093(3) | 14.495(3) | 13.661(3) | 10.517(2) | 18.470(4) | 13.231(3) |
| α [°] | 90 | 81.29(3) | 90 | 90 | 78.62(3) | 90 |
| β [°] | 98.1740(10) | 86.48(3) | 96.72(3) | 90 | 85.06(3) | 90 |
| γ [°] | 90 | 63.53(3) | 90 | 90 | 83.39(3) | 120 |
| V [Å ³] | 2277.00(8) | 1705.0(7) | 800.8(3) | 1885.3(7) | 1431.6(5) | 11887(9) |
| Z | 4 | 2 | 2 | 1 | 1 | 18 |
| F(000) | 1060 | 794 | 316 | 894 | 690 | 4374 |
| ρ _{calcd.} [g⋅cm ⁻³] | 1.502 | 1.524 | 1.237 | 1.541 | 1.585 | 1.193 |
| μ [mm ⁻¹] | 1.225 | 1.443 | 0.073 | 1.450 | 1.887 | 0.945 |
| Total reflections | 13855 | 15617 | 8153 | 14153 | 24291 | 18826 |
| Unique reflections | 4004 | 7640 | 2839 | 2830 | 7084 | 2966 |
| R(int) | 0.0606 | 0.0933 | 0.0367 | 0.0317 | 0.0320 | 0.1653 |
| Scan range θ [°] | 1.74 to 25.00 | 2.521 to 28.154 | 2.773 to 25.682 | 2.265 to 30.015 | 2.254 to 28.327 | 2.470 to 21.334 |
| Completeness to θ_{max} [%] | 99.9 | 93.6 | 99.4 | 99.8 | 99.7 | 99.6 |
| Index ranges | -12 ≤ <i>h</i> ≤ 17 -11 ≤ <i>k</i> ≤ 10 -17 ≤ <i>l</i> ≤ 19 | -14 ≤ <i>h</i> ≤ 14 -15 ≤ <i>k</i> ≤ 15 -19 ≤ <i>l</i> ≤ 19 | -11 ≤ <i>h</i> ≤ 11 -7 ≤ <i>k</i> ≤ 7 -16 ≤ <i>l</i> ≤ 16 | -14 ≤ <i>h</i> ≤ 13 -24 ≤ <i>k</i> ≤ 19 -13 ≤ <i>l</i> ≤ 14 | -11 ≤ <i>h</i> ≤ 11 -12 ≤ <i>k</i> ≤ 11 -24 ≤ <i>l</i> ≤ 24 | -32 ≤ h ≤ 31 -32 ≤ k ≤ 32 -13 ≤ l ≤ 13 |
| Data/restraints/parameters | 4004/0/286 | 7640/804/461 | 2839/1/210 | 2830/2/133 | 7084/0/359 | 2966/0/280 |
| $R1^{[a][b]}, wR2 [l > 4\sigma(l)]^{[c]}$ | 0.0407, 0.0986 | 0.0565, 0.1161 | 0.0419, 0.0893 | 0.0282, 0.0723 | 0.0414, 0.1251 | 0.0663, 0.1208 |
| R1, ^{[a][d]} wR2 (all data) ^{[c][d]} | 0.0524, 0.1050 | 0.1434, 0.1436 | 0.0583, 0.0957 | 0.0348, 0.0759 | 0.0480, 0.1311 | 0.0922, 0.1282 |
| Goodness-of-fit on F ^{2 [e]} | 1.045 | 0.809 | 1.053 | 1.052 | 1.065 | 1.130 |
| Max./min. el. dens. [e.Å-3] | 0.727, -0.710 | 0.918, -0.998 | 0.130, -0.170 | 0.410, -0.514 | 1.942, -0.839 | 0.412, -0.388 |

^[a] $R1 = \sum ||F_c| - |F_c|| / \sum |F_o|$. ^[b] Denotes the value of the residual considering only the reflections with $l > 4\sigma(l)$. ^[c] $wR2 = \{\sum |w(F_o^2 - F_c^2)^2| / \sum |F_o^2|^2 + (aP)^2 + bP\}, P = [max(F_o^2 \text{ or } 0) + 2(F_c^2)]/3$. ^[d] Denotes the value of the residual considering all the reflections. ^[e] $S = [\sum w(F_o^2 - F_c^2)^2] / [(n - p)^{1/2}], n$: number of data, p: parameters used.

Conclusions

The investigations herein showed that the copper complex with bispiperidine (BP) is capable not only of intramolecular ligand hydroxylation but also of oxidation of substrates e.g. benzylalcohol to benzaldehyde. These results are promising, however, further work on that ligand system is necessary because for practical use it still needs to be optimized. In contrast copper complexes with the sterically more demanding ligand BQ do not seem to be useful for substrate oxidation reactions. The reaction behavior of the copper complexes with this ligand had turned out quite complicated and without the crystal structures obtained it would have been difficult to gain a good understanding of the reaction mechanisms. These reactions show again how easily copper chloride can affect organic molecules (in a quite colorful way)^[47] and how a large number of different reactions can be thus triggered. Most interestingly in that regard was a coordination polymer that formed, however here again only a few crystals were obtained and it could not be prepared yet on a real synthetic scale.

Experimental Section

General: All reagents and solvents were purchased from commercial sources. The solvents were purified by distillation and dried by standard procedures or used from the solvent purification system SPS-800 by MBraun (Garching, Germany). Synthesis of the bispiperidine (BP) and bisquinoline (BQ) ligands will be published elsewhere.^[31] Preparations under anaerobic conditions were carried out in Schlenk tubes using dry nitrogen or in a glovebox by MBraun under an argon atmosphere. ¹H and ¹³C NMR spectra were recorded on a Bruker Avance II 200 spectrometer (¹H at 200 MHz; ¹³C at 50 MHz), Bruker Avance II 400 spectrometer (¹H at 400 MHz; ¹³C at 100 MHz) and Bruker Avance III HD 400 spectrometer $(^{1}H at 400 MHz; ^{13}C at 100 MHz)$ in CDCI₃ using TMS as internal standard. The ¹H- and ¹³C- NMR spectra were calibrated against the residual proton and carbon signals of chloroform at δ =7.26 ppm and δ =77.16 ppm. Mass spectra were measured with a MAT 95 sector field mass spectrometer (Thermo Finnigan MAT GmbH, Bremen GER) with electron impact ionization (EI) and with a MicroTOF mass spectrometer (Bruker Daltonics, Bremen GER) with electro spray ionization (ESI). Calibration was done with NaHCOO clusters before measurement. Reactions carried out in a microwave reactor an apparatus from CEM GmbH (Kamp-Lintford, GER) was used in an open system with reflux condenser. Elemental analysis was weighted with a UMX-2 (Mettler-Toledo, Giessen GER) and analyzed with a Carlo Erba 1106 CHN.

Stopped-Flow Measurements: Solutions of copper(I) complexes for stopped-flow measurements were prepared in glass syringes under argon in a glove box. Saturated solutions of dioxygen were prepared by bubbling dry dioxygen (grade 5.5, Messer Griesheim, Germany) through the solvent in a syringe for about 10 min. Dioxygen concentration in a saturated thf solution has been reported to be 7.9×10^{-3} mol/L at $25 \, ^{\circ}\text{C}$.^[46] Stopped-flow analysis was performed at a temperature of -80 $\,^{\circ}\text{C} \pm 1 \,^{\circ}\text{C}$. All measurements were repeated about 5 times at each concentration and temperature and gave consistent results. Data were obtained using a Hi-Tech SF-61SX2 low-temperature stopped-flow unit equipped with a diode array spectrophotometer (Hi-Tech, Salisbury, UK; now TgK Scientific, Bradford-on-Avon, UK). Data were analyzed either using the integrated software Kinetic Studio (TgK Scientific) or Igor Pro (Wavemetrics, Lake

Oswego, USA). Details on the setup and kinetic measurements have been described previously. $^{\left[14,49\right] }$

X-ray crystallography: Details on X-ray crystallography are reported in Supporting Information. CCDC-1557630 (1), CCDC-1557629 (2), CCDC-1557630 (3), CCDC-1557640 (4), CCDC-1557632 (BQ-Ketone), CCDC-1557634 (9), CCDC-1557631 (10), CCDC-1557635 (11), CCDC-1557628 (DMBQ), CCDC-1557636 (12), CCDC-1557637 (13a) and CCDC-1557638 (13b) contain the supplementary crystallographic data for this paper. These data can be obtained, free of charge from the Cambridge Crystallographic Data Centre via www.ccdc.cam.ac.uk/data_request/cif.

Methanonbis(2-quinoline): Bisquinoline (0.4 g, 1.5 mmol) was dissolved in 50 mL of methanol under ambient conditions. While stirring CuCl₂ x H₂O (0.4 g, 3 mmol) was added to the orange solution. After addition of the copper salt the solution obtained a red color and after 1 – 2 h of stirring it turned to a green color. This solution was diluted with 50 mL of water and shake out with aqueous ammonia solution. The solution was extracted with dichloromethane (50 mL), dried with Na₂SO₄ and evaporated. The product (0.34 g, 1.2 mmol, 81 %) was obtained as yellow solid after flash chromatography (pentane/TBME, 1:1 (v/v)). ¹H-NMR (400 MHz, CDCl₃): δ (ppm) = 8.36 (d, ³J = 8.4 Hz, 2H), 8.24 (d, ³J = 8.5 Hz, 2H), 8.19 (d, ³J = 8.5 Hz, 2H), 7.92 (d, ³J = 8.0 Hz, 2H), 7.77 (t, ³J = 8.4 Hz, 2H), 7.65 (t, ³J = 8.1 Hz, 2H). ¹³C-NMR (100 MHz, CDCl₃): δ (ppm) = 193.8, 154.5, 147.6, 136.7, 130.9, 130.2, 129.2, 128.6, 127.8, 121.6. HRMS (EI): calcd. for C₁₉H₁₂N₂O: 284.0950; found: 284.0954. Anal. calcd. for C₁₉H₁₂N₂O: C, 80.27; H, 4.25; N, 9.85; found: C, 79.29; H, 4.29; N, 9.54.

Propane-2,2'-bis(-2-quinoline) (DMBQ): Under inert gas conditions bisquinoline (0.3 g, 1.1 mmol) was dissolved in 10 mL anhydrous THF and cooled to -78 °C were n-BuLi (0.7 mL, 1.2 mmol, 1.6 M in hexane) was dropped to the solution and stirred for 30 min at this temperature. The reaction mixture was allowed to warm to -10 °C for a few minutes and cooled back to -78 °C. Subsequent iodomethane (189 mg, 1.3 mmol) was added to the mixture and the solution was allowed to stirrer overnight while warming up to room temperature. The solvent was evaporated and the residue was re-dissolved in anhydrous THF (10 mL) under inert gas conditions and the procedure was repeated to substitute the second methyl group. After this the reaction mixture was diluted with water (50 mL) extracted with dichloromethane (2 x 50 mL), dried the combined organic phases with Na₂SO₄ and evaporated to dryness. The product (0.221 g, 0.74 mmol, 67 %) was obtained as yellow-orange solid after flash chromatography (pentane/TBME, 1:1 (v/v)). ¹H-NMR (400 MHz, CDCl₃): δ (ppm) = 8.16 (d, ³J = 8.5 Hz, 2H), 7.93 (d, ³J = 8.6 Hz, 2H), 7.75 – 7.69 (m, 4H), 7.51 (dt, ³J = 7.5 Hz, ⁴J = 1.1 Hz, 2H), 7.16 (d, ³J = 8.6 Hz, 2H), 2.02 (s, 6H). 13 C-NMR (100 MHz, CDCl₃): δ (ppm) = 167.3, 147.4, 135.9, 129.7, 129.2, 127.4, 126.8, 126.1, 121.0, 50.0, 28.1. HRMS (ESI+): calcd. for C₂₁H₁₉N₂⁺ [M + H]⁺: 299.1543; found: 299.1550. Anal. calcd. for C₂₁H₁₈N₂: C, 84.53; H, 6.08; N, 9.39; found: C, 83.19; H, 6.26; N, 8.89.

Benzylbisquinoline (BnBQ): Bisquinoline (0.4 g, 1.48 mmol) was dissolved in 10 mL anhydrous THF under inert gas conditions and cooled to -78 °C. To this reaction mixture *n*-BuLi (1.0 mL, 1.6 mmol, 1.6 M in hexane) was added and the solution was allowed to stirrer for 30 minutes at this temperature. The reaction mixture was allowed to warm to -10 °C for a few minutes and cooled back to -78 °C. Subsequent benzylbromide (0.305 g, 1.78 mmol) was added at -78 °C and the mixture was allowed to stirrer overnight while warming up to room temperature. The solution was diluted with water (50 mL) and extracted with dichloromethane (50 mL). The organic layer was dried with Na₂SO₄ and evaporated. The product (0.4 g, 1.11 mmol, 75 %) was obtained as waxy slight red solid after flash chromatography (pentane/TBME, 2:1 (v/v)). ¹H-NMR (200 MHz, CDCl₃): δ (ppm) = 8.04 (d, ³J = 8.3 Hz, 2H), 7.86 (d, ³J = 8.5 Hz, 2H), 7.62 – 7.54 (m, 4H), 7.45 – 7.31 (m, 4H), 7.15 – 7.12 (m, 2H), 7.05 – 6.94 (m, 3H), 4.92 (t,

FULL PAPER

³J = 7.6 Hz, 1H), 3.75 (d, ³J = 7.6 Hz, 2H). ¹³C-NMR (100 MHz, CDCl₃): δ (ppm) = 162.1, 147.9, 140.4, 136.3, 129.44, 129.40, 129.35, 128.2, 127.6, 127.2, 126.1, 125.9, 121.9, 59.2, 40.2.

Pyridylbisquinoline (PyBQ): A 10 mL microwave vessel was charged with bisquinoline (250 mg, 0.925 mmol) and 2-bromopyridine (500 mg, 3.16 mmol). After that one drop of ethereal hydrochloric acid (1 M in Et₂O) were added whereby some solid was formed. The vessel was heated for 10 min at 215 °C in a microwave reactor whereby the mixture turns into dark red. The waxy mixture was dissolved in dichloromethane, washed with 2 mol/L aqueous sodium hydroxide solution whereby the organic layer turns deep orange. The mixture was extracted with dichloromethane (2 x 50 mL), the organic phase was dried with Na₂SO₄ and evaporated. The product (116 mg, 0.48 mmol, 52 %) was obtained as orange-red solid after flash chromatography (pentane/TBME, 1:10 (v/v)). ¹H-NMR (400 MHz, CDCl₃): δ (ppm) = 8.60 (d, ³J = 4.0 Hz, 1H), 8.10 – 8.04 (m, 4H), 7.77 (d, ³J = 8.4 Hz, 2H), 7.67 – 7.60 (m, 6H), 7.50 – 7.43 (m, 4H), 7.16 – 7.13 (m, 1H), 6.39 (s, 1H). ¹³C-NMR (100 MHz, CDCl₃): δ (ppm) = 161.2, 161.1, 149.6, 148.0, 136.6, 136.2, 129.6, 129.3, 127.5, 127.1, 126.3, 124.5, 122.7, 121.9, 65.6. HRMS (ESI+): calcd. for $C_{24}H_{18}N_3^+$ [M + H]⁺: 348.1495; found: 348.1502

Picolylbisquinoline (PicBQ): Under inert gas conditions, picolylbromide hydrobromide (1.0 g, 5.0 mmol) was suspended with NaH (0.18 g, 7.5 mmol) in 5 mL anhydrous THF and stirred over night at room temperature. Bisquinoline (0.36 g, 1.33 mmol) was dissolved in 10 mL anhydrous THF under inert gas conditions and cooled to -78 °C. To this reaction mixture n-BuLi (0.92 mL, 1.46 mmol, 1.6 M in hexane) was added and the solution was allowed to stirrer for 30 minutes at this temperature. The reaction mixture was allowed to warm to -10 °C for a few minutes and cooled back to -78 °C. Subsequent the prepared mixture of α -picolylbromide was added without the precipitate at -78 °C and the mixture was allowed to stirrer overnight while warming up to room temperature. The solution was diluted with water (50 mL) and extracted with dichloromethane (100 mL). The organic layer was dried with Na₂SO₄ and evaporated. The product (0.31 g, 0.85 mmol, 64 %) was obtained as waxy slight red solid after flash chromatography (pentane/TBME, 1:5 (v/v)). ¹H-NMR (400 MHz, CDCl₃): δ (ppm) = 8.46 (d, ³J = 4.0 Hz, 1H), 8.10 (d, 3 J = 8.4 Hz, 2H), 7.93 (d, 3 J = 8.5 Hz, 2H), 7.67 – 7.61 (m, 4H), 7.51 (d, 3 J = 8.5 Hz, 2H), 7.42 (dt, ³J = 7.5 Hz, ⁴J = 1.1 Hz, 2H), 7.32 (dt, ³J = 7.65 Hz, 4 J = 1.8 Hz, 1H), 7.12 (d, 3 J = 7.8 Hz, 1H), 6.93 – 6.90 (m, 1H), 5.35 (t, 3 J = 7.7 Hz, 1H), 4.04 (d, 3 J = 7.7 Hz, 2H). 13 C-NMR (100 MHz, CDCl₃): δ (ppm) = 162.0, 160.2, 149.2, 147.9, 136.2, 135.9, 129.4, 129.2, 127.5, 127.0, 126.0, 123.8, 121.8, 121.0, 56.8, 42.0. HRMS (ESI+): calcd. for $C_{25}H_{20}N_3^{+}$ [M + H]⁺: 362.1652; found: 362.1652.

 $[{\rm Cu}_2({\rm BP}_{meso})_2({\rm CO}_3){\rm Cl}_2]$ (1): To a solution of BP (100 mg, 0.55 mmol) in 2 – 3 mL of methanol, CuCl_2 \cdot 2H₂O (47 mg, 0.28 mmol) dissolved in 2 – 3 mL of methanol were added. Slow evaporation of the dark green colored solution led to formation of a few crystals that could be structurally characterized.

[CuBP]OTf (2): Under an inert atmosphere in a glovebox, the BP ligand (25 mg, 0.137 mmol) was dissolved in anhydrous THF and reacted with $[Cu(CH_3CN)_4]OTf$ (51.6 mg, 0.137 mmol). After stirring for a few minutes, the solution was left to evaporate and the residue was washed with anhydrous diethylether. The product (42 mg, 0.106 mmol, 78 %) was obtained as colourless solid.

 $[Cu_2(BQOH)_2Cl_2]$ (9): BQ (100 mg, 0.37 mmol) was diluted in 3 – 5 mL of methanol resulted in an orange solution. To this solution was added under an Argon atmosphere CuCl_2 · 2H_2O (62 mg, 0.37 mmol). After that the color of the solution changed to red slowly. In a Schlenk flask was stored Et_2O and a glow tube, capped with a septum and rinsed with argon for

10 min. Subsequent 1 – 2 mL of the complex solution was transferred to the glow tube. The formation of red crystals could be achieved by diffuse of the Et_2O into the glow tube. The crystals could be structurally characterized.

copper(II) dichlorido methoxy bis chino-2-yl methanol complex (10): BQ (100 mg, 0.37 mmol) was diluted in 3 – 5 mL of methanol resulted in an orange solution. To this solution was added a solution of $CuCl_2 \cdot 2H_2O$ (62 mg, 0.37 mmol) in 2 – 3 mL of methanol whereby the color of the solution changed to red. After one hour the color of the solution changed to brown and finally to green. Slow evaporation of the green solution led to formation of a few green crystals that could be structurally characterized.

General procedure for the oxidation experiments: Under inert gas conditions in a glovebox BP (50 mg, 0.3 mmol) and $[Cu(CH_3CN)_4]OTf$ (103.2 mg, 0.3 mmol) was dissolved in anhydrous THF and staggered with the same equivalent of the substrate. The reaction mixture was cooled to -80 °C and dioxygen was bubbled through the solution for 10 min. The reaction mixture was allowed to warm to room temperature and diluted with aqueous ammonia solution or water. The organic phase was extracted with dichloromethane, evaporated to dryness and the yield was determined by GC-MS.

Keywords: Copper • Dioxygen • Oxidation • Bispiperidine • Bisquinoline

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Selective Oxidations

Tim-Daniel J. Stumpf, Manfred Steinbach, Christian Würtele, Jonathan Becker, Sabine Becker, Roland Fröhlich, Richard Göttlich, Siegfried Schindler*

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