Journal of Inorganic and General Chemistry
ZAAC
Zeitschrift für anorganische und allgemeine Chemie
DOI: 10.1002/zaac.202100145
ARTICLE



# Mimicking of the histidine brace structural motif in molecular copper(I) compounds

R. Peifer,[a] L. Müller,[a] S. Hoof,[a] F. Beckmann,[a] B. Cula,[a] and C. Limberg*[a]

*Dedicated to Professor Hansgeorg Schnöckel on occasion of his 80th birthday*

L-Nτ-methylhistidine methyl ester, MeHisOMe, has been employed as a potential ligand to mimic the histidine brace-type coordination of copper ions in enzymes such as the particulate methane monooxygenase or lytic polysaccharide monooxygenases. MeHisOMe was prepared by double-methylation of histidine methyl ester. Subsequently, its complexation by diphosphine copper(I) precursors $[Cu(P\wedge P)(MeCN)_2]BF_4$ was tested, which led to the complexes $[Cu(P\wedge P)(MeHisOMe)]BF_4$ (P^P = dpePhos: **1**, P^P = XantPhos: **2**, P^P = dppf: **3**). **1**–**3** were fully characterized, also by single crystal X-ray analysis, thus providing first structural data for copper complexes with a synthetic, authentic histidine brace. The complexes proved inert in contact with dioxygen. To improve the biomimetic character attempts were made to formally replace the diphosphine ligands by bis(pyrazolyl)methanes, Bpm. Correspondingly, $[BpmCu(NCMe)_x]BF_4$ precursors were synthesized, with different substituents at the 3-positions of the pyrazolyl (i.e. Bpm = di(3-(phenyl)-1H-pyrazol-1-yl)diphenylmethane, di(3-(mesityl)-1H-pyrazol-1-yl)methane and di(3-(*tert*-butyl)-1H-pyrazol-1-yl) diphenylmethane). Addition of MeHisOMe to these complexes led to products that were so sensitive towards oxidation by the environment that they eluded isolation. One experiment provided blue crystals as a product of such a reaction. They belonged to a salt with a complex cation consisting of a $Cu(\mu\text{-}OH)_2Cu$ core ligated by two MeHisOMe ligands, which dimerises in the solid state to give $[Cu_4(OH)_4(MeHisOMe)_4]^{4+}$.

## Introduction

For a long time, the constitution and structure of the particulate methanemonooxygenase (pMMO), which catalyses the synthetically challenging oxygenation of methane to methanol, has been a subject of controversial discussions.[1–9] However, within recent years combined crystallographic, biochemical and quantum mechanical investigations by Rosenzweig and coworkers have revealed that the enzyme contains three mononuclear copper site,[10] two of which, $Cu_B$ and $Cu_C$, have been discussed in recent years as the active, methane-oxidizing centres.[10,14] While currently $Cu_C$ is proposed as the active site, $Cu_B$ is essential, too. In numerous reports by the Rosenzweig-group and collaborators the current view on the structure and constitution of $Cu_B$ has been continuously developed.[6,7,9–13] Considering the resting state and disregarding coordinated water, the coordination sphere of the copper(II) ion is best described as square-planar (Figure 1).[10] It consists of three histidine residues, two of which coordinate in the typical fashion observed in the structures of numerous metalloenzymes, i.e. via one N atom of the corresponding imidazole sidechain donors. The third one, however, corresponds to an N-terminal histidine, which binds in a rather special way, namely via one N donor of the imidazole side-chain and the terminal $NH_2$ group in a chelating fashion. This ligation, which is also found in the lytic polysaccharide monooxygenases (LPMOs, Figure 1), has been coined "histidine brace". The N donor sphere of the copper ion in the LPMOs active site is often described as T-shaped, as the $N_\tau$–Cu–$NH_2$ angle is around 96°. An additional water ligand that is located in the plane, completes a square planar coordination environment (Figure 1).[14]

Considering the nature of the active species, which perform the substrate oxygenations in case of active sites with the

[a] R. Peifer, L. Müller, S. Hoof, F. Beckmann, B. Cula, C. Limberg
Institut für Chemie
Humboldt-Universität zu Berlin
Brook-Taylor-Straße 2
12489 Berlin, Germany
E-mail: christian.limberg@chemie.hu-berlin.de
Homepage: http://www2.hu-berlin.de/chemie/aglimberg/

Supporting information for this article is available on the WWW under https://doi.org/10.1002/zaac.202100145



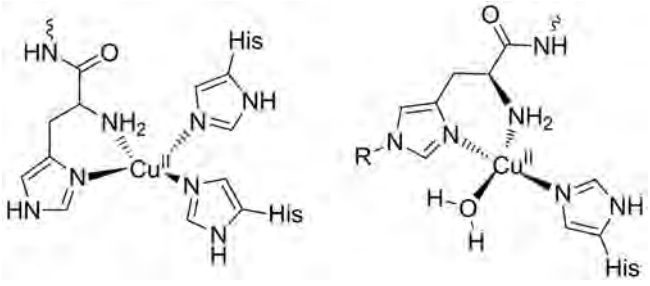



**Figure 1.** $Cu_B$ site of pMMO (left) and active sites of LPMOs (right, R=Me in fungal sources).

histidine brace motif, GAGNON *et al.* have suggested copper(II) oxyl or a tautomeric copper(III) hydroxide species (Scheme 1).[15]

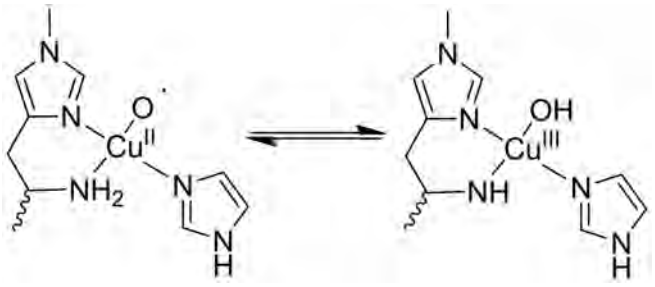
The presence of the histidine brace both in the pMMO and LPMOs naturally raises questions concerning its role.[11,16]

Molecular model systems could contribute to answering such questions, but the preparation of well-defined complexes, which feature a ligand that faithfully mimics the histidine brace and at the same time are sufficiently stable for structural and functional investigations, has proven challenging.

With a focus on dinuclear species, CITEK *et al.* have therefore used the "*core-capture* method" to exchange *in-situ* the TMPD ligands (TMPD=N,N,N′,N′-Tetramethyl-1,3-propanediamine) surrounding a bis-μ-oxo-dicopper(III) core by histamine, mimicking the histidine brace ligation. It was found, that the replacement of TMPD against the histamine ligand results in a thermodynamically more stable copper(III) oxo complex. These histamine braced $Cu_2O_2$ cores were able to oxidise C–H-bonds with energies up to 76 kcal·mol$^{-1}$ at −125 °C.[17]

FUKATSU *et al.* have recently reported a copper(II) complex containing a polypodal ligand that simulates the surroundings of a histidine brace and one further histidine side-chain, thus mimicking the coordination environment found in LPMOs. Apart from the fact that the amine function of the ligand is not a terminal, primary one, like in the histidine brace, this complex reproduces the structural environment of the copper centre in LPMOs closely. The complex is able to oxidize PNPG (PNPG = *p*-nitrophenyl-β-D-galactopyranoside) in the presence of $H_2O_2$ and to hydroxylate cyclohexane to the corresponding alcohol with a TON of 26 after 24 h.[18]

We aimed at the synthesis of copper(I) complexes with a ligand that replicates the histidine brace as faithfully as possible to study their structures and properties. Here we report the preparation of such complexes using a histidine methyl ester as an analogue of the N-terminal histidine ligand.

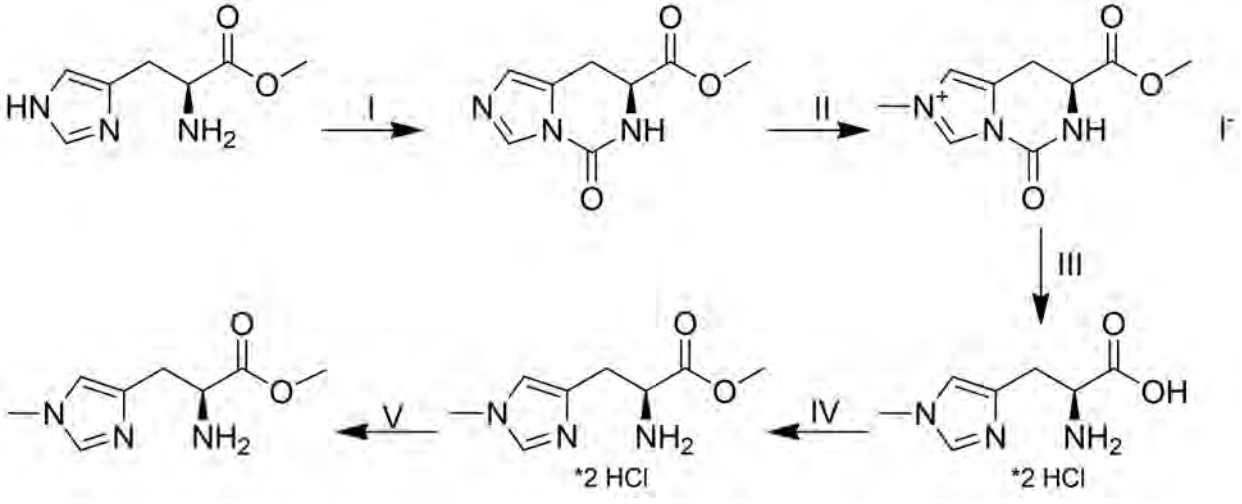


**Scheme 1.** Discussed active histidine brace-copper-oxygen species.

## Results and Discussion

In search for an adequate ligand that mimics the histidine brace we finally chose L-$N_\tau$-methylhistidine methyl ester, MeHisOMe, which can be accessed in enantiomerically pure form starting from L-histidine methyl ester through a five-step reaction sequence that leads to the methylation of the imidazole ring. After protecting the $NH_2$ and $N_\pi$ through conversion into a urea derivate using carbonyldiimidazole the remaining imidazole N atom was methylated with the aid of methyliodide (Scheme 2). Subsequently, the protection group was removed with $HCl_{(aq)}$ and the ester function recuperated with thionylchloride and methanol. Freebasing of the dihydrochloride with $Cs_2CO_3$ in water and extraction with $CHCl_3$ gave MeHisOMe as a light yellow oil that is stable in a freezer for several months, but undergoes cyclization to the diketopiperazine derivate within weeks if stored at room temperature. While MeHisOMe and the intermediates in Scheme 2 have been described in the literature,[19,20] the conversion steps IV and V proved challenging according to published procedures and had to be newly developed by us.

Approaching a molecular copper(I) complex containing MeHisOMe as a chelating ligand, we started our investigations




**Scheme 2.** Synthesis of Nτ-methylhistidine methyl ester I): N,N-carbonyldiimidazole, DMF, 60 °C, 5 h;[19,20] II): $CH_3I$, MeCN, 12 h, reflux;[19,20] III): HCl, 6 M, 24 h, reflux;[19,20] IV): $SOCl_2$, methanol, 12 h, −78 °C → reflux; V): $Cs_2CO_3$, $H_2O/CHCl_3$.

using diphosphines as coligands, as phosphines are known to be well compatible with copper(I) centres due to their soft donor character. We used the commercially available diphosphines dpePhos (oxydi-2,1-phenylene)bis(diphenylphosphine)), XantPhos (4,5-bis(diphenylphosphino)-9,9-dimethylxanthene) and dppf (1,1′-bis(diphenylphosphanyl)ferrocene), which span bite-angles between 96° (dppf) and 107° (XantPhos) and are known to form heteroleptic complexes with certain N^N-donors.[21–25] Addition of MeHisOMe to the respective precursors $[Cu(P\text{^}P)(MeCN)_2]BF_4$[26–28] in DCM led to the formation of the desired complexes $[Cu(P\text{^}P)(MeHisOMe)]BF_4$. (P^P = dpePhos: **1**, P^P = XantPhos: **2**, P^P = dppf: **3**, Figure 2 < pfigr3/ul). Single crystals were grown by diffusion of diethyl ether into saturated solutions of **1**, **2** and **3** in DCM. The crystal structures of ***(S)*-1**·0.5 MeCN, ***(S)*-2** and ***(S)*-3**·$Et_2O$ (Figure 3) feature copper(I) centres in nearly perfect tetrahedral coordination spheres. The calculated $\tau_\delta$-values, which illustrate the degree of deviation from an ideal tetraeder ($\tau_\delta = 1$ for a tetrahedron),[29] confirm this impression also quantitatively, as they are all close to 1 (Table 1). The distances between the histidine brace N atoms and the copper ions ($Cu–NH_2$ and $Cu–N_\pi$) are only slightly shorter than those in the reported LPMO-structure of Ls(aa9A)[14] (Tables 1 and 2).

**Table 1.** Selected structural parameters of the complexes **1**, **2** and **3** in comparison to those of the active site of the LPMO Ls(aa9 A).

| | **1**·0.5 MeCN | **2** | **3**·$Et_2O$ | Active site Ls(aa9A) |
|---|---|---|---|---|
| Nπ–Cu–$NH_2$ in ° | 96.51(15) | 90.15(3) | 95.24(11) | 94 |
| Cu–$NH_2$ in Å | 2.125(4) | 2.196(3) | 2.154(3) | 2.2 |
| Cu–Nπ-distance in Å | 2.009(4) | 2.025(3) | 2.028(3) | 1.9 |
| $\tau_\delta$-value | 0.97 | 0.93 | 0.99 | |

In the $^1H$ NMR spectra a shift of the resonance belonging to the primary amine protons from $\delta = 1.55$ ppm for MeHisOMe to 2.87 (**1**), 2.83 (**2**) and 2.76 (**3**) ppm was observed. The chemical shifts of the $^{31}P$ NMR signals vary only slightly within the series of MeHisOMe-coordinated complexes (Table 3) and are hardly shifted with respect to the corresponding signals of the $[Cu(P\text{^}P)(MeCN)_2]$-precursors (+2.0 (**1**), −0.7 (**2**) and +0.3 (**3**)

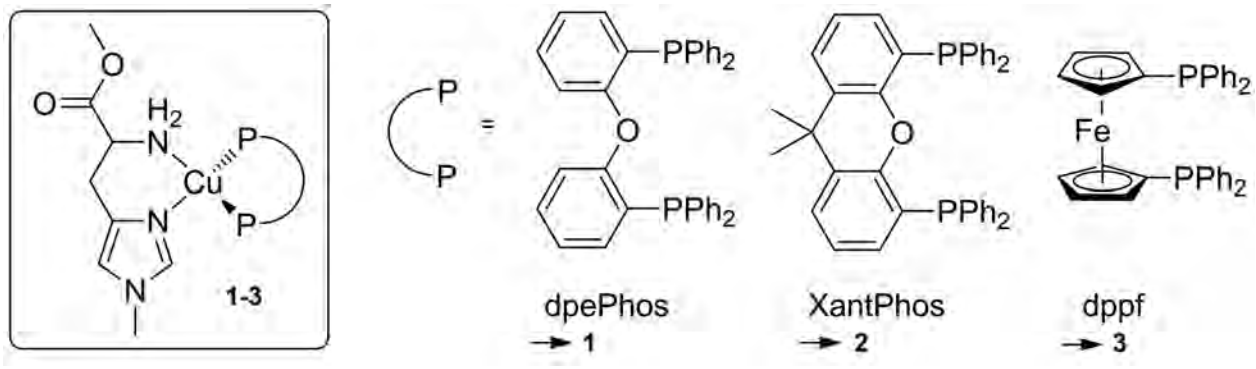



**Figure 2.** Synthesised MeHisOMe copper(I) diphosphino complexes.

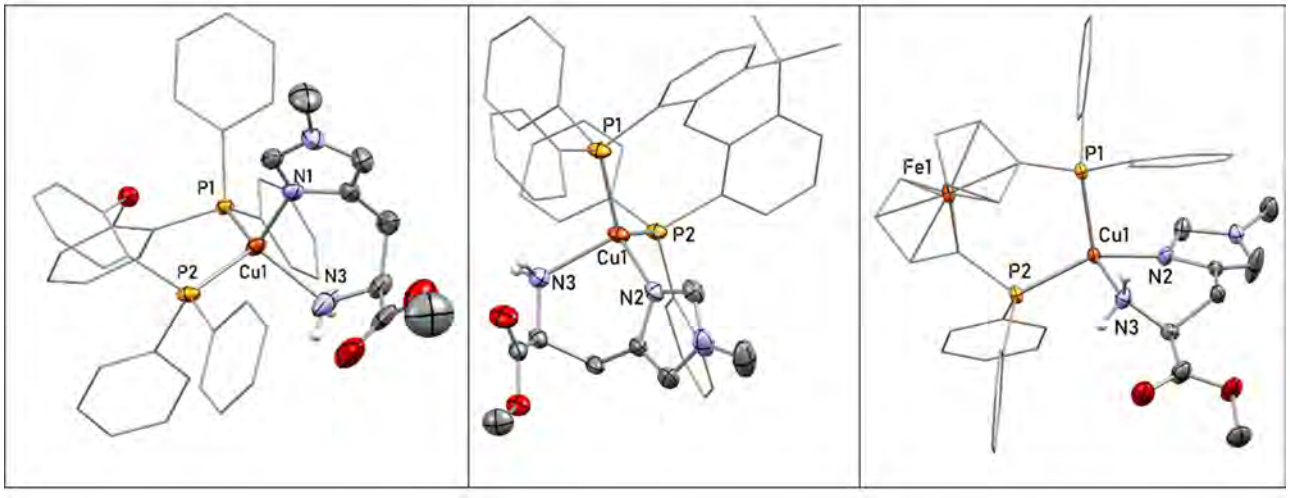



**Figure 3.** ORTEP-display of the structures determined for ***S*-1**·0.5 MeCN (left), ***S*-2** (middle) and ***S*-3**·$Et_2O$ (right). Carbon-bound hydrogen atoms, solvent molecules and anions are not shown for clarity, ellipsoids are drawn at the 50% probability level.

**Table 2.** Selected bond lengths in Å and angles in ° of complexes ***S*-1**·0.5 MeCN, ***S*-2** and ***S*-3**·$Et_2O$.

| ***S*-1**·0.5 MeCN | ***S*-2** | ***S*-3**·$Et_2O$ |
|---|---|---|
| Cu(1)–N(1) 2.009(4) | Cu(1)–N(2) 2.025(3) | Cu(1)–N(2) 2.028(3) |
| Cu(1)–N(3) 2.125(4) | Cu(1)–N(3) 2.196(3) | Cu(1)–N(3) 2.154(3) |
| Cu(1)–P(1) 2.2434(11) | Cu(1)–P(1) 2.2720(9) | Cu(1)–P(2) 2.2346(8) |
| Cu(1)–P(2) 2.2711(11) | Cu(1)–P(2) 2.2962(9) | N(2)–Cu(1)–N(3) 90.15(12), |
| N(1)–Cu(1)–N(3) 96.51(15), | N(2)–Cu(1)–P(1) 118.45(9), | Cu(1)–P(1) 2.2716(8) |
| N(1)–Cu(1)–P(1) 112.91(10), | N(3)–Cu(1)–P(1) 102.83(9), | N(2)–Cu(1)–N(3) 95.24(11), |
| N(3)–Cu(1)–P(1) 117.81(14), | N(2)–Cu(1)–P(2) 112.99(9), | N(2)–Cu(1)–P(2) 128.19(9), |
| N(1)–Cu(1)–P(2) 108.83(10), | N(3)–Cu(1)–P(2) 115.85(10), | N(3)–Cu(1)–P(2) 106.68(8), |
| N(3)–Cu(1)–P(2) 105.27(16), | P(1)–Cu(1)–P(2) 113.91(4) | N(2)–Cu(1)–P(1) 108.45(8), |
| P(1)–Cu(1)–P(2) 113.89(4) | | N(3)–Cu(1)–P(1) 101.03(8), |
| | | P(2)–Cu(1)–P(1) 112.31(3) |

**Table 3.** $^{31}P$ NMR resonances of the complexes **1**, **2** and **3**, dissolved in $CD_2Cl_2$.

| Compound | $^{31}P$ NMR δ (precursor)/ppm | $^{31}P$ NMR δ (complex)/ppm |
|---|---|---|
| **1** | −15.1 | −13.1 |
| **2** | −14.7 | −15.4 |
| **3** | −12.9 | −12.6 |

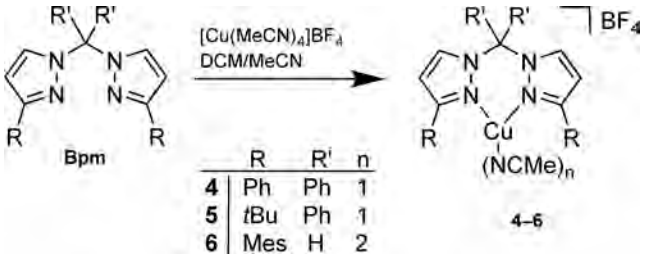
ppm); apparently the binding of MeHisOMe vs. acetonitrile does not translate through the copper centre.

The synthesised compounds are the first isolated and structurally characterised copper(I) complexes with a synthetic histidine brace, and hence their behaviour towards oxidants was of particular interest. However, apparently the diphosphines as coligands stabilise the copper(I) state so strongly, that they do not react with $O_2$.

They neither react with O atom transfer reagents like (2-*tert*-butylsulfonyl)-iodosobenzene. Reaction with peroxides ($H_2O_2$ and *t*Bu–OOH) resulted in the formation of diphosphine oxides and decomposition of the complexes; monitoring of these reactions by UV-vis spectroscopy gave no indication of oxygenated copper intermediates in form of any characteristic bands. Cyclovoltammetric experiments with **1**, **2** and **3** showed redox events corresponding to the irreversible oxidation of copper(I) to copper(II) between 0.67 and 0.88 V and to the reduction of MeHisOMe between −3.19 and −3.34 V (see Table 4 and SI). The iron ion of complex **3** is reversibly oxidized at 0.38 V. The positions of the $Cu^+ \rightarrow Cu^{2+}$ waves do not differ significantly from those observed for the $[Cu(P\wedge P)(MeCN)_2]BF_4$ precursors, so that apparently the phosphine ligands dominate the proceedings. Most notably, the potential for the oxidation of $Cu^+$ in **3** is shifted anodically against the one of [Cu(dppf)$(MeCN)_2$] by 0.12 V.[24,30]

The redox potentials are in line with the lack of reactivity towards dioxygen. Of course, while the histidine brace copper moiety is successfully imitated in complexes **1**, **2** and **3**, the residual donor atom arrangement in the first coordination spheres of the copper ions differ from the one in the pMMO/LPMO active sites and this does not only concern the surrounding atom-types ($P_2$ vs. $N_2$): Although no crystal data are available for the copper(I) states, they likely have distorted square-planar structures, while in **1**, **2** and **3** thermodynamically more favourable tetrahedral ligand arrangements are found. The enzymatic active sites thus may profit from entatic structures and it would certainly be interesting to consider this in future ligand designs through the introduction of constraints. However, the results in the following show, that the lack of constraint does not directly correlate with the lack of reactivity towards dioxygen.

Contemplating the creation of copper(I) complexes of MeHisOMe, which more realistically model the pMMO active site structure with regard to the donor functions, we then decided to use bis(pyrazolyl)methane, Bpm, co-ligands, as the two pyrazolyl donors should nicely simulate the two histidine-based imidazole donors beside the histidine brace (see Figure 1). For the variation of the steric conditions two representatives were newly prepared, namely di(3-(phenyl)-1H-pyrazol-1-yl) diphenylmethane $^{PhPh}$**Bpm** and di(3-(mesityl)-1H-pyrazol-1-yl) methane $^{Mes}$**Bpm**, while a third one, di(3-(tert-butyl)-1H-pyrazol-1-yl)diphenylmethane $^{tBuPh}$**Bpm**, was accessed *via* a literature procedure.[31] Indeed all three ligands could be utilised to generate the desired $[CuBpm(MeCN)_n]^+$ complex cations, *via* treatment of $[Cu(MeCN)_4]BF_4$ in MeCN with the Bpm ligands dissolved in DCM (Scheme 3), while smaller residues at the pyrazolyl donors (like H or Me) are known to result in formation of homoleptic $[Cu(Bpm)_2]^+$-complexes.[32,33] The compounds $[Cu^{PhPh}Bpm(MeCN)]BF_4$ (**4**), $[Cu^{Mes}Bpm(MeCN)_2]BF_4$ (**5**), and $[Cu^{tBuPh}Bpm(MeCN)]BF_4$ (**6**) were isolated after workup in form of colourless solids. Crystals suitable for X-ray diffraction spectroscopy could be grown through diffusion of diethyl ether into a DCM solution of **4**, **5** and **6**. The crystal structures of **4** (Figure 4 left) and **5** (Figure S11) show trigonally planar coordinated copper centres, while the copper ion of compound **6** (Figure 4 right) incorporates an additional molecule of acetonitrile, resulting in a tetrahedral coordination sphere, where the mesityl moieties orientate perpendicularly to the pyrazolyl rings, thus providing space for two acetonitrile molecules in the binding pocket.




**Scheme 3.** Syntheses and details of **4**, **5**, and **6**.

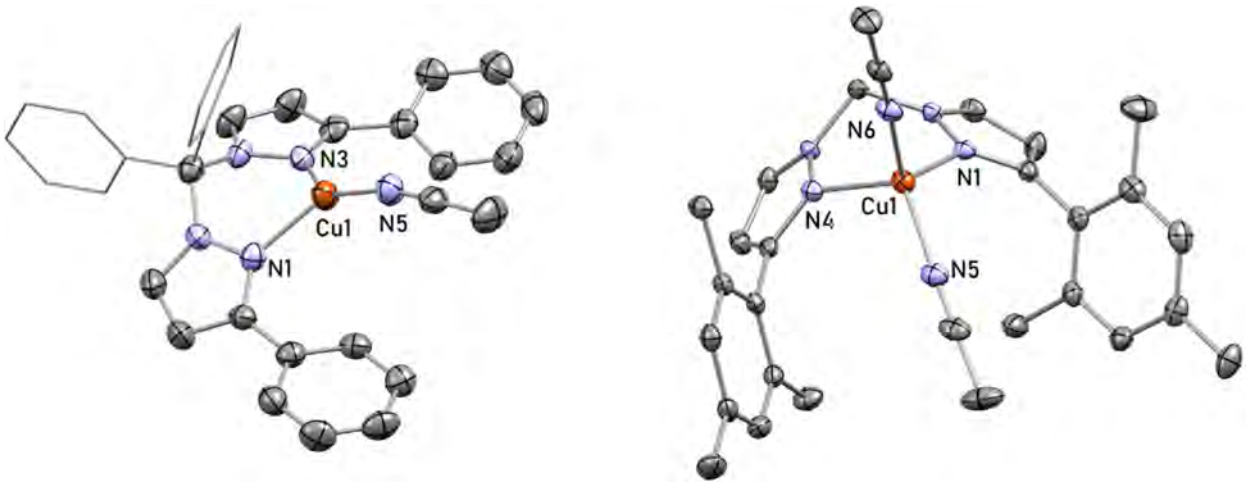



**Figure 4.** ORTEP-display of the structures determined for **4** (left) and **6** (right) (for **5** see SI).Carbon-bound hydrogen atoms, solvent molecules and anions are not shown for clarity, ellipsoids are drawn at the 50 % probability level.

When reacting the complexes **4**, **5** and **6** with MeHisOMe, we encountered a high lability of the resulting reaction mixtures. In various solvents, at high or low temperatures, with different stoichiometric proportions and reaction times, the isolation of defined products failed. The reaction mixtures were highly sensitive against any source of dioxygen. Even in closed, flame dried J. YOUNG-ampules, stored inside a glovebox, the reaction mixtures turned blue over days, which is likely not due to disproportion, as precipitation of elemental copper could not be observed.

In some crystallization experiments with **4**/MeHisOMe, single crystals suitable for X-ray diffraction analysis could be grown (from DCM and nitromethane solutions in less than 10 % yield), and a corresponding analysis led to the structure of an ionic compound, $[Cu_4(OH)_4(MeHisOMe)_4](BF_4)_4$, **7**, the cation of which can be viewed as a dimer of two (MeHisOMe)Cu(μ-$OH)_2$Cu(MeHisOMe) dications (Figure 5). The dimerization occurs through the copper(II) hydroxide entities, so that a cubic $Cu_4(OH)_4$ core results, which is surrounded by four MeHisOMe ligands. The latter are binding in a histidine brace manner *via* the imidazole and amine functions but also the carbonyl O atom weakly interacts; the Cu–$O_{carbonyl}$ distances are 2.749 and 2.737 Å, and hence slightly longer than typical reported axial CuO bonds in JAHN-TELLER-distorted structures.[34]

Each copper centre is thus coordinated facially by three hydroxide ligands and a tridentate MeHisOMe ligand, with the carbonyl O atom located on the JAHN-TELLER axis. The Cu–OH distances within the Cu(μ-$OH)_2$Cu entities average at 1.961(4) Å, the Cu–OH contacts that lead to dimerization are characterized by distances of 2.418(4) and 2.384(4) Å. The Cu–$NH_2$ bond lengths vary between 2.016(5) and 2.023(5) Å, averaging at 2.020(5) Å, which is 0.1 Å shorter than in the copper(I) complexes **1**, **2** and **3** due to the higher charge and Pearson "hardness" of the copper(II) centre. Copper(II) bis-μ-hydroxo complexes are the decay products of highly reactive $CuO_x$-intermediates.[35,36] The formation of **7** thus suggests, that *in-situ*

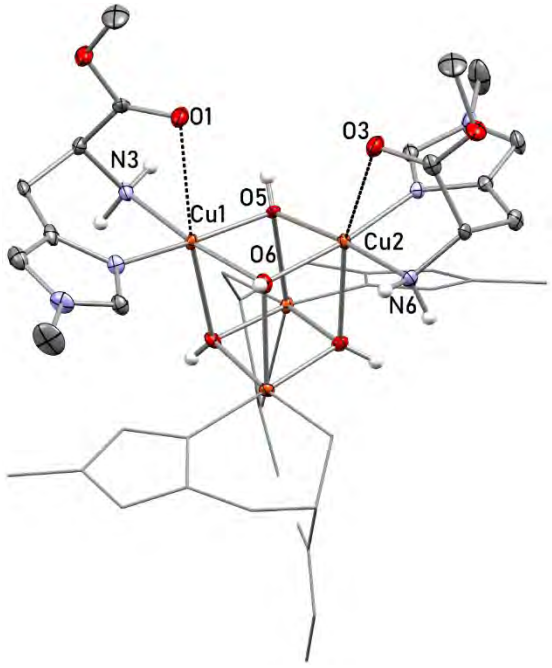



**Figure 5.** ORTEP-display of the structures determined for ***(S,S,S,S)*-7**·4 DCM, one of two independent molecules in the unit cell displayed, carbon-bound hydrogen atoms, solvent molecules and $BF_4^-$ are not shown for clarity, ellipsoids are drawn at the 50 % probability level.

a complex was formed that immediately reacted with its environment. As proton and oxygen sources we can only conceive trace impurities within the glovebox atmosphere or reaction with the surface Si–OH groups of the used glass ware. The high sensitivity of the mixtures, contrasting the behaviour of solutions of **4**, **5** and **6** leads us to the conclusion, that the coordination of the histidine brace to an N-ligated copper(I)

centre drastically changes its reactivity, which bears potential for further investigations.

## Conclusions

Using L-$N_\tau$-methylhistidine methyl ester, MeHisOMe, first complexes with a ligand that faithfully mimics the histidine brace coordination, also with regard to the primary amine donor, have been isolated and structurally characterized. While diphosphines as co-ligands offered sufficient stabilization to isolate and characterize such complexes, the addition of MeHisOMe to copper(I) complexes containing bidentate N-donors (Bpm) triggered a sensitivity of the products that made them inaccessible in our hands. Instead, a polynuclear copper(II) hydroxide complex was isolated, suggesting that activation of adventitious $O_2$ and subsequent reduction to hydroxide has occurred. Assuming that MeHisOMe – as before in case of the diphosphine co-ligands – replaces the acetonitrile molecules of the $[Cu(Bpm)(NCMe)_x]BF_4$ precursors **4**–**6** in the first step after its addition to form the desired complexes $[Cu(Bpm)(MeHisOMe)]BF_4$, the pronounced sensitivity/reactivity of the latter highlights the potential of the pMMO/LPMO active sites in activating dioxygen and rationalizes the enzymatic choice of a histidine brace ligation.

## Experimental Section

### Materials and methods

All manipulations with air-sensitive compounds were carried out in a glovebox or by means of SCHLENK-type techniques involving a dry and oxygen-free argon atmosphere. NMR spectra were recorded with Bruker AV400 ($^1$H 400.1 MHz, $^{13}$C 100.6 MHz, $^{31}$P 162.0 MHz), AV 500 ($^1$H 500.1 MHz, $^{13}$C 125.8 MHz), and AV600 ($^{31}$P 242.8 MHz) NMR spectrometers in $CD_2Cl_2$ and $CDCl_3$ at 25 °C if not reported differently. $^1$H NMR spectra were calibrated against the internal residual proton and natural abundance $^{13}$C resonances of the deuterated solvent. Chemical shifts ($\delta$) were reported in ppm, coupling constants ($J$) in Hz. The assignment of signals was carried out with the help of 2D-analyses. Microanalyses were performed with a Hekatech Euro EA 3000 elemental analyser. ESI-MS spectra were recorded with an Agilent Technologies 6220 TOF-LC-MS. Only selected signals in the recorded mass spectra are reported. Infrared spectra (IR) were recorded with a Bruker Alpha in a region of 4000–400 cm$^{-1}$ as solids or dissolved samples.

Unless stated otherwise, all starting materials were obtained from commercial sources in the highest available purity and were used without further purification. L-1-Methylhistidine dihydrochloride,[19,20] $[(Cu(dpePhos)(MeCN)_2]BF_4$,[26] $[Cu(dppf)(MeCN)_2]BF_4$,[27] $[Cu(XantPhos)(MeCN)_2]BF_4$[28] and di(3-(tert-butyl)-1H-pyrazol-1-yl)diphenylmethane[31] were prepared according to the procedures described in literature. Solvents were dried by using an MBRAUN Solvent Purification System SPS.

### Synthetic procedures

#### MeHisOMe·2HCl L-1-Methylhistidine methyl ester dihydrochloride

L-1-Methylhistidine dihydrochloride[19,20] (1.53 g, 6 mmol, 1 eq) was dissolved in methanol (abs., 48 mL). The solution was cooled to −78 °C and thionylchloride (0.9 mL, 1.48 g, 12 mmol, 2 eq) was added dropwise. After warming to room temperature the mixture was refluxed for 12 h. A colourless solid formed after removing all volatiles in vacuo. Recrystallisation from ethanol/ethyl acetate gave L-1-methylhistidine methyl ester dihydrochloride as a colourless solid in good yields (1.34 g, 5 mmol, 83 %). Spectroscopic data were in agreement with those reported.[37]

#### MeHisOMe L-1-Methylhistidine methyl ester

L-1-Methylhistidine methyl ester dihydrochloride (1.00 g, 3.9 mmol) was dissolved in water (5 mL) and caesium carbonate (2.54 g, 7.8 mmol, 2 eq) was added in small portions. The mixture was stirred for 1 h and extracted with chloroform (5×50 mL). The combined organic layers were dried over sodium sulfate and all volatiles were removed *in vacuo*. To the resulting yellow oil, chloroform (abs, 5 mL) was added. The mixture was transferred to a flame-dried flask and three freeze-pump-thaw-cycles were applied, after which the solvent was removed. L-1-Methylhistidine methyl ester was isolated as a yellow oil (0.34 g, 1.9 mmol, 47 %) and could be stored at −25 °C under argon for several months without decomposition . Spectroscopic data were in agreement with those reported.[38]

#### Diphosphine complexes, general synthesis

To a solution of $[Cu(P\text{^}P)(MeCN)_2]BF_4$ (0.05 mmol, 1 eq) in dichloromethane (2 mL) L-1-methylhistidine methyl ester (10 mg, 0.05 mmol, 1 eq) in dichloromethane (2 mL) was added. The solution was stirred under reflux overnight. Afterwards the solution was concentrated *in vacuo* to a volume of approximately 0.5 mL. Crystallisation was initialised by diffusing diethyl ether into the solution at −30 °C. After filtration, the product was isolated in form of colourless crystals.

**$[Cu(dpePhos)(MeHisOMe)]BF_4$ (1)**. Yield: 65 %; $^1$H NMR (500.1 MHz, $CD_2Cl_2$): $\delta$ = 7.39–7.23 (m, 15 H, *Ph*), 7.14 (br, 7 H, *Ph*), 6.95 (t, $J$ = 6.8 Hz, 4 H, *Ph*), 6.83 (s, 1 H, MeHisOMe-*Im*), 6.72 (m, 2 H, *Ph*), 6.62 (s, 1 H, MeHisOMe-*Im*), 3.60 (m, 4 H, MeHisO*Me* + C*H*), 3.27 (s, 3 H, *Me*HisOMe), 2.95 (d, $J$ = 15.8 Hz 1 H, C$H_2$), 2.87 (br s, 2 H, N$H_2$), 2.61 (dd, $J$ = 15.7 Hz, $J$ = 9.1 Hz, 1 H, C$H_2$) ppm; $^{13}$C{$^1$H} NMR (125.8 MHz, $CD_2Cl_2$): $\delta$ = 173.4 (*C*OOMe), 138.4 (*C*2-MeHisOMe), 137.5 (*C*4-MeHisOMe), 134.8 (dpePhos-*Ph*), 133.6 (dpePhos-*Ph*), 132.1 (dpePhos-*Ph*), 130.5 (dpePhos-*Ph*), 129.2 (dpePhos-*Ph*), 125.4 (dpePhos-*Ph*), 124.9 (dpePhos-*Ph*), 120.8 (dpePhos-*Ph*), 119.0 (*C*5-MeHisOMe), 54.9 (*Cα* MeHisOMe), 53.0 (MeHisO*Me*), 34.2 (*Me*HisOMe), 30.2 (*Cβ*-MeHisOMe) ppm; $^{31}$P{$^1$H} NMR (242.8 MHz, $CD_2Cl_2$): $\delta$ = −13.1 ppm; MS (ESI): $m/z$ = 784.20 ({Cu(dpePhos)-(MeHisOMe)}$^+$); elemental analysis for $C_{44}H_{41}BCuF_4N_3O_3P_2$ calc: C 60.60, H 4.74, N 4.82 %, found: C 60.24, H 4.88, N 4.50 %.

**$[Cu(MeHisOMe)(XantPhos)]BF_4$ (2)**. Yield: 42 %; $^1$H NMR (400.1 MHz, $CD_2Cl_2$): $\delta$ = 7.66 (d, $J$ = 7.0 Hz, 2 H, XantPhos-*Ph*), 7.35–7.05 (m, 2 H, XantPhos-*PPh*$_2$), 7.17 (t, $J$ = 7.7 Hz, 2 H, XantPhos-*Ph*), 6.95 (s, 1 H, MeHisOMe-*Im*), 6.63 (m, 2 H, XantPhos-*Ph*), 6.27 (s, 1 H, MeHisOMe-*Im*), 3.68 (s, 3 H, MeHisO*Me*), 3.42 (s, 3 H, *Me*HisOMe), 3.38 (m, 1 H, C*H*), 3.08 (d, $J$ = 15.4 Hz, 1 H, C$H_2$), 2.83 (d, $J$ = 7.7 Hz, 2 H, N$H_2$) 2.37 (dd, $J$ = 15.5 Hz, $J$ = 10.5 Hz, 1 H, C$H_2$), 1.70 (s, 6 H, XantPhos-*Me*$_2$) ppm; $^{13}$C{$^1$H} NMR (100.6 MHz, $CD_2Cl_2$) $\delta$ = 174.0 (*C*OOMe), 138.2 (*C*4

MeHisOMe), 137.4 (*C2* MeHisOMe), 134.2 (XantPhos P*Ph*$_2$), 133.4 (XantPhos P*Ph*$_2$), 131.6 (Xanthene-*Ph*), 130.4 (Xanthene-*Ph*), 129.2 (XantPhos P*Ph*$_2$), 127.5 (Xanthene-*Ph*), 125.3 (Xanthene-*Ph*), 119.6 (*C5* MeHisOMe), 55.1 (*Cα* MeHisOMe), 53.2 (MeHisO*Me*), 36.3 (Xanthene *C*–Me$_2$), 34.3 (*Me*HisOMe), 30.3 (*Cβ* MeHisOMe), 28.4 (Xanthene *Me*$_2$) ppm; $^{31}P\{^1H\}$ NMR (162.0 MHz, 288 K, $CD_2Cl_2$): $\delta = -15.4$ ppm; ESI-MS: $m/z = 824.2237$ $(M)^+$, 641,1638 $(M–MeHisOMe)^+$; elemental analysis for $C_{47}H_{45}BCuF_4N_3O_3P_2$ calc: C 61.89, H 4.97, N 4.61 %, found: C 58.74, H 4.94, N 4.61 %.

**[Cu(MeHisOMe)(dppf)]BF$_4$ (3)**. Yield 90 %; $^1H$ NMR (500.1 MHz, $CD_2Cl_2$): $\delta = 7.47–7.31$ (m, 20 H, Ph), 6.86 (s, 1 H, MeHisOMe-*Im*), 6.83 (s, 1 H, MeHisOMe-*Im*), 4.43 (s, 4 H, *H*-Cp), 4.20 (s, 2 H, *H*-Cp), 4.16 (s, 2 H, *H*-Cp), 3.63 (m, 1 H, *H*–C*α* MeHisOMe), 3.62 (s, 3 H, MeHisO*Me*), 3.47 (s, 3 H, *Me*HisOMe), 2.94 (dd, $J = 15.2$ Hz, $J = 1.8$ Hz, 1 H, C*H*$_2$), 2.76 (br, 2 H, N*H*$_2$), 2.68 (dd, $J = 15.3$ Hz, $J = 8.5$ Hz, 1 H, C*H*$_2$) ppm; $^{13}C\{^1H\}$ NMR (125.8 MHz, $CD_2Cl_2$) $\delta = 173.3$ (COOMe), 138.9 (ipso-*C*Ph), 137,5 (*C*4 MeHisOMe), 133.6 (*o*-*C*Ph), 133.4 (*m*-*C*Ph), 129.4 (*p*-*C*Ph), 119.2 (*C*5 MeHisOMe), 74.7 (*C1* Cp), 74.5 (*C2* Cp), 73.0 (*Cα* MeHisOMe), 72.8 (*C3* Cp), 54.1 (MeHisO*Me*), 34.4 (*Me*HisOMe), 30.5 (*Cβ* MeHisOMe) ppm; $^{31}P\{^1H\}$ NMR (242 MHz, 288 K, $CD_2Cl_2$): $\delta = -12.6$ ppm; ESI-MS: $m/z = 800.1350$ $(M)^+$, 617.0780 $(M–MeHisOMe)^+$; elemental analysis for $C_{42}H_{41}BCuF_4FeN_3O_2P_2$ calc: C 56.81, H 4.65, N 4.73 %, found: C 56.32, H 4.71, N 4.56 %.

**Di(3-(mesityl)-1H-pyrazol-1-yl)methane $^{Mes}$Bpm**. 3-Mesitylpyrazole (931 mg, 5 mmol), KOH (1.122 g, 20 mmol), $K_2CO_3$ (2.764 g, 20 mmol) and tetrabutylammonium bromide (0.200 g) were dispersed in DCM (30 mL). The slurry was heated to reflux for 3 days, and after completion of the reaction it was filtered. All volatiles were removed *in vacuo* from the filtrate. The resulting solid was dissolved in water and extracted with pentane (3×50 mL). The combined organic layers were dried over $MgSO_4$ before the solvent was removed *in vacuo*. The resulting yellow oil was recrystallised from pentane to give the product as colourless needles in poor yields (221 mg, 0.57 mmol, 23 %). $^1H$ NMR (500.1 MHz, $CDCl_3$): $\delta = 2.10$ (s, 12 H, o-Ar*CH*$_3$), 2.31 (s, 6 H, p-Ar*CH*$_3$), 2.49 (d, $J = 0.7$ Hz, 6 H, Pz*CH*$_3$), 5.93 (d, $J = 0.7$ Hz, 2 H, Pz*CH*$_3$), 6.35 (s, 2 H, *CH*$_2$), 6.85 (s, 4H, *m*-Ar*H*) ppm; $^{13}C\{^1H\}$ NMR (125.8 MHz, $CDCl_3$) $\delta = 20.83$ (o-Ar*CH*$_3$), 20.06 (p-Ar*CH*$_3$), 65.70 (*CH*$_2$), 108.06 (4-PzCH), 128.09 (*m*-ArCH), 130.45 (5-PzCH), 137.52 (*o*-ArCCH$_3$) 137.74 (*p*-ArCCH$_3$), 152.38 (3-PzC) ppm; elemental analysis for $C_{25}H_{28}N_4$, calc: N 14.57, C 77.09, H 7.34 % found: N:14.29, C 77.42, H 7.31 %.

**Di(3-(phenyl)-1H-pyrazol-1-yl)diphenylmethane $^{PhPh}$Bpm**. α,α-Dimethoxydiphenylmethane (350 mg, 1.5 mmol, 1 eq) was mixed with 3-phenyl-1*H*-pyrazole (500 mg, 3 mmol, 2 eq) and *p*-toluenesulfonic acid monohydrate (14 mg, 0.075 mmol, 0.05 eq). The mixture was heated to 85 °C for 2 h, and the resulting methanol was subsequently distilled off. After cooling, the mixture was dissolved in ethyl acetate (20 mL) and concentrated to ca. 5 mL. After layering with *n*-hexane, a white solid precipitated over 12 h. The solid was separated *via* filtration and the filtrate washed with water (3×10 mL). The combined organic layers were dried with sodium sulfate and all volatiles removed *in vacuo*. The resulting solid was recrystallized from diethyl ether and diphenylbis(3-phenyl-1*H*-pyrazol-1-yl)methane was collected as a colourless solid in poor yield (194 mg, 0.43 mmol, 28 %). $^1H$ NMR (500.1 MHz, $CD_2Cl_2$): $\delta = 7.82–7.77$ (m, 4 H) 7.57 (d, $J = 2.5$ Hz, 2 H, Pz–*H*), 7.46–7.36 (m, 10 H), 7.35–7.30 (m, 2 H), 7.26–7.22 (m, 4 H), 6.66 (d, $J = 2.5$ Hz) ppm; $^{13}C\{^1H\}$ NMR (125.8 MHz, $CD_2Cl_2$): $\delta = 152.3$ (3-Pz), 143.9 (Ph), 134.6 (5-Pz), 133.7 (Ph), 129.9 (Ph), 129.5 (Ph), 129.0 (Ph), 128.4 (Ph), 128.3 (Ph), 126.2 (Ph), 103.0 (4-Pz), 88.4 (Pz$_2$-*C*-Ph$_2$) ppm; elemental analysis for $C_{31}H_{24}N_4$ calc: C 82.27, H 5.35, N 12.38 %, found C 81.77, H 5.32, N 12.29 %.

**[Cu$^{PhPh}$Bpm(MeCN)]BF$_4$ (4)**. To a solution of di(3-(phenyl)-1H-pyrazol-1-yl)diphenylmethane (100 mg, 0.22 mmol, 1 eq) in dichloromethane (5 mL) a solution of tetrakis(acetonitrile)copper(I) tetrafluoroborate (77 mg, 0.24 mmol, 1.1 eq) in acetonitrile (5 mL) was added. The mixture was stirred for 1 hour at room temperature and afterwards the solvent was removed *in vacuo*. The resulting colourless oil was dried *in vacuo* and afterwards dissolved in dichloromethane. After removal of the solvent *in vacuo* a colourless solid was obtained. Recrystallisation from dichloromethane/diethyl ether at −30 °C yielded colourless crystals suitable for X-ray crystallography. **4** was isolated as colourless crystals in good yields (92 mg, 0.14 mmol, 65 %). $^1H$ NMR (400.1 MHz, $CD_2Cl_2$): $\delta = 7.82–7.77$ (m, 4 H), 7.67–7.63 (m, 2 H), 7.62 (d, $J = 2.8$ Hz, 2 H, Pz–*H*), 7.57–7.49 (m, 10 H), 6.83 (d, $J = 7.4$ Hz, 4 H, Ph-*H*), 6.76 (d, $J = 2.8$ Hz, 2 H, Pz–*H*), 2.13 (s, 3 H, C*H*$_3$CN) ppm; $^{13}C\{^1H\}$ NMR (100.6 MHz, $CD_2Cl_2$): $\delta = 155.7$ (3-Pz), 137.3 (4-Pz), 136.8, 131.9 (*i*-Ph), 131.1 (*C*H$_3$CN), 130.4, 129.9, 129.2, 127.8 (*p*-Ph), 105.2 (5-Pz), 89.5 (Pz$_2$–C–Ph$_2$), 2.6 (*C*H$_3$CN) ppm; ESI-MS: $m/z = 515.1172$ $(M–MeCN)^+$, 556,1424 $(M)^+$, 309.1331 ($CH_2$–Pz–Ph); elemental analysis for $C_{33}H_{27}BCuF_4N_5$ calc: C 61.55, H 4.23, N 10.88 %, found: C 58.99, H 4.24 N 11.04 %.

**[Cu$^{tBuPh}$Bpm(MeCN)]BF$_4$ (5)**. To a solution of di(3-(tert-butyl)-1H-pyrazol-1-yl)diphenyl-methane (452 mg, 1 mmol, 1 eq) in dichloromethane (10 mL) a solution of tetrakis(acetonitrile)copper(I) tetrafluoroborate (340 mg, 1.1 mmol, 1.1 eq) was added. The solution was stirred for 1 hour at room temperature and afterwards the solvent was removed *in vacuo*. The resulting solid was extracted with dichloromethane. After removal of the solvent *in vacuo* a colourless solid was obtained. Crystals suitable for X-ray analysis could be gained by layering a concentrated solution of **5** in dichloromethane with diethyl ether at room temperature. **5** was isolated as colourless crystals in good yields (505 mg, 0.8 mmol, 83 %). $^1H$ NMR (400.1 MHz, $CD_2Cl_2$): $\delta = 7.62$ (t, $J = 7.6$ Hz, 2 H, Ph-*H*), 7.51 (t, $J = 7.6$ Hz, 4 H, Ph-*H*), 7.44 (d, $J = 2.8$ Hz, 2 H, Pz–*H*), 6.32 (d, $J = 2.8$ Hz, 2 H, Pz–*H*), 7.09 (s, br, 1 H, Pz–*H*), 2.16 (s, 3 H, C*H*$_3$CN), 1.40 (s, 18 H, C(C*H*$_3$)$_3$) ppm; $^{13}C\{^1H\}$ NMR (100.6 MHz, $CD_2Cl_2$): $\delta = 164.8$ (Pz–C3), 135.3 (Pz–C5), 131.7 (Ph), 129.5 (Ph), 117.4 (*C*H$_3$CN), 103.2 (Pz–C4), 88.8 (Pz$_2$–*C*–Ph$_2$), 32.6 (*C*(CH$_3$)$_3$), 30.4 (C(*C*H$_3$)$_3$), 2.6 (*C*H$_3$CN) ppm; ESI-MS: $m/z = 475.1858$ $(M–MeCN)^+$, 516.2149 $(M)^+$, 289.1674 $(CPh_2–PztBu)^+$ ; elemental analysis for $C_{29}H_{35}BCuF_4N_5$ calc: C 57.67, H 5.84, N 11.60 %, found C 53.82, H 6.01, N 10.41 %.

**[Cu$^{Mes}$Bpm(MeCN)$_2$]BF$_4$ (6)**. To a solution of di(3-(mesityl)-1H-pyrazol-1-yl) methane (100 mg, 0.26 mmol, 1 eq) in dichloromethane (5 mL) a solution of tetrakis(acetonitrile)copper(I) tetrafluoroborate (90 mg, 0.28 mmol, 1.1 eq) in acetonitrile (5 mL) was added. The mixture was stirred for 1 hour at room temperature and afterwards the solvent was removed *in vacuo*. The resulting colourless oil was dried *in vacuo* and subsequently dissolved in dichloromethane. After removal of the solvent *in vacuo* a colourless solid was obtained. After recrystallisation from dichloromethane/diethyl ether at −30 °C colourless crystals suitable for X-ray crystallography were obtained. **6** was isolated in form of colourless crystals in good yields (117 mg, 0.20 mmol, 77 %). $^1H$ NMR (400.1 MHz, $CD_2Cl_2$): $\delta = 8.23$ (d, $J = 2.4$ Hz, 2 H, Pz–5*H*), 6.90 (s, 2 H, Mes-*H*), 6.58 (s, 2 H, Pz–*CH*$_2$–Pz), 6.31 (d, $J = 2.4$ Hz, 2 H, Pz–4*H*), 2.28 (s, 6 H, *CH*$_3$CN), 2.00 (s, 12 H, *o*-*CH*$_3$), 1.90 (s, 6 H, *p*-*CH*$_3$) ppm; $^{13}C\{^1H\}$ NMR (100.6 MHz, $CD_2Cl_2$): $\delta = 154.3$ (3-Pz), 138.9 (*p*-Mes), 137.9 (*o*-Mes), 134.4 (*C*H$_3$CN), 129.1 (*i*-Mes), 128.3 (*m*-Mes), 108.1 (4-Pz), 63.3 (Pz–*C*H$_2$–Pz), 21.2 (*C*H$_3$CN), 20.5 (*o*-*Me*), 2.3 (*p*-*Me*) ppm; ESI-MS: $m/z = 447.1740$ $(M–2\cdot MeCN)^+$, 488.1810 $(M–MeCN)^+$; elemental analysis for $C_{29}H_{34}BCuF_4N_6$ calc: C 56.45, H 5.55, N 13.62 %, found C 55.18, H 5.45 N 13.37 %.

## Acknowledgements

This research was funded by the Deutsche Forschungsgemeinschaft (DFG, German Research Foundation) under Germany's Excellence Strategy – EXC 2008 – 390540038 – UniSysCat. Open access funding enabled and organized by Projekt DEAL.

**Keywords:** copper(I) · histidine brace · biomimetic · diphosphines · bis(pyrazolyl)methane

[1] H. H. Nguyen, A. K. Shiemke, S. J. Jacobs, B. J. Hales, M. E. Lidstrom, S. I. Chan, *J. Biol. Chem.* **1994**, *269*, 14995–15005.
[2] S. I. Chan, K. H.-C. Chen, S. S.-F. Yu, C.-L. Chen, S. S.-J. Kuo, *Biochemistry* **2004**, *43*, 4421–4430.
[3] R. L. Lieberman, K. C. Kondapalli, D. B. Shrestha, A. S. Hakemian, S. M. Smith, J. Telser, J. Kuzelka, R. Gupta, A. S. Borovik, S. J. Lippard, B. M. Hoffman, A. C. Rosenzweig, T. L. Stemmler, *Inorg. Chem.* **2006**, *45*, 8372–8381.
[4] S. I. Chan, V. C.-C. Wang, J. C.-H. Lai, S. S.-F. Yu, P. P.-Y. Chen, K. H.-C. Chen, C.-L. Chen, M. K. Chan, *Angew. Chem. Int. Ed.* **2007**, *46*, 1992–1994; *Angew. Chem.* **2007**, *119*, 2038–2040.
[5] A. S. Hakemian, K. C. Kondapalli, J. Telser, B. M. Hoffman, T. L. Stemmler, A. C. Rosenzweig, *Biochemistry* **2008**, *47*, 6793–6801.
[6] R. Balasubramanian, S. M. Smith, S. Rawat, L. A. Yatsunyk, T. L. Stemmler, A. C. Rosenzweig, *Nature* **2010**, *465*, 115–119.
[7] S. M. Smith, S. Rawat, J. Telser, B. M. Hoffman, T. L. Stemmler, A. C. Rosenzweig, *Biochemistry* **2011**, *50*, 10231–10240.
[8] S. Sirajuddin, D. Barupala, S. Helling, K. Marcus, T. L. Stemmler, A. C. Rosenzweig, *J. Biol. Chem.* **2014**, *289*, 21782–21794.
[9] M. A. Culpepper, G. E. Cutsail III, W. A. Gunderson, B. M. Hoffman, A. C. Rosenzweig, *J. Am. Chem. Soc.* **2014**, *136*, 11767–11775.
[10] M. O. Ross, F. MacMillan, J. Wang, A. Nisthal, T. J. Lawton, B. D. Olafson, S. L. Mayo, A. C. Rosenzweig, B. M. Hoffman, *Science* **2019**, *364*, 566–570.
[11] R. L. Lieberman, A. C. Rosenzweig, *Nature* **2005**, *434*, 177–182.
[12] R. Balasubramanian, A. C. Rosenzweig, *Acc. Chem. Res.* **2007**, *40*, 573–580.
[13] L. Cao, O. Caldararu, A. C. Rosenzweig, U. Ryde, *Angew. Chem. Int. Ed.* **2018**, *57*, 162–166; *Angew. Chem.* **2018**, *130*, 168–172.
[14] K. E. H. Frandsen, T. J. Simmons, P. Dupree, J.-C. N. Poulsen, G. R. Hemsworth, L. Ciano, E. M. Johnston, M. Tovborg, K. S. Johansen, P. von Freiesleben, L. Marmuse, S. Fort, S. Cottaz, H. Driguez, B. Henrissat, N. Lenfant, F. Tuna, A. Baldansuren, G. J. Davies, L. Lo Leggio, P. H. Walton, *Nat. Chem. Biol.* **2016**, *12*, 298–303.
[15] N. Gagnon, W. B. Tolman, *Acc. Chem. Res.* **2015**, *48*, 2126–2131.
[16] R. J. Quinlan, M. D. Sweeney, L. L. Leggio, H. Otten, J.-C. N. Poulsen, K. S. Johansen, K. B. R. M. Krogh, C. I. Jørgensen, M. Tovborg, A. Anthonsen, T. Tryfona, C. P. Walter, P. Dupree, F. Xu, G. J. Davies, P. H. Walton, *Proc. Nat. Acad. Sci.* **2011**, *108*, 15079–15084.
[17] C. Citek, S. Herres-Pawlis, T. D. P. Stack, *Acc. Chem. Res.* **2015**, *48*, 2424–2433.
[18] A. Fukatsu, Y. Morimoto, H. Sugimoto, S. Itoh, *Chem. Commun.* **2020**, *56*, 5123–5126.
[19] A. Noordam, L. Maat, H. C. Beyerman, *Recl. Trav. Chim. Pays-Bas* **1978**, *97*, 293–295.
[20] R. Jain, L. A. Cohen, *Tetrahedron* **1996**, *52*, 5363–5370.
[21] P. Dierkes, P. W. N. M. van Leeuwen, *J. Chem. Soc. Dalton Trans.* **1999**, *10*, 1519–1530.
[22] C. Femoni, S. Muzzioli, A. Palazzi, S. Stagni, S. Zacchini, F. Monti, G. Accorsi, M. Bolognesi, N. Armaroli, M. Massi, G. Valenti, M. Marcaccio, *Dalton Trans.* **2012**, *42*, 997–1010.
[23] A. Kaeser, M. Mohankumar, J. Mohanraj, F. Monti, M. Holler, J.-J. Cid, O. Moudam, I. Nierengarten, L. Karmazin-Brelot, C. Duhayon, B. Delavaux-Nicot, N. Armaroli, J.-F. Nierengarten, *Inorg. Chem.* **2013**, *52*, 12140–12151.
[24] C. Bravo, M. P. Robalo, F. Marques, A. R. Fernandes, D. A. Sequeira, M. F. M. Piedade, M. H. Garcia, M. J. V. de Brito, T. S. Morais, *New J. Chem.* **2019**, *43*, 12308–12317.
[25] D. Schweinfurth, N. Büttner, S. Hohloch, N. Deibel, J. Klein, B. Sarkar, *Organometallics* **2013**, *32*, 5834–5842.
[26] D. Asil, J. A. Foster, A. Patra, X. de Hatten, J. del Barrio, O. A. Scherman, J. R. Nitschke, R. H. Friend, *Angew. Chem. Int. Ed.* **2014**, *53*, 8388–8391; *Angew. Chem.* **2014**, *126*, 8528–8531.
[27] J. Díez, M. P. Gamasa, J. Gimeno, A. Aguirre, S. García-Granda, J. Holubova, L. R. Falvello, *Organometallics* **1999**, *18*, 662–669.
[28] J. Yuasa, M. Dan, T. Kawai, *Dalton Trans.* **2013**, *42*, 16096–16101.
[29] M. H. Reineke, M. D. Sampson, A. L. Rheingold, C. P. Kubiak, *Inorg. Chem.* **2015**, *54*, 3211–3217.
[30] S.-M. Kuang, D. G. Cuttell, D. R. McMillin, P. E. Fanwick, R. A. Walton, *Inorg. Chem.* **2002**, *41*, 3313–3322.
[31] S. Tsuji, D. C. Swenson, R. F. Jordan, *Organometallics* **1999**, *18*, 4758–4764.
[32] M. J. Calhorda, P. J. Costa, O. Crespo, M. Concepción Gimeno, P. G. Jones, A. Laguna, M. Naranjo, S. Quintal, Y.-J. Shi, M. D. Villacampa, *Dalton Trans.* **2006**, *0*, 4104–4113.
[33] A. Boni, G. Pampalon, R. Peloso, D. Belletti, C. Graiff, A. Tiripicchio, *J. Organomet. Chem.* **2006**, *691*, 5602–5609.
[34] P. L. Dedert, T. Sorrell, T. J. Marks, J. A. Ibers, *Inorg. Chem.* **1982**, *21*, 3506–3517.
[35] S. Herres-Pawlis, P. Verma, R. Haase, P. Kang, C. T. Lyons, E. C. Wasinger, U. Flörke, G. Henkel, T. D. P. Stack, *J. Am. Chem. Soc.* **2009**, *131*, 1154–1169.
[36] E. A. Lewis, W. B. Tolman, *Chem. Rev.* **2004**, *104*, 1047–1076.
[37] L. Santagostini, M. Gullotti, R. Pagliarin, E. Bianchi, L. Casella, E. Monzani, *Tetrahedron: Asymmetry* **1999**, *10*, 281–295.
[38] R. Jain, J. Singh, J. H. Perlman, M. C. Gershengorn, *Bioorg. Med. Chem.* **2002**, *10*, 189–194.

Manuscript received: April 22, 2021
Revised manuscript received: May 19, 2021
Accepted manuscript online: May 20, 2021