The Reaction of μ-η^2:η^2-Peroxo- and Bis(μ-oxo)dicopper Complexes with Flavonol

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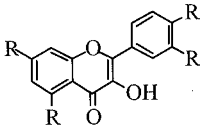
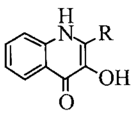
The $[Cu_2(\mu\text{-}O)_2]^{2+}$ and $[Cu_2(\mu\text{-}\eta^2{:}\eta^2\text{-}O)_2]^{2+}$ motifs with coordinated *N,N,N*-tribenzyl-1,4,7-triazacyclononane and *N,N,N*-triisopropyl-1,4,7-triazacyclononane auxiliary ligands in their reaction with flavonol do not lead to ring scission products of the heterocycle, but the formation of the corresponding (flavonolato)copper(II) complexes [Cu(fla)(Bz-TAC)]ClO_4 and [Cu(fla)(*i*Pr-TAC)]ClO_4. The subsequent oxygenolysis of the coordinated flavonolate ligand leads to *O*-benzoylsalicylate at elevated temperature, resulting in the enzyme mimicking products [Cu(*O*-bs)(Bz-TAC)]ClO_4, [Cu(*O*-bs)(*i*Pr-TAC)]ClO_4) as well as carbon monoxide. The X-ray structures of [Cu(fla)(Bz-TAC)]ClO_4, [Cu(*O*-bs)(Bz-TAC)]ClO_4, and [Cu(*O*-bs)(*i*Pr-TAC)]ClO_4) are presented.

Introduction

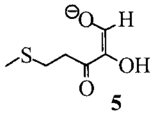
Biological oxygenations catalyzed by oxygenases are very important processes in nature for the metabolism of various organic substances.[1−5] To date, four prokaryotic dioxygenases are known, which catalyze an oxidative C−C bond cleavage with incorporation of two O-atoms into, and release of CO from the substrates quercetin (**1**) (flavonol 2,4-dioxygenase),[6−13] 3-hydroxy-4-oxo-1*H*-quinaldine (**3**) (3-hydroxy-4-oxo-1*H*-quinaldine 2,4-dioxygenase), 3-hydroxy-4-oxo-1*H*-quinoline (**4**) (3-hydroxy-4-oxo-1*H*-quinoline 2,4-dioxygenase),[14,15] and (*S*)-1,2-dihydroxy-3-oxo-5-(methylthio)pentene anion (**5**) [(*S*)-1,2-dihydroxy-3-oxo-5-(methylthio)pentene anion 1,3-dioxygenase].[16,17] Flavonol 2,4-dioxygenase ("quercetinase"), which catalyzes the cleavage of quercetin to carbon monoxide and phenolic carboxylic acid ester was produced by the species *Aspergillus flavus* and *Pullularia* (Scheme 1).[18]



1; R = OH
2; R = H



3; R = H
4; R = Me



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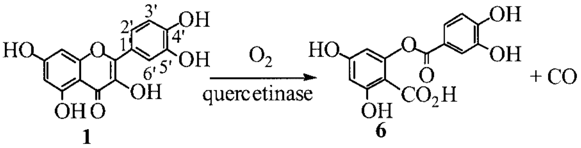

Scheme 1

Quercetinase has been reported to contain two Cu^{II} centers per molecule.[19,20] Recent diffraction studies on single crystals of quercetin 2,3-dioxygenase obtained from *Aspergillus japonicus*, at a resolution of 1.8 Å, showed that the enzyme forms homodimers, which are stabilized by an *N*-linked heptasaccharide at the dimer interface.[21] Each unit is mononuclear, with a type 2 copper center displaying two distinct geometries: a distorted tetrahedral coordination with three histidine units and one water molecules, and a distorted trigonal bipyramidal environment with an additional carboxylate. Substrate docking studies hinted to the eventual catalytic importance of the different geometries. In general, the process of oxygenase catalyzed reactions may be divided into three steps in an organic chemical sense. The first step is the activation of molecular oxygen and/or a substrate. The second step is the formation of a reactive intermediate, which would be a peroxidic compound in the case of dioxygenases,[22] and an oxygenated compound such as an arene oxide in the case of monooxygenases.[2,5,23] The third step involves the transformation of such an intermediate into the final product. From our earlier results obtained with redox[24−32] and non-redox[33,35] metal-containing model systems we concluded, that the oxygenolysis of the coordinated flavonolate ligand in aprotic solvents takes place mainly *via* an endoperoxide intermediate resulting in *O*-benzoylsalicylate as an enzyme-like

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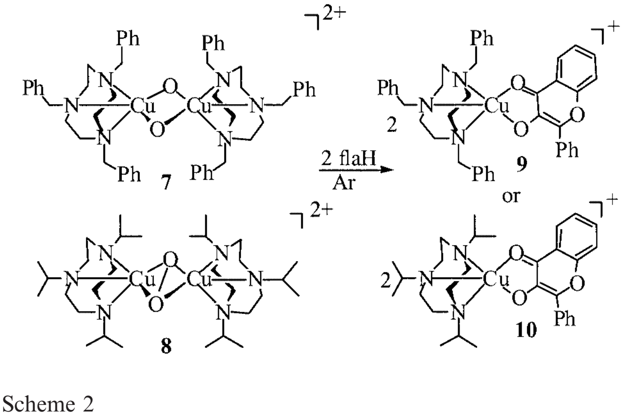
product,[36] and to a lesser extent through a 1,2-dioxethane intermediate.[37] Apart from these mechanisms, and despite recent suggestions in the literature,[38] the oxygenation of flavonol to enzyme-like products can also be postulated with the primary formation of copper-dioxygen species as the key reaction step. Earlier studies assumed coordination of quercetin to the copper(II) site through its 3-OH and 4-C=O groups.[39−41] Model studies have reinforced this hypothesis, and a fair number of copper complexes of flavonolate ligands have been isolated and structurally characterized.[24,25,28−30,42] It has also been postulated, that monodentate coordination of quercetin may be responsible for the substrate activation.[21,38,43] Since we have found in our model studies, that the oxygenation of flavonolate coordinated either to copper(I) or copper(II) requires higher reaction temperatures (around 100 °C) it cannot be excluded, that the first step in the catalytic cycle is the activation of dioxygen. In order to gain experimental support for this possibility we have directly evaluated the feasibility of this transformation by examining the reaction of flavonol with (μ-η^2:η^2-peroxo)- and bis(μ-oxo)dicopper complexes.[44−47] Herein we report that $[Cu_2(\mu\text{-}O)_2]^{2+}$ and $[Cu_2(\mu\text{-}\eta^2{:}\eta^2\text{-}O)_2]^{2+}$ cores coordinated to *N*-trisubstituted triazacyclononanes do not promote the ring cleavage reaction of the heterocycle but react with two equivalents of flavonol yielding (flavonolato)copper(II) complexes. Subsequent oxygenation of the (flavonolato)copper(II) complexes by dioxygen at elevated temperatures results in (*O*-benzoylsalicylato)copper(II) complexes and CO.

Results and Discussion

Addition of two equivalents of flavonol (**2**; flaH) to a solution of $[\{Cu(Bz\text{-}TAC)\}_2(\mu\text{-}O)_2](ClO_4)_2$ or $[\{Cu(i\text{Pr-}TAC)\}_2(\mu\text{-}\eta^2{:}\eta^2\text{-}O)_2](ClO_4)_2$ in CH_2Cl_2 at −80 °C caused bleaching of their respective optical absorption features (Bz-TAC = *N*,*N*,*N*-tribenzyl-1,4,7-triazacyclononane, *i*Pr-TAC = *N*,*N*,*N*-triisopropyl-1,4,7-triazacyclononane). Upon subsequent warming and workup, the green complexes $[Cu(fla)(Bz\text{-}TAC)]ClO_4$ (**9**) or $[Cu(fla)(i\text{Pr-}TAC)]ClO_4$ (**10**) (fla = flavonolate) were isolated as crystalline solids in yields of 95 and 90%, respectively (Scheme 2). The reaction products were identified on the basis of spectroscopic comparisons with previously reported examples, magnetic properties, and X-ray crystallography. Tests for the concomitant formation of H_2O_2 did not give convincing results irrespective of whether there was a selectivity in terms of forming either H_2O_2 or H_2O from the peroxo or oxo copper complexes.



Scheme 2

The IR spectra of the complexes $[Cu(fla)(Bz\text{-}TAC)]ClO_4$ and $[Cu(fla)(i\text{Pr-}TAC)]ClO_4$ show principal bands corresponding to coordinated flavonolate at 1545 and 1554 cm^{-1}, respectively. Decreases of approximately 50 cm^{-1} in the ν(CO) bands compared with that of flavonol [ν(CO) = 1602 cm^{-1}] are due to chelation and formation of stable five-membered rings.[48] The charge transfer region in the electronic spectra of the complexes $[Cu(fla)(Bz\text{-}TAC)]ClO_4$ and $[Cu(fla)(i\text{Pr-}TAC)]ClO_4$ exhibit bands of the coordinated flavonolate ligand at 432 and 434 nm. Bands at 615 and 653 nm are associated with d-d transitions of the complexes.

The molecular structure together with selected bond lengths and angles of $[Cu(fla)(Bz\text{-}TAC)]ClO_4$ are shown in Figure 1. The molecule is monomeric in the solid state. The copper(II) center is in a distorted square-pyramidal environment as judged by the method of Allison and co-workers (τ = 0.12)[49] with basal planes defined by two nitrogen atoms derived from the tridentate *N*,*N*,*N*-tribenzyl-1,4,7-triazacyclononane ligand [Cu−N19, 2.040(3); Cu−N22, 2.027(3) Å], and two oxygen atoms of the flavonolate [Cu−O1, 1.917(3); Cu−O8, 2.012(3) Å]. The third nitrogen atom of the *N*,*N*,*N*-tribenzyl-1,4,7-triazacyclononane ligand [Cu−N25, 2.231(3) Å] is in the apical position. The Cu−O8 bond is 0.095 Å longer than the Cu−O1 bond. The C2−O1 distance is shorter while the C7−O8 distance is longer than those in the uncoordinated flavonol [1.357(3) and 1.232(3) Å].[50] Due to coordination to the copper ion there are also

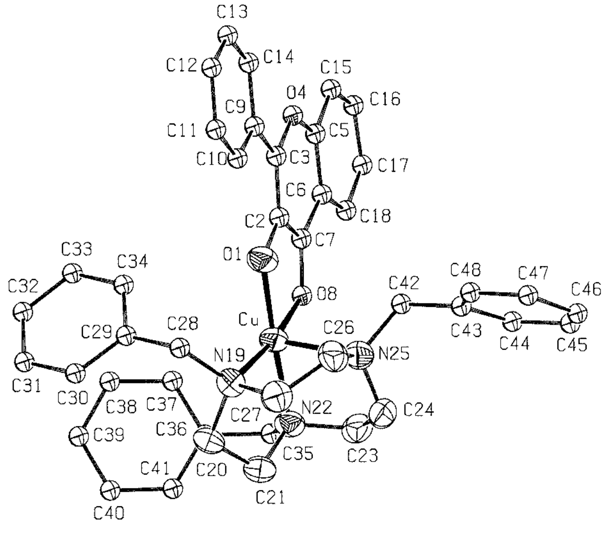
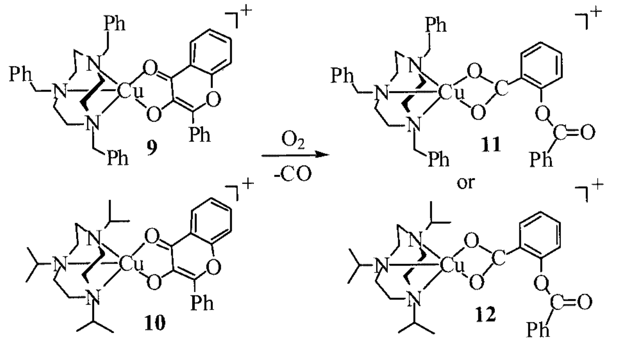


Figure 1. View showing the structure of $[Cu(fla)(Bz\text{-}TAC)]ClO_4$ (**9**); selected bond lengths (Å) and angles (deg): Cu−O1 1.917(3), Cu−O8 2.012(3), Cu−N22 2.027(3), Cu−N19 2.040(3), Cu−N25 2.231(3), O1−C2 1.339(4), O8−C7 1.273(4), C2−C3, 1.381(5), C2−C7 1.401(5); O1−Cu−N22 177.60(12), O8−Cu−N19 170.25(12), N19−Cu−N25 85.94(12), C2−O1−Cu 111.5(2), C7−O8−Cu 109.9(2)

changes in the bond lengths of the pyranone ring. The O4−C3 [1.362(4) Å] and C5−C6 [1.381(5) Å] bond lengths become longer, and the C2−C7 bond length [1.401(5) Å] is somewhat shorter, which may be assigned to delocalization of the π-system over the whole molecule. Similar reactions of peroxo- and bis(μ-oxo)dicopper complexes bearing the *N*,*N*,*N*-trisubstituted 1,4,7-triazacyclononane ligands with catechols resulted in the corresponding copper(II) semiquinone complexes.[51] Since the amine macrocyclic ligands are hard, and prefer copper(II), the copper ion remained in this oxidation state. It was not specified, however, whether H_2O or H_2O_2 was formed as the reduction product from O_2.

Treatment of the (flavonolato)copper complexes [Cu(fla)(Bz-TAC)]ClO$_4$ or [Cu(fla)(*i*Pr-TAC)]ClO$_4$ with dioxygen in DMF solution at elevated temperatures leads to the corresponding (*O*-benzoylsalicylato)copper complexes [Cu(*O*-bs)(Bz-TAC)]ClO$_4$ (**11**) and [Cu(*O*-bs)(*i*Pr-TAC)]ClO$_4$ (**12**) (Scheme 3). The IR spectra of the complexes [Cu(*O*-bs)(Bz-TAC)]ClO$_4$ and [Cu(*O*-bs)(*i*Pr-TAC)]ClO$_4$ show principal bands corresponding to ν(CO) at 1741 and 1747 cm^{-1}, respectively. Bands corresponding to ν(CO$_2$) for the two complexes appear at 1586 and 1432, and 1584 and 1428 cm^{-1}, respectively.



Scheme 3

The molecular structure together with selected bond lengths and angles of [Cu(*O*-bs)(Bz-TAC)]ClO$_4$ are shown in Figure 2. The copper(II) center is in a distorted square pyramidal environment (τ = 0.16)[49] with basal planes defined by two nitrogen atoms derived from the tridentate *N*,*N*,*N*-tribenzyl-1,4,7-triazacyclononane ligand, and two oxygen atoms of the bidentate carboxylate group. The apical position is occupied by the other nitrogen atom of the *N*,*N*,*N*-tribenzyl-1,4,7-triazacyclononane ligand. The copper−nitrogen bond lengths [Cu−N1 2.000(2), Cu−N4 2.010(2), and Cu−N7 2.182(2) Å] are similar to values obtained for [Cu(fla)(Bz-TAC)]ClO$_4$. The Cu−O bond lengths are shorter than those in [Cu(*O*-bs)(idpaH)]ClO$_4$ [1.995(5) and 2.344(6) Å].[30]

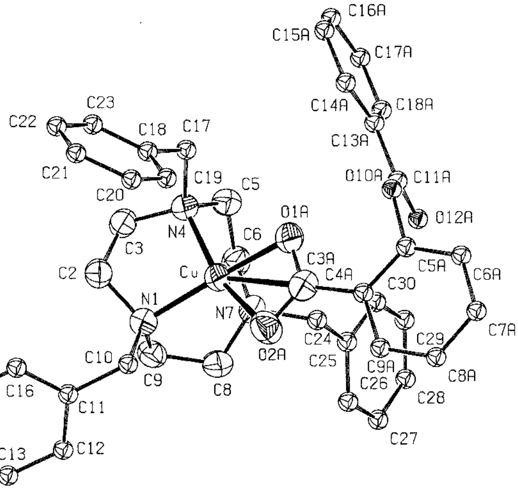


Figure 2. View showing the structure of [Cu(*O*-bs)(Bz-TAC)]ClO$_4$ (**11**); selected bond lengths (Å) and angles (deg): Cu−O1A 1.9772(17), Cu−O2A 2.0685(19), Cu−N1 2.000(2), Cu−N4 2.010(2), Cu−N7 2.182(2) O1A−C3A, 1.273(3) O2A−C3A, 1.256(3); O1A−Cu−N1 171.19(8), O1A−Cu−O2A 64.87(7), N4−Cu−O2A 161.55(8), N4−O1−N7 86.94(8)

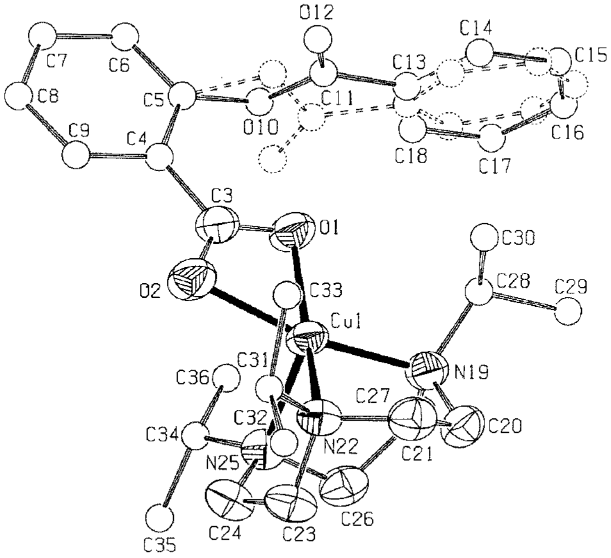
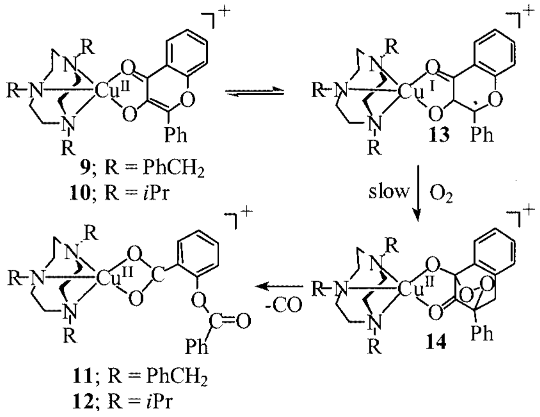


Figure 3. View showing the structure of [Cu(*O*-bs)(*i*Pr-TAC]ClO$_4$ (**12**); selected bond lengths (Å) and angles (deg): Cu1−O1 1.981(6), Cu1−O2 2.020(7), Cu1−N19 2.020(7), Cu1−N22 2.033(6), Cu1−N25 2.208(7), O1−C3 1.261(10), O2−C3 1.268(10); O1−Cu1−N22 159.8(3), O1−Cu1−O2 64.8(2), N19−Cu1−O2 165.6(2), N22−Cu1−N25 87.7(3)

Crystallographic characterization has shown that in [Cu(*O*-bs)(*i*Pr-TAC)]ClO$_4$ (**12**, Figure 3), the copper(II) ion has a distorted square pyramidal arrangement (τ = 0.10)[49] with basal planes defined by two nitrogen atoms derived from the tridentate *N*,*N*,*N*-triisopropyl-1,4,7-triazacyclononane ligand, and two oxygen atoms of the bidentate carboxylate group. The apical position is occupied by the other nitrogen atom of the *N*,*N*,*N*- triisopropyl-1,4,7-triazacyclononane ligand. A view of the coordination geometry as well as selected bond lengths and angles are given in Figure 2. The copper−nitrogen bond lengths [Cu1−N19 2.020(7), Cu1−N22 2.033(6), Cu1−N25,= 2.208(7) Å] are similar to values obtained for [Cu(*O*-bs)(Bz-TAC)]ClO$_4$. The value of (Cu1−O2) − (Cu1−O1) (0.039 Å) is somewhat shorter than that found in the complex [Cu(*O*-bs)(Bz-TAC)]ClO$_4$ (0.0913 Å), which may be assigned to the higher degree of delocalization in the carboxylate group.

Oxygenation reactions of [Cu(fla)(Bz-TAC)]ClO_4 and [Cu(fla)(*i*Pr-TAC)]ClO_4 complexes were followed by UV-Vis spectroscopy. Plots of log[Cu(fla)(Bz-TAC)]ClO_4 and log[Cu(fla)(*i*Pr-TAC)]ClO_4 versus time showed linear dependences under pseudo-first-order conditions (constant dioxygen pressure) in agreement with a rate equation of first-order dependence with respect to [Cu(fla)(Bz-TAC)]-ClO_4 and [Cu(fla)(*i*Pr-TAC)]ClO_4, respectively. Experiments performed at different dioxygen concentrations showed that both of the reactions are also first order with respect to dioxygen concentration. According to the kinetic data obtained, the oxygenation reactions obey an overall second-order rate equation, from which the mean values of the kinetic constants k_{obs} of $3.31 \pm 0.01 \times 10^{-3}$ ([Cu-(fla)(Bz-TAC)]ClO_4) and $1.51 \pm 0.01 \times 10^{-3}$ $mol^{-1}\cdot dm^3\,s^{-1}$ ([Cu(fla)(*i*Pr-TAC)]ClO_4) at 120 °C were obtained. The calculated rate constant is, in the case of [Cu(fla)(Bz-TAC)]-ClO_4, almost two times larger than that for [Cu(fla)(*i*Pr-TAC)]ClO_4. Oxidative cleavage of the C2−C3 double bond of the pyranone ring of the coordinated flavonolato ligand in both cases takes place in a similar fashion as in the enzymatic reaction. Stoichiometric oxygenation reactions can be interpreted as shown in Scheme 4. We are inclined to assume a redox role for the copper(II). Due to the valence isomerism of the copper(II) flavonolate complexes, copper(I) flavonoxy radical species are also formed, as suggested earlier.[37] Similar electromeric effects between metal catecholate and metal semiquinone complexes have been demonstrated.[52,53] They have two redoxactive sites, the flavonoxy radical ligand and the Cu^I center, which can react with dioxygen in a slow step to form the endoperoxide intermediates. These then break down rapidly to the corresponding (*O*-benzoylsalicylato)copper(II) complexes and CO.



Scheme 4

Conclusion

In conclusion, we have found that $Cu_2^{III}(\mu\text{-}O)_2$ and $Cu_2^{II}(\mu\text{-}\eta^2{:}\eta^2\text{-}O)_2$ complexes with triazacyclononane auxiliary ligands are not able to cleave the C2−C3 double bond in flavonol under mild reaction conditions. Instead, the corresponding (flavonolato)copper(II) complexes are formed. The latter complexes, however, undergo ring scission in their reaction with dioxygen under more forcing conditions resulting in the (*O*-benzoylsalicylato)copper(II) complexes and carbon monoxide. These results enable us to conclude, that in the enzyme catalyzed reaction, the activation of the substrate flavonol through its coordination to the copper(II) center probably takes place, and its oxygenation and subsequent reaction of the copper-dioxygen species with flavonol is the real catalytic situation.

Experimental Section

General Remarks: All reagents and solvents were purchased from commercial sources and were of reagent quality unless otherwise stated. All air-sensitive compounds were handled under argon using standard Schlenk techniques.[54]

Caution! *Perchlorate salts of metal complexes with organic ligands are potentially explosive. Only small amounts of material should be prepared, and these should be handled with great care.*

Synthesis of [Cu(fla)(Bz-TAC)]ClO_4 (9): A solution of [{Cu(Bz-TAC)}$_2$(μ-O)$_2$](ClO_4)$_2$ in CH_2Cl_2 (15 mL) at −80 °C was prepared as described previously (0.164 g, 0.5 mmol scale of Cu^I precursor).[46,47] After removal of excess dioxygen by purging with argon at −80 °C for 10 min, a solution of flavonol (0.119 g, 0.5 mmol) in CH_2Cl_2 (5 mL) was added, resulting in an instantaneous color change from red-brown to intense green. The reaction mixture was stirred at −80 °C for 1 h, and then warmed to room temperature. After concentrating the solution by evaporation under vacuum, Et_2O was added to induce precipitation of a green solid which was collected by filtration, washed with Et_2O, and air-dried (95%, m.p. 224−226 °C). The crude product was recrystallized from CH_3CN. $C_{42}H_{42}ClCuN_3O_7$ (799.80): calcd. C 63.1, H 5.3, N 5.3; found C 62.9, H 5.5, N 5.5. UV-Vis (DMF): $\lambda_{max.}$ (log ε) = 269 (4.23) 432 (2.23), 615 (2.90), 1040 (1.73) nm. IR (KBr, cm^{-1}): $\tilde{\nu}$ = 1097 (vs, νClO_4^-), 634 (s, νClO_4^-), 1545 (s, νCO). EPR (MeCN): $g = 2.115$, $A = 66.0$ G. $\mu_{eff} = 1.93$ BM.

Synthesis of [Cu(fla)(*i*Pr-TAC)]ClO_4 (10): This compound was prepared analogously to [Cu(fla)(Bz-TAC)]ClO_4 but by treating [{Cu(*i*Pr-TPA)}$_2$(μ-η^2:η^2-O)$_2$](ClO_4)$_2$ [44] with flavonol (90%, m.p. 235−237 °C). The crude product was recrystallized from CH_3CN. $C_{30}H_{42}ClCuN_3O_7$ (655.7): calcd. C 55.0, H 6.5, N 6.4; found C 54.8, H 6.3, N 6.5. UV-Vis (DMF): $\lambda_{max.}$ (log ε) = 274 (3.54) 434 (3.52), 653 (2.15), 1065 (1.89) nm. IR (KBr, cm^{-1}): $\tilde{\nu}$ = 1097 (vs, νClO_4^-), 628 (s, νClO_4^-), 1554 (s, νCO). EPR (MeCN): $g = 2.116$, $A = 66.4$ G. $\mu_{eff} = 1.89$ BM.

Oxygenation of [Cu(fla)(R-TAC)]ClO_4 (R = Bz, *i*Pr): [Cu(fla)(Bz-TAC)]ClO_4 or [Cu(fla)(*i*Pr-TAC)]ClO_4) (0.25 mmol) was dissolved in DMF (5 mL) and stirred at 120 °C under dioxygen for 12 h. The formation of [Cu(*O*-bs)(Bz-TAC)]ClO_4 or [Cu(*O*-bs)(*i*Pr-TAC)]-ClO_4 from [Cu(fla)(Bz-TAC)]ClO_4 or [Cu(fla)(*i*Pr-TAC)]ClO_4 requires dioxygen but no apparent uptake was observed because the absorption of dioxygen, and the liberation of carbon monoxide compensate each other. Dilute NH_3 solution (0.5 mL) was added to a portion of the reaction mixture (1 mL) at room temperature, and the organic phase was extracted with diethyl ether. Diazomethane solution (1 mL) was then added and the conversion to the coordinated flavonolate (78 and 57%) was determined by GC.

Synthesis of [Cu(*O*-bs)(Bz-TAC)]ClO$_4$ (11): To a solution of [Cu(CH$_3$CN)$_4$]ClO$_4$ (0.119 g, 0.5 mmol) and Bz-TAC (0.13 g, 0.5 mmol) in CH$_3$CN (10 mL) was added *O*-benzoylsalycilic acid (0.121 g, 0.5 mmol) in CH$_3$CN (10 mL), and the solution was heated to reflux for 5 h under O$_2$. After concentrating the solution by evaporation under vacuum, Et$_2$O was added to induce precipitation of a blue solid, which was collected by filtration, washed with Et$_2$O, and air-dried (92%, m.p. 198−200 °C). X-ray quality crystals were obtained by slow evaporation of a CH$_3$CN solution. C$_{41}$H$_{42}$ClCuN$_3$O$_8$ (803.8): calcd. C 61.3, H 5.3, N 5.2; found C 60.8, H 5.1, N 5.0. UV-Vis (DMF): $\lambda_{\max.}$ (log ε) = 276 (3.81), 650 (1.96), 1035 (1.62) nm. IR (KBr, cm^{-1}): $\tilde{\nu}$ = 1097 (vs, νClO$_4^-$), 628 (s, νClO$_4^-$), 1741 (s, νCO), 1586 (s, ν_{as}CO$_2$). 1432 (s, ν_sCO$_2$). EPR (MeCN): g = 2.120, A = 62.0 G. μ_{eff} = 1.99 BM.

Synthesis of [Cu(*O*-bs)(*i*Pr-TAC)]ClO$_4$ (12): This compound was prepared analogously to [Cu(*O*-bs)(Bz-TAC)]ClO$_4$ but using the *i*Pr-TAC ligand instead (90%, m.p. 235−237 °C). X-ray quality crystals were obtained by slow evaporation of a CH$_3$CN solution. C$_{29}$H$_{42}$ClCuN$_3$O$_8$: calcd. C 52.8, H 6.4, N 6.4; found C 52.4, H 6.2, N 6.6. UV-Vis (DMF): $\lambda_{\max.}$ (log ε) = 278 (3.23), 670 (1.43), 1060 (1.73) nm. IR (KBr, cm^{-1}): $\tilde{\nu}$ = 1095 (vs, νClO$_4^-$), 627 (s, νClO$_4^-$), 1747 (s, νCO), 1584 (s, ν_{as}CO$_2$). 1428 (s, ν_sCO$_2$). EPR (MeCN): g = 2.121, A = 60.3 G. μ_{eff} = 1.97 BM.

Kinetic Measurements: Reactions of [Cu(fla)(Bz-TAC)]ClO$_4$ and [Cu(fla)(*i*Pr-TAC)]ClO$_4$ with dioxygen were performed in DMF solutions. In a typical experiment [Cu(fla)(Bz-TAC)]ClO$_4$ or [Cu(fla)(*i*Pr-TAC)]ClO$_4$ was dissolved under argon in a thermostatically controlled reaction vessel with an inlet for taking samples with a syringe, and connected to a mercury manometer to maintain a constant pressure. The solution was then heated to the appropriate temperature. A sample was then taken by syringe and the initial concentration of [Cu(fla)(Bz-TAC)]ClO$_4$ or [Cu(fla)(*i*Pr-TAC)]ClO$_4$ was determined by UV-Vis spectroscopy measuring the absorbance of the reaction mixture at 432 nm or 434 nm {$\lambda_{\max.}$ of a typical band of [Cu(fla)(Bz-TAC)]ClO$_4$ or [Cu(fla)(*i*Pr-TAC)]ClO$_4$}, respectively. The argon was then replaced by dioxygen and consumption of the latter was periodically monitored. The rate of oxygenation was independent of the stirring rate, excluding

Table 1. Crystal data, data collection, and structural refinement details

	9	**12**	**11**
Empirical formula	C$_{84}$H$_{84}$Cl$_2$Cu$_2$N$_6$O$_{14}$	C$_{29}$H$_{42}$ClCuN$_3$O$_8$	C$_{41}$H$_{42}$ClCuN$_3$O$_8$
Molecular mass	1599.55	659.65	803.77
Temperature	293(2) K		
Radiation and wavelength	Mo-K_α, λ = 0.71073 Å		
Crystal system	triclinic	triclinic	monoclinic
Space group	$P\bar{1}$	$P\bar{1}$	$P2_1/c$
Unit cell dimensions			
a (Å)	9.831(3)	10.756(1)	19.373(3)
b (Å)	12.065(2)	12.589(1)	11.683(3)
c (Å)	16.512(3)	12.787(2)	19.355(2)
α (°)	87.33(2)	79.47(1)	90
β (°)	83.26(1)	73.31(1)	117.82(1)
γ (°)	76.07(2)	75.13(1)	90
Volume (Å^3)	1887.4(7)	1591.8(3)	3874.4(12)
Z	1	2	4
Density (calcd.) (Mg·m^{-3})	1.41	1.38	1.38
Absorption coeff., μ (mm^{-1})	0.71	0.82	0.69
F(000)	834	694	1676
Crystal color	grayish green	dark green	bluish green
Crystal description	plate	block	plate
Crystal size (mm)	0.60 × 0.15 × 0.05	0.40 × 0.35 × 0.25	0.50 × 0.30 × 0.25
Absorption correction	psi-scan		
Transmission, max. and min.	0.9811 and 0.8005	0.9854 and 0.7605	0.9817 and 0.9781
θ Range [°]	2.42 ≤ θ ≤ 26.97	2.28 ≤ θ ≤ 29.96	2.38 ≤ θ ≤ 27.97
Index ranges	$-12 \le h \le 12$	$-15 \le h \le 15$	$-25 \le h \le 22$
$-15 \le k \le 15$	$-17 \le k \le 17$	$0 \le k \le 15$	
$-21 \le l \le 21$	$-17 \le l \le 17$	$0 \le l \le 25$	
Reflections collected	17820	19419	9786
Completeness to 2θ	0.992	0.986	0.994
Number of standard reflections	3		
Decay	0%	1%	4%
Independent reflections	8152 [R(int) = 0.0422]	9112 [R(int) = 0.0265]	9280 [R(int) = 0.0142]
Reflections I>2σ(I)	3692	5140	4537
Refinement method	full-matrix least-squares on F^2		
Data/restraints/parameters	8152 /47/497	9112 /34 /463	9280 /93 /530
Goodness-of-fit on F^2	0.856	0.902	0.867
Final R indices I>2σ(I)	$R1$ = 0.0544, $wR2$ = 0.1257	$R1$ = 0.0559, $wR2$ = 0.1446	$R1$ = 0.0427, $wR2$ = 0.0970
R indices (all data)	$R1$ = 0.1411, $wR2$ = 0.1478	$R1$ = 0.1026, $wR2$ = 0.1621	$R1$ = 0.1171, $wR2$ = 0.1098
Max. and mean shift/esd.	0.001; 0.000	0.067; 0.002	2.637; 0.112
Largest diff. peak and hole (e·Å^{-3})	0.749 and −0.456	1.000 and −0.689	0.363 and −0.312

eventual diffusion control effects. The dioxygen concentration was calculated from literature data (as 6.96×10^{-3} M)[55] taking into account the partial pressure of DMF,[56] and assuming the validity of Dalton's law.

X-ray Crystallographic Studies: Intensity data were collected on an Enraf−Nonius CAD4 diffractometer (graphite monochromator; Mo-K_α radiation, $\lambda = 0.71073$ Å) at 293(2) K using $\omega/2\theta$ scans. The intensities of three standard reflections were monitored regularly (every 60 min). Psi-scan absorption corrections were applied to the data.[57]

The structures were solved by direct methods (and subsequent difference syntheses),[58] and refined by anisotropic full-matrix least-squares on F^2 for all non-hydrogen atoms.[59] Hydrogen atomic positions were calculated from assumed geometries. Hydrogen atoms were included in structure factor calculations but they were not refined. The isotropic displacement parameters of the hydrogen atoms were approximated from the U_{eq} value of the atom to which they were bonded. Crystal data, data collection, and refinement details are shown in Table 1. The ClO_4^- anions are disordered in all three structures. In **11** the perchlorate O1c atom is ordered and the remaining three oxygens split into seven partially occupied positions. The sum of these occupation factors were bound to give three. The high maximum and mean shift/esd is due to the site occupation factor of O3c. In **12** (Figure 3) only one perchlorate oxygen atom splits but the O10···C18 (Ph−COO) moiety is, however, disordered with 2/3:1/3 occupancies. For the presentation of the molecular structures, the molecular graphics program PLATON was used.[60]

CCDC-201803 (for **9**), -201804 (for **11**), and -201805 (for **12**) contain the supplementary crystallographic data for this paper. These data can be obtained free of charge at www.ccdc.cam.ac.uk/conts/retrieving.html or from Cambridge Crystallographic Data Center, 12, Union Road, Cambridge CB2 1EZ, UK [Fax: (internat.) +44-1223/336-033; E-mail: deposit@ccdc.cam.ac.uk].

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