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Influence of Ligand Denticity and Flexibility on the Molecular Copper Mediated Oxygen Reduction Reaction

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ABSTRACT: To date, the copper complex with the tris(2-pyridylmethyl)amine (tmpa) ligand (Cu-tmpa) catalyzes the ORR with the highest reported turnover frequency (TOF) for any molecular copper catalyst. To gain insight into the importance of the tetradentate nature and high flexibility of the tmpa ligand for efficient four-electron ORR catalysis, the redox and electrocatalytic ORR behavior of the copper complexes of 2,2′:6′,2″-terpyridine (terpy) and bis(2-pyridylmethyl)amine (bmpa) (Cu-terpy and Cu-bmpa, respectively) were investigated in the present study. With a combination of cyclic voltammetry and rotating ring disk electrode measurements, we demonstrate that the presence of the terpy and bmpa ligands results in a decrease in catalytic ORR activity and an increase in Faradaic efficiency for H2O2 production. The lower catalytic activity is shown to be the result of a stabilization of the CuI state of the complex compared to the earlier reported Cu-tmpa catalyst. This stabilization is most likely caused by the lower electron donating character of the tridentate terpy and bmpa ligands compared to the tetradentate tmpa ligand. The Laviron plots of the redox behavior of Cu-terpy and Cu-bmpa indicated that the formation of the ORR active catalyst involves relatively slow electron transfer kinetics which is caused by the inability of Cu-terpy and Cu-bmpa to form the preferred tetrahedral coordination geometry for a CuI complex easily. Our study illustrates that both the tetradentate nature of the tmpa ligand and the ability of Cu-tmpa to form the preferred tetrahedral coordination geometry for a CuI complex are of utmost importance for ORR catalysis with very high catalytic rates.

INTRODUCTION

The transition from fossil fuels to sustainable energy sources is an important step to achieve a renewable future. For this purpose, both the storage and the conversion of fuels such as hydrogen play a key role. To minimize energy loss during the fuel-to-energy conversion, efficient fuel cells are required. A significant obstacle which limits applicability of fuel cells on a large scale is the energy loss related to the overpotential required for the cathodic oxygen reduction reaction (ORR).1,2

In nature, multicopper oxidases couple the oxidation of substrate near a mononuclear copper site to efficient ORR catalysis at a trinuclear copper site. For multicopper oxidase laccase, ORR catalysis takes place with TOFs from 2 to 560 s−1,3−8 and when immobilized on electrodes, laccases have been reported to be able to operate significantly closer to the equilibrium potential of water than the platinum-based heterogeneous catalysts that are typically employed in fuel cell chemistry.9−16 In order to shed light on how the ORR can be mediated in a more efficient manner in an artificial system, a wide range of copper systems has been reported in the last three decades as biomimetic models for active sites in multicopper oxidases due to their dioxygen activation reactivity.17−36

With almost 2 million turnovers per second (1.8·106 s−1), the highest catalytic rates reported thus far for oxygen reduction mediated by a homogeneous copper catalyst have been reported for a copper complex with the tris(2-pyridylmethyl)amine (tmpa) ligand (Cu-tmpa).17−22 The dioxygen binding chemistry and catalytic ORR behavior of Cu-tmpa have been studied extensively.22−44 Reduction of dioxygen occurs via a stepwise mechanism wherein hydrogen peroxide is obtained as an isolable and obligatory intermediate.45 The binding constant kO2 = 1.3·109 M−1 s−1 of dioxygen binding to [CuI(tmpa)]+ determined in THF is roughly in the same ballpark as the TOF under aqueous conditions where the oxygen concentration equals 1.1 mM.19

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It therefore seems likely that binding of dioxygen to [Cu(‘tmpa)]− is rate limiting. Formation of dinuclear species via coupling of [Cu(‘tmpa)]− with [Cu2(‘tmpa)]-superoxide as detected in organic solvent is most likely too slow to play a role under catalytic conditions.38,40 Due to the very high activity of Cu-tmpa, rates are typically mass-transport limited in either dioxygen or phosphate buffer. At diluted concentrations, however, a first order dependence in copper was observed.37 Noteworthy is that the onset potential and activity of the ORR with respect to the reduction of hydrogen peroxide lie in favor of the first reaction resulting in a buildup of hydrogen peroxide under conditions where the reaction is not run under mass-transport limitations of dioxygen. The overpotential of an optimized catalyst therefore is probably limited by the equilibrium potential of hydrogen peroxide at 0.68 V versus RHE. Questions that remain are to which extent the activity, selectivity, and overpotential of the ORR can be adjusted individually and whether a direct four-electron reduction of dioxygen near the equilibrium potential of water is feasible.

Marcus theory dictates that the rates of redox reactions are affected by their accompanying reorganization energies.55 This largely relates to the ability of ligands to accommodate the metal site at multiple oxidation states and to switch between these geometries via facile transitions. To investigate how the overall TOF for the ORR mediated by single copper sites is affected by intrinsic reorganization barriers, and which effect this has on the catalyst selectivity and the entire catalyst profile, we investigated the ORR mediated by copper complexes employed with the rigid terpy and the more dynamic bmpa ligands (terpy = 2,2′:6′,2″-terpyridine), bmpa = (bis(2-pyridylmethyl)amine)).

■ RESULTS AND DISCUSSION

Synthesis. As previously reported, complexation of terpy and bmpa with one equivalent of a CuII salt is expected to result in the complexes [Cu(terpy)LX2] and [Cu(bmpa)LX2], respectively.46−50 The triflate complexes [Cu(terpy)(H2O)(OTf)2] and [Cu(bmpa)(H2O)(OTf)2] will be referred to as Cu-terpy and Cu-bmpa, respectively (Figure 1). The structures depicted in Figure 1 are a simplification of a situation in which either the trflate counterions or additional water molecules are expected to coordinate weakly at the axial positions. The synthesis of the mononuclear copper complexes Cu-terpy and Cu-bmpa is described in Section 1.2 of the Supporting Information. Both complexes were characterized by elemental analysis and UV-visible spectroscopy (see Section 1.2 in the Supporting Information). The latter indicated that both complexes are stable in an aqueous pH 7 buffered solution for at least a few days (Figure S1). EPR spectroscopy and X-ray diffraction studies are in line with an elongated octahedral, square pyramidal, or square planar geometry for Cu-bmpa and an elongated octahedral geometry for Cu-terpy, respectively (see Sections 3 and 4 in the Supporting Information).

Redox Behavior of Cu-terpy and Cu-bmpa. Using a glassy carbon working electrode (GC WE), the redox behavior of mononuclear copper complexes Cu-terpy and Cu-bmpa was investigated by performing cyclic voltammetry (CV) measurements in an aqueous pH 7 buffered electrolyte. Under 1 atm Ar, Cu-terpy shows one CuII/CuI redox couple in 0.1 M pH 7 phosphate buffer (Figure 2a). At a scan rate of 100 mV s−1, this redox couple is located at a half-wave potential ($E_{1/2}$) of 0.31 V vs RHE. The peak-to-peak potential separation ($\Delta E_p$) amounts to 76 mV. This relatively large $\Delta E_p$ value indicates that the CuII/CuI redox couple of Cu-terpy is not a perfect reversible one-electron redox process at a scan rate of 100 mV s−1.51 The slight irreversibility is confirmed by an observed difference of ∼5 μC in buildup charge during the anodic and cathodic events, for which 13 and 8 μC were recorded, respectively. For Cu-bmpa, at least two overlapping CuII/CuI redox couples were observed in pH 7 phosphate buffer under 1 atm Ar (Figure S4a). However, only one CuII/CuI redox couple was observed for Cu-bmpa in 0.1 M pH 7 HEPES buffer in 0.1 M NaClO4 (Figure 2b). It can therefore be concluded that the observed additional redox couple of Cu-bmpa in the presence of phosphate buffer is most likely the result of the formation of a phosphate coordinated Cu-bmpa complex. At a scan rate of 100 mV s−1, the CuII/CuI redox couple of Cu-bmpa is located at $E_{1/2} = 0.30$ V vs RHE in HEPES buffered NaClO4 electrolyte with $\Delta E_p$ amounting to 56 mV. This peak-to-peak separation is in agreement with a homogeneous system undergoing a reversible one-electron redox process.51 The more reversible character of the redox couple of Cu-bmpa compared to the redox couple of Cu-terpy is confirmed by a smaller difference in buildup charge during the anodic and cathodic events of the redox couple of Cu-bmpa which amounts to only ∼2 μC in favor of the former.

Scan Rate Dependence Study of Redox Behavior. The redox behavior of Cu-terpy and Cu-bmpa was further assessed by performing a scan rate dependence study under 1 atm Ar (Figure 2). During this study, it was found that the $\Delta E_p$ value of the CuII/CuI redox couple of Cu-terpy increases significantly with the scan rate. At the lowest applied scan rate (10 mV s−1), the $\Delta E_p$ value for the CuII/CuI redox couple of Cu-terpy amounts to 55 mV. For Cu-bmpa, the $\Delta E_p$ value of the CuII/CuI redox couple was found to increase slightly for scan rates above 100 mV s−1. At the highest scan rate applied during this study (500 mV s−1), this $\Delta E_p$ value amounts to 71 mV. The increase in the $\Delta E_p$ value above a scan rate of 100 mV s−1 indicates that the electron transfer of the CuII/CuI redox couple of Cu-bmpa becomes relatively slow above this scan rate.

For both Cu-terpy and Cu-bmpa, the observed increase in $\Delta E_p$ value with higher applied scan rate is the result of a significant positive shift in peak potential of the anodic event of the CuII/CuI redox couple and a minor negative shift in peak potential of the cathodic event of the CuII/CuI redox couple. This effect is depicted in the Laviron plots of Figure 3 in which the peak potentials of the anodic and cathodic events have been plotted vs the logarithm of the scan rate.

As shown in Figure 3, the positive shift in peak potential of the anodic event with increasing scan rate is larger than the negative shift in peak potential of the cathodic event for both complexes. It can therefore be concluded that electron transfer is especially limited by charge transfer kinetics for the oxidation.
of the Cu\textsuperscript{I} state of Cu-terpy and Cu-bmpa back to the initial Cu\textsuperscript{II} state. This basically means that the low electron transfer rate is only able to keep up with the scan rate when the latter is kept low. The difference between the scan rate at which the Cu\textsuperscript{II}/Cu\textsuperscript{I} redox couple of Cu-terpy and Cu-bmpa is still reversible (10 mV s\textsuperscript{-1} for Cu-terpy and 100 mV s\textsuperscript{-1} for Cu-bmpa) indicates that the electron transfer kinetics of the anodic event is faster for Cu-bmpa than it is for Cu-terpy. For both complexes, a linear dependence between the peak current and the square root of the scan rate (\(\nu^{1/2}\)) is obtained, which is...
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Figure 5. RRDE linear sweep voltammograms of 0.3 mM Cu-terpy (a) and Cu-bmpa (b) under 1 atm O$_2$ (solid lines) and 1 atm Ar (dotted lines) at 1600 rpm as a function of applied disk potential. The reference voltammogram in the absence of complex under 1 atm O$_2$ is depicted as a dashed gray line. Conditions: 0.1 M pH 7 phosphate buffer, 293 K, GC disk, Pt ring at 1.2 V vs RHE, 50 mV s$^{-1}$ scan rate.

in good agreement with a diffusion controlled redox process (see Section 8 in the Supporting Information).

**ORR Catalysis.** The ORR behavior of Cu-terpy and Cu-bmpa was investigated with CV in an aqueous pH 7 buffered electrolyte under 1 atm O$_2$ at a scan rate of 100 mV s$^{-1}$. For these measurements, a GC WE was used. The electrolyte consisted of 0.1 M pH 7 phosphate buffer. The ORR catalytic wave which is indicative of substrate depletion (Figure 4). Additionally, a relatively high half-wave potential of the catalytic wave ($E_{1/2}$) is observed for both catalysts. $E_{1/2}$ is defined as the potential at which the catalytic wave reaches half its maximum current. Generally, half of the catalyst present near the electrode exists in its active form at this potential, which results in $E_{1/2} = E_{1/2}^{\text{cat}}$. For Cu-terpy and Cu-bmpa, $E_{1/2}$ amounts to 0.34 and 0.37 V vs RHE, respectively. Considering the $E_{1/2}$ of 0.31 V vs RHE for Cu-terpy and 0.30 V vs RHE for Cu-bmpa (vide supra), this results in $E_{1/2}^{\text{cat}} > E_{1/2}$ for both complexes. Just as reported for Cu-tmpa, this is also indicative of substrate depletion.

It is important to verify whether some Cu-terpy or Cu-bmpa material was left behind on the surface of the GC WE after contact with the 0.3 mM catalyst solutions. For this purpose, various deposit checks were performed (see Section 9 in the Supporting Information). These experiments showed an enhanced catalytic activity which points to the presence of some deposit on the surface of the working electrode after one cyclic voltammetry scan in a 0.3 mM solution of Cu-terpy or Cu-bmpa. This deposit proved to be less catalytically active for the ORR than the homogeneous catalyst dissolved in solution, validating that the first scan of each cyclic voltammetry measurement represents the behavior of the homogeneous system.

As shown in Figure S7, the ORR activity of 0.3 mM Cu-bmpa in 0.1 M pH 7 phosphate buffer is similar to the ORR activity observed in 0.1 M pH 7 HEPES buffered NaClO$_4$. This means that the formation of a phosphate coordinated Cu-bmpa complex in the presence of phosphate buffer does not affect the ORR behavior of this catalyst. However, taking into account potential issues with the presence of both HEPES and peroxide (see Section 16 in the Supporting Information), we carried out further catalytic experiments in phosphate buffer despite potential issues with phosphate coordination to copper.

**ORR Product Selectivity. Rotating Ring Disk Electrode.** In order to investigate the product selectivity of the ORR catalyzed by Cu-terpy and Cu-bmpa, a setup with a rotating ring disk electrode (RRDE) was used. Using this setup, the ORR occurs at a GC disk electrode. A Pt ring electrode is surrounding the GC disk and is set at a fixed potential of 1.2 V vs RHE. This potential is above the onset potential of 0.9 V vs RHE for H$_2$O oxidation by Pt and below the onset potential of 1.5 V vs RHE for H$_2$O$_2$ oxidation by Pt, both in pH 7 phosphate buffer. This means that at this fixed ring potential of 1.2 V vs RHE, H$_2$O$_2$ is oxidized whereas H$_2$O is not, enabling determination of the product selectivity of the catalyzed ORR. Even though the RRDE setup is mostly used to study heterogeneous catalytic reactions, it can be used to study homogeneous catalytic reactions under certain conditions as well.

The main difficulty of employing RRDE methods for a homogeneous catalyst is that the substrate, the catalyst, and the product are all present in solution. For complex multistep
multielectron reactions like the ORR, this results in the presence of more than one diffusing species in the liquid phase. For the ORR, these diffusing species comprise of the CuII and CuI state of the catalyst, the O2 substrate, the CuII−superoxide, CuII−hydroperoxo and CuII−hydroxo adducts, and the H2O2 intermediate. Since these diffusing species can all reach the ring electrode, the true origin of the observed oxidizing ring current when it is set at a fixed potential of 1.2 V vs RHE should be established. This was done by studying the ring current when the ring electrode was set at a fixed potential below the onset potential for H2O2 oxidation by platinum.

The product selectivity of the ORR catalyzed by Cu-terpy and Cu-bmpa was studied in 0.1 M pH 7 phosphate buffer for both catalysts. For this purpose, the RRDE setup was used to perform linear sweep voltammetry (LSV) at the GC disk and chronoamperometry (CA) at the Pt ring while rotating the RRDE at a speed of 1600 rpm (Figure 5). LSV was performed between an upper potential limit of 1.0 V vs RHE and a lower potential limit of −0.2 V vs RHE for Cu-terpy and −0.15 V vs RHE for Cu-bmpa (see Section 11 in the Supporting Information for the reason for this difference in the lower potential limit), while CA was performed at 1.2 V vs RHE. Additional RRDE experiments with a ring potential set at 0.8 V vs RHE did not show any ring current, which indicates that no reduced catalytic species are being diffused toward and oxidized at the Pt ring electrode (Figure S9). Since the oxidation potential of both Cu-terpy and Cu-bmpa is located below 0.8 V vs RHE, the absence of ring current during the additional RRDE experiments illustrates that the observed ring current during ORR catalysis with a ring potential set at 1.2 V vs RHE corresponds to the oxidation of the formed H2O2 product only.

The ORR onset potential of the complexes has been defined in the context of the RRDE LSV measurements as the potential at which \( i_{\text{c}} / i_{\text{GC}} > 3 \), in which \( i_{\text{c}} \) is the disk current observed during ORR catalysis performed by the catalyst and \( i_{\text{GC}} \) is the disk current observed in absence of the catalyst (Figure 5 bottom panels: solid lines vs dashed gray lines). For Cu-terpy and Cu-bmpa, this onset potential occurs at 0.45 and 0.49 V vs RHE, respectively. Considering the ORR onset potential of 0.50 V vs RHE for Cu-tmpa in 0.1 M pH 7 phosphate buffer, the overpotential for the ORR catalyzed by Cu-terpy and Cu-bmpa is slightly higher than the ORR overpotential of Cu-tmpa. This is not in line with the higher \( E_{1/2} \) values of 0.31 and 0.30 V vs RHE for Cu-terpy and Cu-bmpa, respectively, compared to the reported \( E_{1/2} \) of 0.21 V vs RHE for Cu-tmpa.

The RRDE LSV data of Cu-bmpa recorded under 1 atm Ar shows two cathodic events at the disk electrode and two anodic events at the ring electrode (Figure Sb dotted line and zoom in Figure S4). This is in agreement with our earlier conclusion based on CV that some Cu-bmpa partly coordinates to phosphate in the presence of a phosphate buffer.

The RRDE LSV data of Cu-terpy and Cu-bmpa recorded under 1 atm O2 show maximum catalytic disk current \( (i_{\text{cat}}) \) values of 0.66 and 0.57 mA at −0.20 and −0.15 V vs RHE, respectively (Figure 5). These \( i_{\text{cat}} \) values are substantially lower...
than the reported \( \text{i}_{\text{cat}} \) value of Cu-tmpa obtained at a rotation speed of 1600 rpm which amounts to 0.99 mA at potentials below 0.15 V vs RHE.37 However, significantly higher ring currents were detected in the case of Cu-terpy and Cu-bmpa compared to Cu-tmpa, indicating that substantial amounts of hydrogen peroxide are formed. Especially the absence of a significant ring current during both the RRDE LSV data recorded under 1 atm Ar (Figure 5 dotted lines) and under 1 atm O2 with a ring potential set at 0.8 V vs RHE (Figure S9) indicates that the ring current observed during ORR catalysis is the result of hydrogen peroxide formation and not due to diffusion of a reduced catalytic species toward the ring electrode. Since the formation of H2O2 is associated with a two-electron reduction as opposed to the four-electron reduction for the formation of water, the formation of H2O2 is associated with a lower catalytic disk current.

Quantification of H2O2. To quantify the formation of H2O2 along the potential regime for ORR catalysis, the percentage of H2O2 produced during ORR catalysis (\( \% \text{H}_2\text{O}_2 \)) and the associated electron transfer number (\( \eta_{\text{RRDE}} \)) were determined according to eqs 1 and 2, respectively

\[
\% \text{H}_2\text{O}_2 = \frac{2 \times \left( \frac{\text{i}_{\text{ring}}}{\text{N}_{\text{H}_2\text{O}_2}} \right)}{\text{i}_{\text{disk}} + \left( \frac{\text{i}_{\text{ring}}}{\text{N}_{\text{H}_2\text{O}_2}} \right)} \times 100\% \tag{1}
\]

\[
\eta_{\text{RRDE}} = \frac{4 \times \text{i}_{\text{disk}}}{\text{i}_{\text{disk}} + \left( \frac{\text{i}_{\text{ring}}}{\text{N}_{\text{H}_2\text{O}_2}} \right)} \tag{2}
\]

where \( \text{i}_{\text{ring}} \) and \( \text{i}_{\text{disk}} \) are the observed ring and disk current, respectively, and \( \text{N}_{\text{H}_2\text{O}_2} \) is the collection efficiency of the Pt ring for H2O2.57 In a previous publication, we showed that this collection efficiency amounts to 0.125 for the same RRDE setup.37 Figure 6 shows the \( \% \text{H}_2\text{O}_2 \) and \( \eta_{\text{RRDE}} \) values along the potential regime for ORR catalysis of Cu-terpy and Cu-bmpa obtained from the RRDE LSV data (red and blue lines). For Cu-terpy, the percentage of H2O2 produced during ORR catalysis increases from \( \sim \)60% near the ORR onset potential to \( \sim \)80% at the lower potential limit with a maximum of \( \sim \)90% at 0.3 V vs RHE (Figure 6a). For Cu-bmpa, the initial \( \% \text{H}_2\text{O}_2 \) of \( \sim \)75% near the ORR onset potential decreases to \( \sim \)70% at the lower potential limit with a maximum of \( \sim \)90% at 0.3 V vs RHE as well (Figure 6b). The high Faradaic efficiencies for H2O2 production observed at low applied disk potential agree with the observed lower maximum catalytic disk currents for the ORR catalyzed by Cu-terpy and Cu-bmpa compared to Cu-tmpa. The \( \eta_{\text{RRDE}} \) values obtained from the RRDE LSV data indicate a slight decrease from \( \sim \)2.7 to \( \sim \)2.5 for Cu-terpy and a slight increase from \( \sim \)2.5 to \( \sim \)2.7 for Cu-bmpa. This trend observed for the electron transfer number reflects the inverse trend observed for the \( \% \text{H}_2\text{O}_2 \) values, since a decrease in production of H2O2 (\( n = 2 \)) is associated with an increase in production of H2O (\( n = 4 \)) and vice versa. Noteworthy, a contribution of the GC disk toward H2O2 production cannot be excluded below 0.1 V vs RHE (Figure 5 dashed gray lines).

Figure 7. Disk and ring current responses for 0.3 mM Cu-terpy (a) and Cu-bmpa (b) obtained during RRDE CA measurements as a function of time for various applied disk potentials. Each measurement is preceded by a background measurement at an applied disk potential of 0.8 V vs RHE for 1 min. To prevent underestimation of \( \% \text{H}_2\text{O}_2 \) values and overestimation of \( \eta_{\text{RRDE}} \) values due to formation of a Cu deposit at low applied disk potential over time (see Section 13 in the Supporting Information), the resulting \( \% \text{H}_2\text{O}_2 \) and \( \eta_{\text{RRDE}} \) values obtained from these RRDE CA measurements were averaged between 80 and 90 s. Conditions: 0.1 M pH 7 phosphate buffer under 1 atm O2, 293 K, GC disk, Pt ring at 1.2 V vs RHE, 1600 rpm.
Additionally, the values for %H₂O₂ and n_{RRDE} were determined by RRDE CA measurements as a function of time. These RRDE CA measurements were performed at an applied disk potential of 0.35, 0.30, 0.20, and 0.0 V vs RHE for 5 min and additionally at −0.20 V vs RHE for 5 min for Cu-terpy (Figure 7). A duplicate RRDE CA measurement was performed at 0.35 V vs RHE for Cu-terpy and at 0.20 V vs RHE for Cu-bmpa. As shown in Figure 6, the %H₂O₂ values obtained from the RRDE CA data correlate well with the values obtained from the RRDE LSV data.

During the RRDE CA measurements performed at an applied disk potential of 0.0 and −0.20 V vs RHE for Cu-terpy, the current responses did not stabilize (Figure 7). Instead, the disk current increases and the ring current decreases over time at these applied potentials. A similar effect is observed for Cu-bmpa at an applied disk potential of 0.0 V vs RHE, whereas at 0.20 V vs RHE the ring current decreases over time while the disk current stabilizes. The mismatch between the disk and ring current responses indicates that the selectivity of the ORR changes over time at these low applied disk potentials. This phenomenon appears to start at a slightly higher potential for Cu-bmpa than for Cu-terpy. A deposit study performed for Cu-bmpa after the RRDE CA measurements indicates that the change in selectivity of the ORR is the result of the formation of a Cu⁶⁺ deposit at low applied disk potential (see Section 13 in the Supporting Information). Additional RRDE CA measurements performed at 0.35 V vs RHE for 40 min indicate that the disk and ring current responses of Cu-terpy and Cu-bmpa are stable upon prolonged cathodic exposure at slightly higher applied disk potentials (Figure S12).

In addition to quantification of the H₂O₂ formation during ORR catalysis with the aid of the RRDE setup, the Faradaic efficiency of Cu-terpy and Cu-bmpa for H₂O₂ production was also determined by measuring the concentration of H₂O₂ present in the electrolyte after performing bulk ORR catalysis at 0.20 V vs RHE for 5 min (see Section 15 in the Supporting Information). The H₂O₂ concentration was determined with a peroxidase-based photometric measurement (see Section 1.4.5 in the Supporting Information for the experimental details). The obtained absolute concentration of H₂O₂ after performing RDE CA at 0.20 V vs RHE for 5 min amounted to (0.022 ± 0.001) mM for Cu-terpy and (0.030 ± 0.001) mM for Cu-bmpa in 15 mL electrolyte. Comparison of the expected charge buildup for these amounts of produced H₂O₂ with the observed charge buildup during the 5 min RDE CA measurement results in a Faradaic efficiency for H₂O₂ production of (72 ± 2)% for Cu-terpy and (72 ± 3)% for Cu-bmpa. These values are slightly lower than the %H₂O₂ values determined by RRDE LSV and RRDE CA measurements at 0.20 V vs RHE for both catalysts (Figure 6). This is the result of the smaller amount of electrolyte which was used during the RDE CA measurements (15 mL vs 50 mL for RRDE LSV and RRDE CA), resulting in an increase of the H₂O₂ concentration and therefore more reduction of H₂O₂ to H₂O. The obtained H₂O₂ concentrations and therefore the Faradaic efficiencies are the average of six measurements and are reported with the standard error.

H₂O₂ Reduction Behavior. As discussed above, the RRDE LSV data of both Cu-terpy and Cu-bmpa result in relatively high %H₂O₂ and low n_{RRDE} values along the entire potential window for ORR catalysis (Figure 6). This means that both catalysts do not catalyze the full four-electron ORR (n_{RRDE} = 4) in the investigated potential window. Considering that n_{RRDE} is larger than two along the ORR active potential window of both catalysts, limitations seem to arise after the initial two-electron reduction of O₂ to H₂O₂. Therefore, the H₂O₂ reduction behavior of both Cu-terpy and Cu-bmpa was investigated by performing LSV under 1 atm Ar in a 0.3 mM catalyst solution in pH 7 buffered electrolyte containing H₂O₂ (Figure 8 dotted lines). The H₂O₂ concentration amounted to 1.1 mM in order to reproduce the concentration of O₂ in an O₂ saturated pH 7 buffered electrolyte under 1 atm O₂ which was used during ORR catalysis. Just like for the stationary ORR catalysis measurements, the electrolyte during the stationary H₂O₂ reduction measurements consisted of 0.1 M pH 7 phosphate buffer for Cu-terpy and 0.1 M pH 7 HEPES buffered NaClO₄ for Cu-bmpa.

The H₂O₂ reduction profile observed for Cu-terpy and Cu-bmpa does not show a clear peak-shaped catalytic wave as observed for the ORR behavior (Figure 8). Instead, an S-shaped catalytic wave is observed. This represents catalysis that does not involve a change in substrate concentration, indicating that substrate depletion is not taking place during H₂O₂ reduction. The absence of substrate depletion confirms that the H₂O₂ reduction activity of both catalysts is low and indeed the limiting factor during ORR catalysis. In contrast, a peak-shaped catalytic wave indicative of substrate depletion and therefore high catalytic activity has been confirmed...
reported for H$_2$O$_2$ reduction catalysis performed by Cu-tmpa.\textsuperscript{37}

The H$_2$O$_2$ reduction onset potential of the complexes has been determined by RDE LSV measurements in 0.1 M pH 7 phosphate buffer and is defined in this context as the potential at which $i_1/i_{GC} > 2$, in which $i_1$ is the current observed during H$_2$O$_2$ reduction catalysis performed by the catalyst (see Section 16 in the Supporting Information) and $i_{GC}$ is the disk current observed during ORR catalysis in the absence of the catalyst (Figure S dashed gray lines in bottom panels). For Cu-terpy and Cu-bmpa, this onset potential is located at 0.31 and 0.42 V vs RHE, respectively. These onset potentials observed for H$_2$O$_2$ reduction are lower than the corresponding onset potentials for ORR catalysis of 0.45 and 0.49 V vs RHE, respectively. After performing the H$_2$O$_2$ reduction RDE LSV measurement for Cu-bmpa in 0.1 M pH 7 HEPES buffered 0.1 M NaClO$_4$ electrolyte, the color of the catalytic solution changed over time from light blue to light yellow (see Section 17 in the Supporting Information).

**Catalytic Rate.** The TOF for the partial reduction of O$_2$ to H$_2$O$_2$ can be determined by the foot-of-the-wave analysis (FOWA). The FOWA was introduced by Savéant et al. as a method to determine the TOF for heterogeneous and homogeneous electrocatalysts.\textsuperscript{61} The method excludes side phenomena like substrate consumption, catalyst deactivation, and product inhibition by only considering the onset region of the catalytic wave observed during a standard CV measurement. At this region, catalysis is considered to take place under kinetic conditions. Since substrate consumption does play an important role during the ORR due to limitations in O$_2$ concentration, the FOWA is an excellent tool to study the ORR in more depth. Considering the lower onset potential observed for the H$_2$O$_2$ reduction reaction compared to the ORR for both Cu-terpy and Cu-bmpa (*vide supra*), the amount of H$_2$O$_2$ reduced in solution at the foot of the catalytic wave is limited. This results in a H$_2$O$_2$ reduction rate which is negligible compared to the rate for the two-electron reduction of O$_2$ at this onset region. Therefore, the FOWA results in the TOF associated with the partial reduction of O$_2$ to H$_2$O$_2$ (TOF). Noteworthy, this TOF is in fact the theoretical maximum TOF for O$_2$ to H$_2$O$_2$ reduction (TOF$_{max}$), as the FOWA excludes the experimental limitation of O$_2$ diffusion due to substrate consumption. Furthermore, it is assumed that the reported fast ligand exchange kinetics of copper results in fast exchange of the formed H$_2$O$_2$ intermediate with H$_2$O originating from the electrolyte solution, which means that the intermediate is not immediately further reduced to produce water as the four-electron product of the ORR.\textsuperscript{62} Electrochemical quartz crystal microbalance (EQCM) experiments (see Section 18 in the Supporting Information) indicate that over time Cu-terpy accumulates at the working electrode at negative potentials and under conditions where on the basis of selectivity no Cu$^0$ is expected yet. However, these effects appear to be minimal in the potential domain where the FOWA is carried out.

To determine the TOF$_{max}$ for the partial reduction of O$_2$ to H$_2$O$_2$, the FOWA was applied to the ORR profile that was obtained by stationary CV (Figure 4). However, to be able to apply the FOWA correctly to the obtained catalytic data, the rate law of the two-electron ORR has to be obtained. Both the binding of O$_2$ to Cu-tmpa and the ORR catalyzed by Cu-tmpa have previously been shown by Karlin et al. to involve a dimerization step in organic solvent.\textsuperscript{37,36,38--40} However, as recently indicated by our group, ORR catalysis performed by Cu-tmpa in aqueous pH 7 buffered solution proceeds via reactions at mononuclear species that are significantly faster than the formation of [μ-(O$_2$)]-bridged dimers.\textsuperscript{37} For Cu-terpy and Cu-bmpa, a mononuclear mechanism is also expected for ORR catalysis in pH 7 buffered aqueous solution, since significant catalytic ORR activity was still observed for both species at micromolar catalyst concentration (see Section 19 in the Supporting Information). The first order mechanism in catalyst for the two-electron ORR catalyzed by both Cu-terpy and Cu-bmpa is supported by a poor linear fit of the FOWA for a second order relationship in catalyst (see Section 22 in the Supporting Information). It is therefore expected that both Cu-terpy and Cu-bmpa follow the same initial elemental steps during ORR catalysis as described for Cu-tmpa in aqueous pH 7 buffered solution.\textsuperscript{37} These elemental steps are as follows:

\[
\begin{align*}
\text{Cu}^{II} + e^{-} &\rightarrow \text{Cu}^{I} + E_{Cu^{I}/Cu^{II}} \\
\text{Cu}^{I} + O_2 &\rightarrow \text{Cu}^{II}O_2^{-}^* \\
\text{Cu}^{II}O_2^{-}^* + H^+ + e^- &\rightarrow \text{Cu}^{II}OH \quad k_2
\end{align*}
\]

In this equation, $i_1$ is the observed catalytic current in A, $E_{1/2}$ is the half-wave potential of the catalyst’s Cu$^{II}$/Cu$^{I}$ redox couple, and $k_{obs}$ is the observed rate constant with $k_{obs} = TOF_{max}^{1/2}$.\textsuperscript{61,63} Noteworthy, all electron transfer steps are considered to occur at the electrode surface in this current–potential approximation, without any homogeneous electron transfer taking place between species. Normalization of eq 3 with the observed peak current of the one-electron reduction of the catalyst ($i_{p,red}$) using the Randles-Sevcik eq 1 results in eq 4 (see Section 20 in the Supporting Information):

\[
i_{p,red} = \frac{2.24AM^{4/3}C_{dl}^{1/6}D_{cat}^{1/2}k_{obs}}{1 + \exp\left(\frac{F}{RT}(E - E_{1/2})\right)}
\]

In this equation, $n$ is the number of electrons involved in the catalytic cycle. Since only the partial reduction of O$_2$ to H$_2$O$_2$ is considered during the FOWA, $n$ equals 2 in this specific case. Applying eq 4, the TOF$_{max}$ of the two-electron reduction of O$_2$ to H$_2$O$_2$ can be determined via the slope of the $i_{p,red}$ vs $1/(1 + \exp(F/RT(E - E_{1/2})))$ plot (Figure S19a,b). A linear fit was obtained between the onset potential of the ORR and 0.40 V vs RHE for Cu-terpy (Figure S19c) and between the onset potential of the ORR and 0.42 V vs RHE for Cu-bmpa (Figure S19d). Averaging of the resulting TOF$_{max}$ values over three individual ORR measurements resulted in a TOF$_{max}$ for the...
partial reduction of O2 to H2O2 of (3.0 ± 0.6)·10^{-7} s^{-1} for Cu-terpy and (2.4 ± 1.9)·10^{-4} s^{-1} for Cu-bmpa, both in pH 7 buffered electrolyte and reported with the standard error. Compared to the reported TOF_{max} of (1.8 ± 0.6)·10^{-6} s^{-1} for the partial reduction of O2 to H2O2 catalyzed by Cu-tmpa in 0.1 M pH 7 phosphate buffer, the TOF_{max} for O2 to H2O2 reduction catalyzed by Cu-terpy and Cu-bmpa is 4 and 2 orders of magnitude smaller, respectively.

**Origin of Relatively Low TOF.** As mentioned in the EPR spectroscopy section in the Supporting Information, CuII centers generally adopt a distorted octahedral, square pyramidal, square planar, or trigonal bipyramidal coordination geometry. In contrast, CuI centers favor a tetrahedral coordination geometry.64 This difference in preferred coordination geometry for the +I and +II oxidation states of copper can result in large reorganization barriers during electron transfer. As indicated by the crystal structure of Cu-terpy (Figure S3) and the EPR data of Cu-bmpa (see Section 3 in the Supporting Information), the CuII state of these complexes adopts an octahedral geometry and an elongated octahedral, square pyramidal, or square planar geometry, respectively. Upon reduction to the CuI state, the rigidity of the terpy ligand prevents formation of the preferred tetrahedral coordination geometry for a CuI complex. In contrast, the reported trigonal bipyramidal geometry of [Cu(tmpa)(MeCN)]^{+} has been shown to possess an elongated Cu–N_{amine} bond compared to [Cu(tmpa)(MeCN)]^{2-}.65 The elongation from 2.10 to 2.43 Å upon reduction of the copper center suggests that formation of the preferred tetrahedral coordination geometry for a CuI complex can occur for Cu-tmpa by dissociation of the tertiary amine (Figure 9a). Even though the bmpa ligand of Cu-bmpa can relatively easily convert from a meridional to a facial orientation (Figure 9b),66 this conversion does not result in a tetrahedral geometry. As a result of the difference in ability to form the preferred tetrahedral coordination geometry for a CuI complex, a higher energetic barrier for the formation of the CuI state of the complex is expected for Cu-terpy and Cu-bmpa compared to Cu-tmpa. However, as mentioned in the ORR catalysis section, the $E_{1/2}$ values of Cu-terpy and Cu-bmpa are shifted positively by 0.10 and 0.09 V vs RHE, respectively, compared to the reported $E_{1/2}$ of 0.21 V vs RHE for Cu-tmpa.57 These positive shifts correspond to a thermodynamically more favorable reduction to the CuI state of the complex for Cu-terpy and Cu-bmpa than for Cu-tmpa.

The absence of a fourth binding arm for the terpy and bmpa ligands with respect to the tmpa ligand suggests that the electron donating ability is lower for terpy and bmpa. Correspondingly, the poor electron donating ability might cause the thermodynamically less favorable reoxidation of the CuI state of Cu-terpy and Cu-bmpa to the CuII state, which was indicated by the slow electron transfer kinetics for this anodic event (see Laviron plots in Figure 3). The difference between the scan rate at which the CuIII/CuI redox couple of Cu-terpy and Cu-bmpa is still reversible (10 mV s^{-1} for Cu-terpy and 100 mV s^{-1} for Cu-bmpa) indicates that the electron transfer kinetics of the anodic event is faster for Cu-bmpa than for Cu-terpy.

As mentioned for the determination of the TOF_{max} (vide supra), the formation of the CuI-superoxide adduct is expected to be the rate-determining step during ORR catalysis performed by Cu-terpy and Cu-bmpa. Overall, the increasing electron donating ability along terpy < bmpa < tmpa results in a decrease of the barrier between the CuI state of the complex and the CuII-superoxide adduct along Cu-terpy > Cu-bmpa > Cu-tmpa. Additionally, the increasing ability to form the preferred tetrahedral coordination geometry for a CuI complex along Cu-terpy < Cu-bmpa < Cu-tmpa results in the observed increase in electron transfer kinetics for the reoxidation along the same trend and correspondingly more rapid formation of the active ORR catalyst. The lower TOF_{max} of (3.0 ± 0.6)·10^{-7} and (2.4 ± 1.9)·10^{-4} s^{-1} obtained for O2 to H2O2 reduction by Cu-terpy and Cu-bmpa, respectively, compared to a TOF_{max} of (1.8 ± 0.6)·10^{-6} s^{-1} reported for Cu-tmpa,57 indicates that the ORR activity increases along Cu-terpy < Cu-bmpa < Cu-tmpa. This is clearly in line with both the decrease of the barrier between the CuI and CuII states of the complex and the increase in electron transfer kinetics of the reoxid couple.

## CONCLUSION

Cu-tmpa has been shown to be a more active catalyst for the ORR than Cu-terpy and Cu-bmpa. Our data shows that this trend in activity is also observed for the electron transfer kinetics of the CuII/CuIII redox couples. Laviron plots of all three complexes show that electron transfer rates are relatively slow in the case of Cu-terpy and Cu-bmpa compared to Cu-tmpa.57 The underlying phenomenon is the reorganization energy that must be overcome to convert tetrahedral CuI into nontetrahedral CuII, which is most facile in the case of Cu-tmpa which can easily decoordinate one of its four N-donors. It can therefore be concluded that both the tetradentate nature of the tmpa ligand and the ability of Cu-tmpa to form the preferred tetrahedral coordination geometry for a CuI complex are of utmost importance for the great success of the Cu-tmpa catalyzed ORR.

In addition, the use of the tetradentate tmpa ligand also is beneficial in terms of catalyst stability and product selectivity. However, the high Faradaic efficiencies observed for H2O2 production along the ORR active potential window of Cu-terpy and Cu-bmpa indicate that these mononuclear Cu complexes employed with N3-donor ligands are highly selective for the two-electron reduction of O2 to H2O2. This might open up an alternative pathway for the production of H2O2.
Experimental methods, stability of Cu-terpy and Cu-bmpa in pH 7 buffered electrolyte, EPR spectroscopy, single crystal X-ray crystallography, crystallographic data of Cu-terpy, selected bond distances and angles for Cu-terpy, redox behavior of Cu-bmpa in pH 7 phosphate buffer, Randles-Sevcik equation, deposit formation for Cu-terpy and Cu-bmpa, ORR behavior of Cu-bmpa in pH 7 phosphate buffer, difference in lower potential limit for RRDE measurements, RRDE linear sweep voltammery with $E_{\text{oxy}}$ at 0.8 V, formation of Cu²⁺ deposit at low potential, prolonged RRDE chronoamperometry measurements, photometric measurements of H₂O₂ production, H₂O₂ reduction catalysis by RDE LSV, color change for Cu-bmpa with H₂O₂, EQCM experiment of Cu-terpy, catalytic ORR activity at low [catalyst], derivation of eq 4, foot-of-the-wave analysis, and catalytic reaction order (PDF).

Accession Codes
CCDC 2016453 contains the supplementary crystallographic data for this paper. These data can be obtained free of charge via www.ccdc.cam.ac.uk/data_request/cif, or by emailing data_request@ccdc.cam.ac.uk, or by contacting The Cambridge Crystallographic Data Centre, 12 Union Road, Cambridge CB2 1EZ, UK; fax: +44 1223 336033.

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Notes
The authors declare no competing financial interest.

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