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Role of Ligand to Control the Mechanism of Nitric Oxide Reduction of Copper(II) Complexes and Ligand Nitrosation

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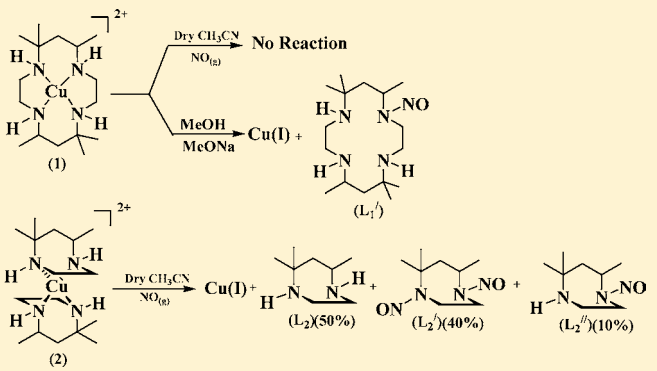
Supporting Information

ABSTRACT: The nitric oxide reactivity of two copper(II) complexes, **1** and **2** with ligands L_1 and L_2, respectively, [L_1 = 5,5,7,12,12,14-hexamethyl-1,4,8,11-tetraazacyclotetradecane, L_2 = 5,5,7-trimethyl-[1,4]-diazepane] have been studied. The copper(II) center in complex **1** was found to be unreactive toward nitric oxide in pure acetonitrile; however, it displayed reduction in methanol solvent in presence of base. The copper(II) center in **2**, in acetonitrile solvent, on exposure to nitric oxide has been found to be reduced to copper(I). The same reduction was observed in methanol, also, in case of complex **2**. In case of complex **1**, presumably, the attack of nitric oxide on the deprotonated amine is the first step, followed by electron transfer to the copper(II) center to afford the reduction. Alternatively, first NO coordination to the Cu(II) followed by NO^+ migration to the secondary amine is the most probable in case of complex **2**. The observation of the transient intermediate in UV−visible and FT-IR spectroscopy prior to reduction in case of complex **2** also supports this possibility. In both cases, the reduction resulted into N-nitrosation; in **1**, only mononitrosation was observed whereas complex **2** afforded dinitrosation as major product along with a minor amount of mononitrosation. Thus, it is evident from the present study that the macrocyclic ligands prefer the deprotonation pathway leading to mononitrosation; whereas nonmacrocyclic ones prefer the [Cu^{II}−NO] intermediate pathway resulting into nitrosation at all the available sites of the ligand as major product.



INTRODUCTION

Activation of nitric oxide (NO) by transition metal ions have attracted the chemists' attention as various biological and physiological reactivities of nitric oxide are attributed to the formation of nitrosyl complexes of metallo-proteins, mostly iron or copper-proteins.[1−3] In this direction, the iron-nitrosyls, both in protein and synthetic model systems have been studied extensively. Ferriheme proteins are known to undergo reduction in aqueous media in the presence of NO following a two-step process: (i) the formation of iron(III)-nitrosyl intermediate; (ii) followed by pH dependent reduction.[4,5] It is believed that in the next step the hydroxide ion attacks the activated nitrosonium group to afford nitrite ion and iron(II).[4] The ferrous protein then reacts with excess of nitric oxide to form stable ferroheme nitrosyl.[6−8]

The reduction of Cu(II) centers in some proteins, such as cytochrome *c* oxidase and laccase, to Cu(I) on exposure to nitric oxide has been known for a long time, though has not been studied as extensively as in iron systems.[9−12] In model systems, this has been exemplified by a number of copper(II) complexes in recent years.[13−23]

The Cu(II) center in $[Cu(dmp)_2(X)]^{2+}$ (dmp = 2,9-dimethyl-1,10-phenanthroline, X = solvent) and in analogous complexes is found to undergo reduction in presence of nitric oxide, and the detailed study of the reduction mechanism has been reported by Ford et al.[24,25] It is observed that the reduction was accompanied by the nitrosation of the solvent resulting into methylnitrite or NO_2^- in case of methanol or water, respectively (eq 1).[24,25]

$$[Cu(dmp)_2(X)]^{2+} + NO + CH_3OH \rightarrow [Cu(dmp)_2]^+ + CH_3ONO + H^+ \quad (1)$$

The copper(II) center in $[Cu^{II}(DAC)]^{2+}$ {DAC = 1,8-bis(9-anthracylmethyl) derivative of the macrocyclic tetraamine cyclam (1,4,8,11-tetraazacyclotetradecane)} in methanol solution is reported to undergo reduction by nitric oxide with a concomitant nitrosation of the ligand.[26] In contrast, copper(I) complexes with electron rich *β*-diketiminate ligands are found to induce reductive cleavage of the N-nitrosoamine bond leading to the release of nitric oxide and the formation of Cu(II)-amide complex.[27] It would be worth mentioning here that $[Cu^{II}(DAC)]^{2+}$ is reported as fluorescence sensor for NO.[26] Lippard's group used the same reduction strategy to develop copper complex based NO sensors and reported the

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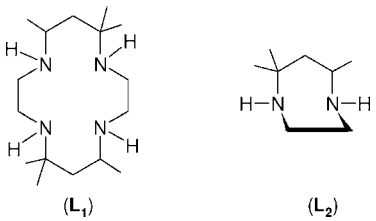
examples of copper(II) complexes of anthracenyl and dansyl fluorophore ligands in this regard.[28,29] The quenched fluorescence intensity of the ligand fluorophore was observed to restore in presence NO in methanol/dichloromethane solutions of the complexes. In addition, $[Cu(Ds\text{-}en)_2]$ and $[Cu(Ds\text{-}AMP)_2]$ [Ds-en and Ds-AMP are the conjugate bases of dansylethylenediamine (Ds-Hen) and dansyl aminomethylpyridine (Ds-HAMP), respectively], have been found to detect NO in aqueous solution, also.[27] Similar observations were reported for the reactions of $[Cu(Fl_n)]$ (Fl_n = a Fluorescine modified with a functionalized 8-aminoquinoline group) with NO which gave N-nitrosation of the Fl_n ligands.[28,29] From detail quantitative and theoretical studies, it has been established that in case of $[Cu^{II}(DAC)]^{2+}$, the reaction proceeds through a pathway analogous to the inner-sphere mechanism for electron transfer between two metal centers through a bridging ligand. In this case, NO is the reductant, Cu(II), the oxidant, and the coordinated amido anion behaves as the bridging ligand. Owing to the preference of Cu(I) for tetrahedral coordination and the decrease in donor ability of the nitrosated ligand, demetalation of the macrocyclic ring was observed after the reduction.

An example of such a mechanism is reported by Armor et al. where the reaction of $[Ru(NH_3)_6]^{3+}$ with NO in alkaline solution results into the Ru(II)-dinitrogen complex, $[Ru(NH_3)_5(N_2)]^{2+}$.[30] Since, Ru(III) complexes are substitution inert and the reaction is base catalyzed, the N_2 ligand must be originated from one of the ammines. Nitrosation of a coordinated amide ligand with the concomitant reduction of Ru(III) to Ru(II) leads to the formation of a coordinated nitroso amine, which on subsequent dehydration results in the coordinated dinitrogen complex.

The alternative mechanism, which is more close to that of ferriheme reduction, for the nitrosation would be the one involving the initial nitric oxide coordination to the Cu(II) center to form $[Cu^{II}\text{–}NO \leftrightarrow Cu^{I}\text{–}NO^{+}]$.[31] In the successive steps, amine deprotonation and migration of NO^+ to the coordinated amide would result into the nitrosoamine. Subsequently, demetalation from the ligand will occur. This, indeed, has been suggested earlier by Wayland and others.[32−36]

In our recent studies, with $[Cu^{II}(TREN)(CH_3CN)]^{2+}$, $[Cu^{II}(TAEA)(CH_3CN)]^{2+}$, $[Cu^{II}(TIAEA)(CH_3CN)]^{2+}$, $[Cu(pymea)_2]^{2+}$, and $[Cu(baea)(CH_3CN)]^{2+}$ [TREN = tris(2-aminoethyl)amine; TAEA = tris(2-ethylaminoethyl)amine; TIAEA = tris (2-isopropylaminoethyl)amine; pymea = pyridine-2-methylamine and baea = bis(2-aminoethyl)amine], the reduction was found to proceed through the formation of a thermally unstable $[Cu^{II}\text{–}NO]$ intermediate.[37] This difference in mechanistic pathway is, perhaps, because of the difference in ligand environment. Hence, it is logical to believe that the ligand frameworks have a significant role in controlling the mechanistic pathway for the reduction of copper(II).

To study the role of ligand on the reactivity of the complex toward nitric oxide, here we report the examples of copper(II) complexes with a cyclam derivative ($\mathbf{L_1}$) and cyclic amine ($\mathbf{L_2}$) ligands (Figure 1). Both the ligands have been known for a long time for their coordination chemistry with various transition metal ions.[38−45] The similar structural feature (Results and Discussion section) of the corresponding complexes derived from these ligands essentially prompted us to choose them for the present study.



($\mathbf{L_1}$) ($\mathbf{L_2}$)

Figure 1. Ligands used for the present study.

EXPERIMENTAL PROCEDURES

General Procedures. All reagents and solvents were purchased from commercial sources and were of reagent grade. Acetonitrile was distilled from calcium hydride. Deoxygenation of the solvent and solutions was effected by repeated vacuum/purge cycles or bubbling with nitrogen for 30 min. NO gas was purified by passing through KOH and P_2O_5 column. UV−visible spectra were recorded on a Perkin-Elmer lambda 25 UV−visible spectrophotometer. FT-IR spectra were taken on a Perkin-Elmer spectrophotometer with either sample prepared as KBr pellets or in solution in a potassium bromide cell. Solution electrical conductivity was checked using a Systronic 305 conductivity bridge. ^{1}H NMR spectra were obtained with a 400 MHz Varian FT-spectrometer. Chemical shifts (ppm) were referenced either with an internal standard (Me_4Si) for organic compounds or to the residual solvent peaks. The X-band Electron Paramagnetic Resonance (EPR) spectra of the complexes and of the reaction mixtures were recorded on a JES-FA200 ESR spectrometer. Electrochemical measurements were made using a CH Instruments 660A potentiostat. A Pt working electrode, Pt wire auxiliary electrode, and a Ag/Ag^+ reference electrode were used in a three-electrode configuration. All electrochemical measurements were done at 298 K under nitrogen atmosphere in acetonitrile solvent containing tetra-butylammonium perchlorate (TBAP) as supporting electrolyte. The scan rate used was 50 mV/s. The half-wave potential E^0_{298} was set equal to $0.5(E_{pa} + E_{pc})$, where E_{pa} and E_{pc} are anodic and cathodic cyclic voltammetric peak potentials, respectively. All the electrochemical data are uncorrected for junction potential. Elemental analyses were obtained from a Perkin-Elmer Series II Analyzer. The magnetic moment of complexes were measured on a Cambridge Magnetic Balance. Mass spectra of the compounds in methanol were recorded in a Waters Q-Tof Premier and Aquity instrument.

Single crystals were grown by slow diffusion followed by slow evaporation technique. The intensity data were collected using a Bruker SMART APEX-II CCD diffractometer, equipped with a fine focus 1.75 kW sealed tube MoKα radiation (λ = 0.71073 Å) at 273(3) K, with increasing ω (width of 0.3° per frame) at a scan speed of 3 s/frame. The SMART software was used for data acquisition. Data integration and reduction were undertaken with the SAINT and XPREP software.[46] For complex **2**, empirical absorption corrections were applied to the data using the program SADABS.[47] Structures were solved by direct methods using SHELXS-97 and refined with full-matrix least-squares on F^2 using SHELXL-97.[48] All non-hydrogen atoms were refined anisotropically. The hydrogen atoms were located from the difference Fourier maps and refined. Structural illustrations have been drawn with ORTEP-3 for Windows.[49] The disorder present in the crystal structure has been tried to be minimized by use of SHELXL.

Density functional theory (DFT) calculations were done for complexes **1**, **2**, and their respective $[Cu^{II}\text{–}NO]$ complexes. The complexes **1** and **2** were generated from their X-ray crystallographic data. Both the complexes were fully optimized using the BP functional and DNP basis sets as implemented in the program DMol^3.[50] The BP model was chosen as the use of other DFT models like BLYP or B3LYP results in larger error to the bond lengths for copper complexes.[51] The geometry of $[Cu^{II}\text{–}NO]$ species obtained from complexes **1** and **2** were also optimized at the BP/DNP level. Finally to confirm the stability of the complexes the vibrational frequencies calculations were done at the optimized structures. The relative

stabilities of the [Cu^{II}–NO] for complexes **1** and **2** are compared by calculating the value of the gap between their highest occupied molecular orbital (HOMO) and lowest unoccupied molecular orbital (LUMO) and chemical hardness values.

Preparation of L_1 Ligand. The macrocyclic ligand (L_1) was prepared by using the procedure described by Curtis et al.[52] It is characterized by elemental analyses, FT-IR, ^{1}H- NMR, and ^{13}C- NMR spectroscopy. Elemental analyses: Calcd.(%) for $C_{16}H_{36}N_4$: C, 67.55; H, 12.75; N, 19.69. Found(%): C, 67.52; H, 12.75; N, 19.66. FT-IR (in KBr): 753, 1177, 1372, 1465, 2832, 2923, 2965, 3275 cm^{-1}; ^{1}H NMR (400 MHz, $CDCl_3$): δ_{ppm}, 2.96(m, 2H), 2.66(t, 8H), 2.24(s, 4H), 1.79(d, 4H), 1.13(s, 12H), 1.09(d, 6H). ^{13}C NMR (100 MHz, $CDCl_3$): δ_{ppm}, 53.94, 48.26, 46.48, 45.55, 45.23, 29.73, 28.21, 24.46.

Preparation of L_2 Ligand. The synthesis of ligand L_2 was carried out by a method adapted from Curtis.[53] It is characterized by microanalysis, FT-IR, ^{1}H- NMR and ^{13}C- NMR spectroscopy. Elemental analyses: Calcd.(%) for $C_8H_{18}N_2$: C, 67.55; H, 12.75; N, 19.69. Found(%): C, 67.59; H, 12.76; N, 19.71. FT-IR: 1014, 1329, 1397, 1622, 2979 cm^{-1}; ^{1}H NMR (400 MHz, $CDCl_3$): δ_{ppm}, 3.01(m, 1H), 2.58(t, 4H), 1.56(d, 2H), 1.03(s, 9H). ^{13}C NMR (100 MHz, $CDCl_3$): δ_{ppm}, 52.68, 49.30, 47.15, 44.48, 44.42, 29.64, 28.18, 22.77.

Synthesis of Complex 1, $[Cu(L_1)](ClO_4)_2$. The complex was reported earlier.[54] Copper(II) perchlorate hexahydrate, $[Cu(H_2O)_6](ClO_4)_2$ (2 g, 5.4 mmol) was dissolved in 20 mL of freshly distilled acetonitrile, and to this blue solution, the ligand L_1 (1.53 g, 5.4 mmol), was added dropwise. The color of the solution changed to red. The resulting mixture was stirred for 1 h. Then the volume of the solution was reduced to ~5 mL and layered with benzene. It was then kept in a freezer for overnight which resulted in a red crystalline compound. Yield: 2.51 g (~85%). Elemental analyses: Calcd.(%) for $CuC_{16}H_{36}N_4O_8Cl_2$: C, 35.19; H, 6.64; N, 10.26. Found(%): C, 35.23; H, 6.66; N, 10.31. UV–visible (acetonitrile): λ_{max}, 523 nm (ε = 120 M^{-1} cm^{-1}. FT-IR (KBr pellet): 1082, 627, 2970, 1448, 2812 cm^{-1}. Molar conductance: 247 S cm^{-1} mol^{-1}. The observed magnetic moment is found to be 1.65 μ_B.

Synthesis of Complex 2, $[Cu(L_2)_2](ClO_4)_2$. Copper(II) perchlorate hexahydrate, $[Cu(H_2O)_6](ClO_4)_2$ (2 g, 5.4 mmol), was dissolved in 20 mL of freshly distilled acetonitrile, and to this blue solution, the ligand L_2 (1.53 g, 10.8 mmol), was added dropwise. The color of the solution changed to red. The resulting mixture was stirred for 1 h. Then the volume of the solution was reduced to ~5 mL and layered with benzene. The mixture was then kept in freezer for overnight which resulted in a red crystalline compound. Yield: 2.55 g (~85%). Elemental analyses: Calcd.(%) for $CuC_{16}H_{36}N_4O_8Cl_2$: C, 35.19; H, 6.64; N, 10.26. Found(%): C, 35.15; H, 6.64; N, 10.21. UV–visible(acetonitrile): λ_{max}, 454 nm (ε = 279 M^{-1} cm^{-1}). FT-IR (KBr pellet): 1082, 627, 2959, 3077, 3178 cm^{-1}. Molar conductance: 224 S cm^{-1} mol^{-1}. The observed magnetic moment is found to be 1.60 μ_B.

Isolation of Modified Ligand, L_1'. To 10 mL of degassed, distilled methanolic solution of complex **1** (0.546 g, 1 mmol), nitric oxide was bubbled for 1 min in presence of 1 equiv sodium methoxide. The solution turned colorless. The excess nitric oxide was removed by vacuum and purging argon gas for several cycles. The colorless solution was then opened to air and stirred at room temperature for 2 h to ensure the complete conversion of copper(I) to copper(II). Then the solvent was removed under reduced pressure using rotavapor. Water (5 mL) was added to the dried mass followed by the addition of 5 mL of saturated Na_2S solution. The black precipitate of CuS was filtered out. The crude organic part was then extracted from the aqueous layer using $CHCl_3$ (25 mL × 4 portions). The crude product, obtained after removal of solvent, was then purified by column chromatography using neutral alumina column and hexane/ethyl acetate solvent mixture to get the pure modified ligand L_1'. Yield: 265 mg (~85%). Elemental analyses: Calcd.(%) for $C_{16}H_{35}N_5O$: C, 61.30; H, 11.25; N, 22.34. Found(%): C, 61.27; H, 11.26; N, 22.37. FT-IR: 1440, 1385, 1177, 2925, and 2858 cm^{-1}; ^{1}H NMR (400 MHz, $CDCl_3$): δ_{ppm}, 4.43, 2.79, 2.62, 1.84, 1.43, 1.21. Mass: (m+H^+)/z: Calcd. 314.49; Found, 314.42.

Isolation of Modified Ligands, L_2' and L_2''. To 10 mL of degassed, distilled acetonitrile solution of complex **2** (0.546 g, 1 mmol), nitric oxide was bubbled for 1 min. The red color of the solution became blue and finally colorless. The excess nitric oxide was removed by vacuum and purging argon gas for several cycles. The colorless solution was then opened to air and stirred at room temperature for 2 h to ensure the complete conversion of copper(I) to copper(II). Then the solvent was removed under reduced pressure using rotavapor. Water (5 mL) was added to the dried mass followed by the addition of 5 mL of saturated Na_2S solution. The black precipitate of CuS was filtered out. It would be worth to mention here that direct addition of aqueous saturated Na_2S solution to Cu(I) solution affords the precipitation of Cu_2S leading to the same result. The crude organic part was then extracted from the aqueous layer using $CHCl_3$ (25 mL × 4 portions). The crude product, obtained after removal of solvent, was then purified by column chromatography using neutral alumina column and hexane/ethyl acetate solvent mixture to get the pure L_2' and L_2''. Unreacted L_2 was recovered from the column by using pure methanol solvent.

L_2': Yield: 0.155 g (~ 40%). Characterization of L_2': Elemental analyses: Calcd.(%) for $C_8H_{16}N_4O_2$: C, 47.99; H, 8.05; N, 27.98. Found(%): C, 47.97; H, 8.06; N, 28.03. FT-IR(in KBr): 1475, 1135, 1363, 1138, 2975 cm^{-1}; ^{1}H NMR (400 MHz, $CDCl_3$): δ_{ppm}, 4.53, 3.85, 2.12, 1.56, 1.31. Mass: (m+Na^+)/z: Calcd. 223.24; Found, 223.21.

L_2'': Yield: 0.028 g (~ 10%). Characterization of L_2'': Elemental analyses: Calcd.(%) for $C_8H_{17}N_3O$: C, 56.11; H, 10.01; N, 24.54. Found(%): C, 56.08; H, 10.01; N, 24.56. FT-IR(in KBr): 1478, 1138, 1363, 1361, 2987, 3021 cm^{-1}; ^{1}H NMR (400 MHz, $CDCl_3$): δ_{ppm}, 4.68, 3.57, 1.97, 1.64, 1.48. Mass: (m+Na^+)/z: Calcd. 194.24; Found, 194.26.

RESULTS AND DISCUSSIONS

Two Cu(II) complexes, **1** and **2**, were synthesized with ligands, L_1 and L_2 [L_1 = 5,5,7,12,12,14-hexamethyl-1,4,8,11-tetraazacyclotetradecane, L_2 = 5,5,7-trimethyl-[1,4]-diazepane], respectively, as their perchlorate salts. The complexes were characterized by various analytical techniques (Experimental Section). Elemental analyses were found to be satisfactory for both the complexes (Experimental Section). The single crystal structure of complex **1** was reported earlier.[55] The single crystal structures of both complexes were determined. The perspective ORTEP view for **2** is shown in Figure 2. In **1**, Cu(II) is found

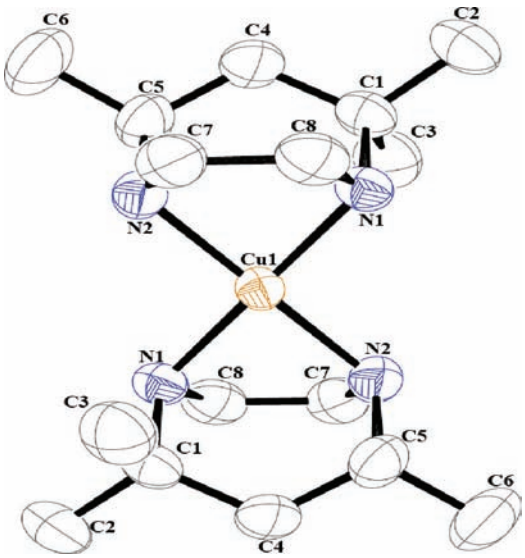


Figure 2. ORTEP diagram of complex **2** (50% thermal ellipsoid plot). Hydrogen atoms and perchlorate ions are not shown for clarity.

to be surrounded by four nitrogen donor atoms from L_1 in a distorted square-planar geometry (Supporting Information). In **2**, the Cu(II) center is coordinated with two L_2 in square-planar

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fashion (Figure 2). The crystallographic data, important bond distances, and angles are listed in Tables 1, 2, and 3, respectively.

Table 1. Crystallographic Data for Complexes 1, 2, and L_2'

	complex **1**	complex **2**	L_2'
formulas	$C_{16}H_{36}Cl_2CuN_4O_8$	$C_{16}H_{36}Cl_2CuN_4O_8$	$C_8H_{16}N_4O_2$
mol. wt.	546.94	546.94	200.25
crystal system	monoclinic	monoclinic	monoclinic
space group	$P2_1/n$	$P2_1/n$	$P2_1/c$
temperature/K	296(2)	296(2)	296(2)
wavelength /Å	0.71073	0.71073	0.71073
a/Å	9.9191(4)	8.4581(4)	5.9207(7)
b/Å	10.4189(4)	9.1705(4)	15.3528(17)
c/Å	11.9274(4)	15.5388(7)	12.8203(15)
α/deg	90.00	90.00	90.00
β/deg	97.283(2)	98.063(2)	114.452(8)
γ/deg	90.00	90.00	90.00
V/Å^3	1222.71(8)	1193.35(9)	1060.8(2)
Z	2	2	4
density/Mg m^{-3}	1.486	1.522	1.254
abs. coeff. /mm^{-1}	1.158	1.187	0.093
abs. correction	none	multiscan	none
$F(000)$	574.0	574.0	432
total no. of reflections	3411	2956	2563
reflections, $I > 2\sigma(I)$	2360	2466	817
max. 2θ/deg	30.01	28.35	28.42
ranges (h, k, l)	$-13 \le h \le 12$	$-9 \le h \le 11$	$-7 \le h \le 7$
	$-14 \le k \le 14$	$-11 \le k \le 12$	$-20 \le k \le 20$
	$-14 \le l \le 16$	$-20 \le l \le 20$	$-17 \le l \le 15$
complete to 2θ (%)	95.5	99.3	96.4
refinement method	full-matrix least-squares on F^2	full-matrix least-squares on F^2	full-matrix least-squares on F^2
GoF (F^2)	1.077	0.999	1.626
R indices [$I > 2\sigma(I)$]	0.0425	0.0373	0.0969
R indices (all data)	0.0606	0.0438	0.2077

Table 2. Selected Bond Length (Å) for Complexes 1, 2, and L_2'

	complex **1**	complex **2**	L_2'
Cu(1)−N(1)	2.046(1)	1.999(2)	
Cu(1)−N(2)	2.027(2)	2.010(3)	
N(1)−C(8)	1.480(3)	1.498(4)	1.440(8)
N(2)−C(7)	1.476(2)	1.484(5)	
C(7)−C(8)	1.516(3)	1.537(5)	1.535(9)
N(1)−N(2)			1.318(7)
N(3)−N(4)			1.420(1)
N(2)−O(1)			1.226(6)
N(4)−O(2)			1.118(9)

The Cu(1)−N(1) and Cu(1)−N(2) distances in complexes **1**/**2** are found to be 2.045(14)/1.998(2)Å and 2.026(14)/2.010(3)Å, respectively, which are within comparable ranges. The other bond distances of the coordinated ligands in both complexes are very similar. For instance, the N(1)−C(1), C(1)−C(4), C(4)−C(5), and C(5)−N(2) distances in **1**/**2** are 1.504(3)/1.509(4)Å, 1.536(3)/1.534(5)Å, 1.515(3)/1.525(5) Å, and 1.496(2)/1.518(4) Å, respectively. The N(1)−C(8), N(2)−C(7), and C(7)−C(8) distances in **1**/**2** are found to be 1.480(3)/1.498(4) Å, 1.476(2)/1.484(5) Å, and 1.516(3)/1.537(5) Å, respectively. From the structural parameters, it is evident that both complexes have similar ligand environment

Table 3. Selected Bond Angles (deg) for Complexes 1, 2, and L_2'

	complex **1**	complex **2**	L_2'
N(1)−Cu(1)−N(2)	94.24(6)	79.41(9)	
N(2)−C(7)−C(8)	107.7(2)	110.1(3)	
Cu(1)−N(1)−C(1)	122.7(1)	110.2(2)	
Cu(1)−N(1)−C(8)	106.2(1)	103.7(2)	
N(1)−C(8)−C(7)	107.9(2)	110.1(3)	111.8(5)
Cu(1)−N(2)−C(7)	106.2(1)	104.4(2)	
N(1)−N(2)−O(1)			114.2(5)
N(3)−N(4)−O(2)			101.3(7)

and geometry around the copper center. The only difference is in complex **1** where the ligand is a tetradentate macrocycle and in complex **2** the ligand is a bidentate cyclic amine. The complexes **1** and **2**, in acetonitrile solvent, exhibit broad d-d bands at $\lambda_{max}(\varepsilon/M^{-1}\ cm^{-1})$, 523 nm (120), and 454 nm (275), along with relatively strong intraligand absorptions in the UV region (Supporting Information).

The acetonitrile solutions of the complexes displayed characteristic four line axial spectra in X-band EPR studies at 77 K (Supporting Information).[56] The calculated spectral parameters, $g_{\|}$, $g_{\perp}$, and $A_{\|}$ are 2.152, 2.040, and 192 × 10^{-4} cm^{-1} for complex **1** and 2.118, 2.011, and 190 × 10^{-4} cm^{-1} for complex **2**, respectively. Both the complexes exhibit one electron paramagnetism at room temperature, as expected.

The cyclic voltammetirc studies of the pure complexes have been carried out in acetonitrile solvent. Complex **1** exhibited one irreversible couple at −1.15 V versus Ag/Ag$^+$, and this has been attributed to the Cu^{II}/Cu^{I} couple (Supporting Information). Earlier, Olson et al. also reported this couple to appear at −1.161 V versus Ag/Ag$^+$ electrode.[57] The Cu^{II}/Cu^{I} couple was also observed to appear in this range for analogous reported compounds.[58] On the other hand, for complex **2**, irreversible reduction was observed at −0.91 V versus Ag/Ag$^+$ (Supporting Information). The difference in reduction potential for the two complexes is attributed to the difference in ligand framework.[59] The cyclic voltammograms of complex **1** in presence of sodium methoxide was also recorded (Supporting Information). However, the voltammogram becomes progressively ill-defined with the increasing amount of sodium methoxide which essentially precluded its further studies.

NITRIC OXIDE REACTIVITY

Nitric oxide reactivity of the complexes were studied in acetonitrile and methanol media. Complex **1**, in dry and degassed acetonitrile, did not react with nitric oxide. Even after purging NO gas into the acetonitrile solution of complex **1** for 2 min, no spectral change has been observed. However, in methanol solution, complex **1** was found to react with nitric oxide in presence of base to result in a colorless solution indicating the reduction of Cu(II) center to Cu(I) (Scheme 1). The reduction was monitored by UV−visible spectroscopic studies. The intensity of the d-d band was found to decrease with time and finally diminished suggesting the complete reduction of Cu(II) center to Cu(I) (Figure 3).[60]

The reaction was found to be very slow in absence of base. The decrease of intensity of the d-d band was found to be retarded considerably upon addition of acids. Similar behavior was reported for the nitric oxide reactivity of $[Cu^{II}(DAC)]^{2+}$ complex.[60] In case of $[Cu^{II}(DAC)]^{2+}$, the spectral changed were found to be strongly dependent on conditions. In this case, in unbufferred MeOH/water mixture, the spectroscopic

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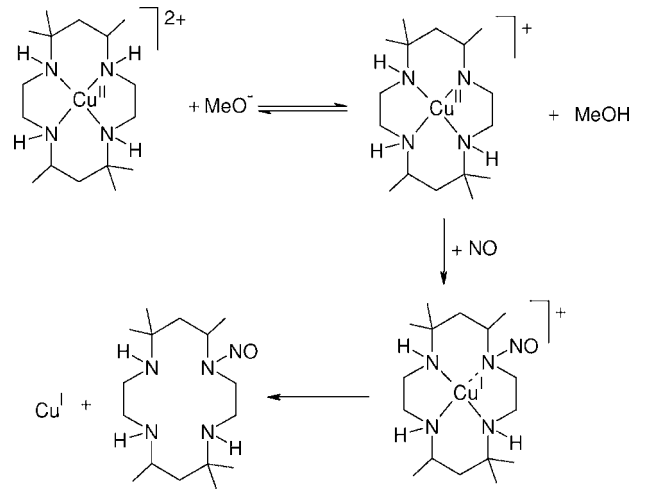
Scheme 1



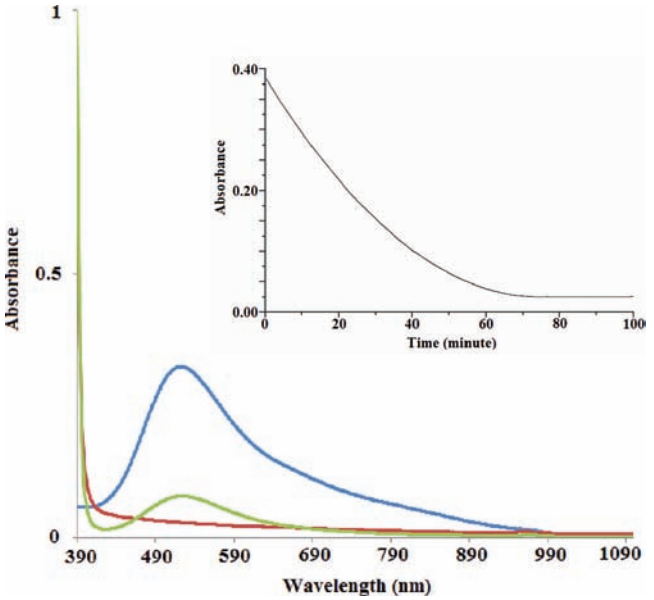


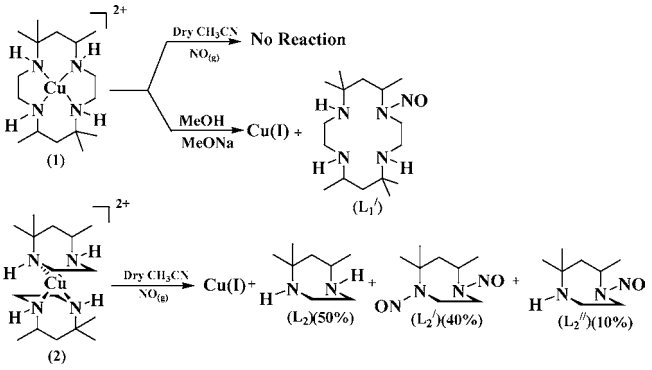
Figure 3. UV−visible spectra of the reaction of complex **1** (blue trace) (λ_{max}, 523 nm) with nitric oxide in methanol solvent and in presence of sodium methoxide, at room temperature. Green and red traces represent the spectral change at an intermediate stage and after complete reduction of Cu(II) to Cu(I), respectively. Inset: plot of the intensity decay for the absorption at 523 nm with time.

changes appeared to show an induction period which was no longer apparent in the buffered medium. This is, presumably, because of the shift in effective pH in the course of the reaction. In the present study, we have also observed an induction period in methanol/water (8:2, v/v) medium in unbufferred condition. When the absorbance of a single wavelength (at 523 nm) was plotted versus time, however, there was no indication of the presence of an induction period in neutral medium (Figure 3, inset). This plot fits well with the exponential decay curve from which the observed pseudo first order rate constant with 10 equivalent of base has been calculated and found to be 5.49×10^{-4} s^{-1} at 298 K. The rate of the reaction was observed to be dependent on the base concentration (Supporting Information).

The reduction of the copper(II) center by nitric oxide further has been authenticated by the X-band EPR spectroscopic studies. The square planar complex **1** was found to display a characteristic spectrum in EPR at room temperature. The colorless solution resulting from the reaction of complex **1** in presence of base and NO was observed to be EPR inactive. This is attributed to the formation of diamagnetic copper(I) species from the reduction of copper(II) by nitric oxide (Supporting Information). It would be worth mentioning here that the [Cu^{II}−NO] intermediate is also expected to be EPR inactive; however, the bleached color (i.e., the absence of d-d transition band after reaction of copper(II) and NO) of the solution clearly ruled out this option.

The reduction of Cu^{II} center, in case of complex **1**, was observed to afford a concomitant nitrosation of L_1 resulting in the formation of L_1' (Scheme 2). The nitrosation product, L_1',

Scheme 2



has been isolated and characterized (Experimental Section). In case of the analogous $[Cu(DAC)]^{2+}$ complex, similar results were exemplified by Ford et al.[6]

The Cu(II) center in complex **2**, on the other hand, was observed to undergo reduction by nitric oxide in pure acetonitrile solvent. The reddish solution of **2**, in dry and degassed acetonitrile, on exposure to nitric oxide gas resulted in a thermally unstable blue intermediate with a shift of λ_{max} to 600 nm (Figure 4). The intermediate was found to be EPR

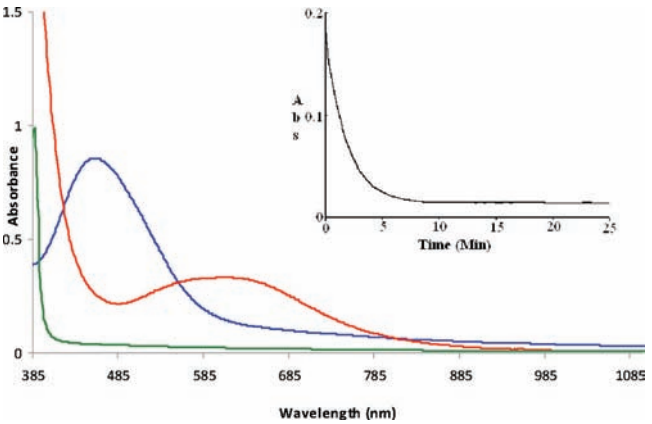


Figure 4. UV−visible spectra of complex **2** (blue); [Cu^{II}−NO] intermediate (red) and its decomposition to Cu^{I} species (green) in acetonitrile. Inset: first order kinetic trace (λ = 600 nm) of decay of [Cu^{II}−NO] intermediate to Cu^{I} species in case of complex **2** in acetonitrile.

silent.[37,61] This intermediate was decomposed gradually to afford a colorless solution following first order kinetics, and the spectral changes were monitored by UV−visible spectrophotometry (Figure 4). The observed rate constant at 298 K is 8.45×10^{-3} s^{-1}.

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The FT-IR spectra of the acetonitrile solutions of complex **2** before and after purging NO were recorded. A new intense and sharp band was found to appear at ~1635 cm^{-1}, corresponding to the vibration of NO coordinated to the Cu(II) center (Figure 5 and Supporting Information). This band was found to decrease in intensity with time (Figure 5).

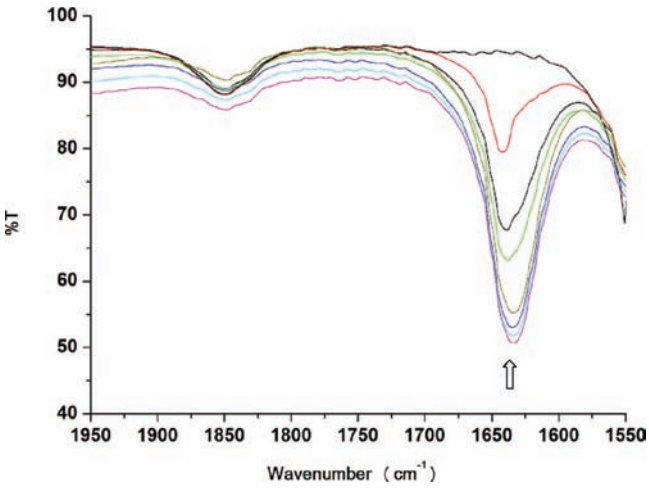

Figure 5. Solution FT-IR spectrum of complex **2** and after reaction with nitric oxide in acetonitrile solvent at room temperature. Arrow head indicates the gradual decrease of the band intensity with time.

The appearance of the thermally unstable band at ~1635 cm^{-1} supports the formation of the $[Cu^{II}–NO]$ intermediate prior to the reduction of the Cu(II) center in the cases of complex **2**. In case of $[Cu(TREN)(CH_3CN)]^{2+}$ complex, the ν_{NO} of $[Cu^{II}–NO]$ was found to appear at 1650 cm^{-1}.[37] It would be worth mentioning here that for the air-stable solid copper-nitrosyl of copper(II)-dithiocarbamate, the ν_{NO} for the NO coordinated to copper appears at 1682 cm^{-1}.[62]

The colorless solution was also observed to be EPR silent (Figure 6) which is consistent with the reduction of Cu(II) to

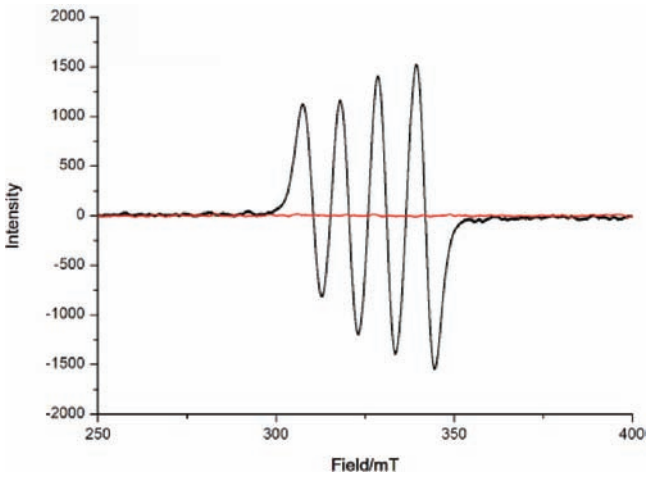

Figure 6. X-band EPR spectra of the complex **2** (black trace) and after its reaction with NO (red trace) in acetonitrile solvent at room temperature.

Cu(I).[37,61] Thus, in the case of complex **2**, presumably a unstable Cu(II)-nitrosyl intermediate was formed, prior to the reduction of Cu(II) to Cu(I). Since both $[Cu^{I}–NO^{+}]$ and $[Cu^{II}–NO^{\bullet}]$ are EPR silent, it is hard to assign the electronic nature of the intermediate precisely. However, in the UV–visible spectrum of the intermediate, the presence of the d-d band supports the existence of the Cu^{II} state rather Cu^{I}. The same result was observed in methanol solution also (Supporting Information).

With $[Cu^{II}(TAEA)(CH_3CN)]^{2+}$ and $[Cu^{II}(TIAEA)(CH_3CN)]^{2+}$, the formation of $[Cu^{II}–NO]$ intermediates were observed earlier.[37] In the reduction of copper(II) dithiocarbamates with nitric oxide in aqueous solution, the formation of air-stable copper-nitrosyl and dinitrosyl species were reported by Cao et al.[62] Detailed kinetics studies of the Cu(II)/NO reactions are still limited. It would be worth mentioning here that in the NO reduction of the copper(II) complexes, $[Cu(dmp)_2(H_2O)]^{2+}$ and $[Cu(dpp)_2]^{2+}$ (dmp = 2,9-dimethyl-1,10-phenanthroline; dpp = 2,9-diphenyl-1,10-phenanthroline), in aqueous solution and in various mixed solvents, though a putative inner sphere complex $[Cu(dmp)_2(NO)]^{2+}$ was proposed to form, no spectral evidence was observed.[24a] Even in the early stage of spectral changes when the reactive aqueous solutions were mixed in the stopped-flow kinetics spectrophotometer, there was no obvious indication of the formation of the $[Cu^{II}–NO]$ intermediate, in case of $[Cu(dmp)_2(NO)]^{2+}$.[24a]

The nitric oxide reduction of Cu(II) ion in complex **2**, in acetonitrile, was accompanied with a simultaneous nitrosation of the ligand and release of the modified nitrosoamines; $\mathbf{L_2}'$ (~ 40%) and $\mathbf{L_2}''$ (~10%) were isolated and characterized (Scheme 2)(Supporting Information). The single crystal X-ray structure of $\mathbf{L_2}'$ has been determined (Figure 7). The crystallo-

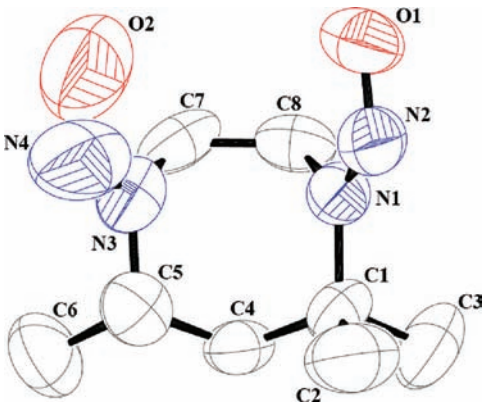

Figure 7. ORTEP diagram of $\mathbf{L_2}'$ (50% thermal ellipsoid plot; H-atoms are omitted for clarity).

graphic data, important bond distances and bond angles are listed in Tables 1, 2 and 3, respectively. The crystal structure of $\mathbf{L_2}'$ displays some disorder; we have tried several times to get better structures; however, we have not succeeded. The 1440 cm^{-1}, 1478 cm^{-1}, and 1475 cm^{-1} bands in the FT-IR spectra of $\mathbf{L_1}'$, $\mathbf{L_2}'$, and $\mathbf{L_2}''$, respectively, were consistent with the expected ν_{NO} of nitrosoamine.[26] During solution FT-IR studies, a broad band appears at 1480–1375 cm^{-1} region (Supporting Information) and even after several attempts, we were not able to get a better resolved spectrum. Hence, though it is expected that the disappearance of the ~1635 cm^{-1} band should correspond to the appearance of the ν_{NO} of nitrosoamine from the modified ligand, we could not assign them.

It is important to note that the free ligands do not react with NO at the reaction condition.

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The reactivity pathway, thus, depends on the ligand environment which is also playing a key role in controlling the degree of ligand nitrosation. With macrocyclic ligands, both $\mathbf{L_1}$ and DAC, the Cu^{II} centers were found to react with nitric oxide in presence of base through a plausible Cu^{II}-amide complex formation, whereas in complex **2**, it has been found that the Cu(II) center reacts with nitric oxide leading to the formation of a $[Cu^{II}-NO]$ intermediate prior to the reduction of Cu(II) to Cu(I). The similar observation was reported for $[Cu^{II}(TAEA)(CH_3CN)]^{2+}$, $[Cu^{II}(TIAEA)(CH_3CN)]^{2+}$, and $[Cu^{II}(TREN)(CH_3CN)]^{2+}$.[37] Thus, the proposed mechanism of the attack of nitric oxide on the deprotonated amine site followed by electron transfer to the copper center as reported in case of $[Cu^{II}(DAC)]^{2+}$ is true for macrocyclic ligands only. Alternatively, first NO coordination to the Cu(II) followed by NO^+ migration to the secondary amine is true in case of other amine ligands. The observation of the transient intermediates in UV−visible and EPR spectroscopy prior to reduction also supports this possibility. This is, perhaps, because of the extra stability of the complex imparted by the macrocycle compared to the others.[59] Since long ago, it is well documented in the literature that the copper(II) complexes of macrocyclic tetraammine ligands are kinetically and electrochemically more inert compared to the nonmacrocyclic analogues.[59] This perhaps prevents the formation of an inner-sphere $[Cu^{II}-NO]$ complex prior to the reduction of the copper(II) center as observed in case of nonmacrocyclic ligands. It should be noted that though the N-nitrosation was reported in cases of $[Cu(Fl_n)]$ complexes (Fl_n = fluorophore ligands), the mechanism was not very clear.[29] It was proposed that N-nitrosation of Fl_n might happen through initial NO coordination to Cu(II) followed by internal electron transfer and migration of NO^+ from Cu(I) center to the secondary amine group with loss of proton or through an alternative deprotonation mechanism as observed in case of $[Cu(II)(DAC)]^{2+}$.[29]

DFT calculations were performed to have some insight into the likelihood of the formation of the $[Cu^{II}-NO]$ intermediates in the reaction sequences for both the complexes. The calculated structures for the cationic part of complexes **1** and **2** in gas phase are in good agreement with the crystal structures (Supporting Information). In the vibrational frequency calculations, no imaginary frequency was found for the complexes suggesting their stable structures (local minima) in the potential energy surface. Similar calculations were performed for complexes **1** and **2** after NO coordination (i.e., for respective $[Cu^{II}-NO]$ species) (Supporting Information). It is interesting to note that no negative vibrational frequency (imaginary frequency) was observed for these, also. Thus, on the basis of vibrational frequency calculations, $[Cu^{II}-NO]$ species for both complexes **1** and **2** are possible. To have more insight on the stability of these $[Cu^{II}-NO]$ species for both the complexes, the HOMO−LUMO gaps were calculated. The calculated HOMO−LUMO gap of $[Cu^{II}-NO]$ species for complex **1** and complex **2** are 0.206 and 1.020 eV, respectively. This suggests that complex **2** is more likely to form $[Cu^{II}-NO]$ upon reaction with NO and the same for complex **1** is somewhat unfavorable. The higher chemical hardness value of $[Cu^{II}-NO]$ species for the complex **2** (0.510 eV) compared to that for **1** (0.103 eV) also supports this.[51] It would be worth mentioning here that for $[Cu(DAC)]^{2+}$ also, the formation of an NO coordinated intermediate was reported to be unfavorable.[60] From the theoretical studies, it has been found that for complex **1**, the calculated geometry of the $[Cu^{II}-NO]$ species is square pyramidal with the NO group in the axial position whereas for complex **2**, it is trigonal bipyramidal with NO coordinated to the copper at an equatorial site. It should be noted that for the structurally characterized copper(II)-nitrosyl complex, $[Cu(CH_3NO_2)_5(NO)][PF_6]_2$, the NO group was reported to be coordinated to the copper center in a bent geometry [Cu−N−O, 121.0(3)°] at an equatorial site.[61] In the case of complex **2**, the calculated geometry of $[Cu^{II}-NO]$ also suggests a bent geometry for NO coordination to the copper center with an angle of 125.78°. Hence, presumably, the geometry of the $[Cu^{II}-NO]$ species might be crucial in controlling the observed reactivity pathways of the respective complexes. Further, the NBO calculations support the $[Cu^{II}-NO]$ electronic distribution rather than $[Cu^{I}-NO^+]$ for the intermediate. This, indeed, is in agreement with the experimentally observed data.

CONCLUSION

In conclusion, in case of complex **1**, the reduction of Cu^{II} to Cu^{I} takes place in methanol medium in presence of base; whereas, the same in case of **2** was observed to be very facile in dry acetonitrile. The Cu(II) to Cu(I) reduction in **2** was found to proceed through a $[Cu^{II}-NO]$ intermediate. In both cases, the reduction resulted into N-nitrosation; in **1**, only mononitrosation was observed whereas complex **2** afforded dinitrosation as major product along with a minor amount of mononitrosation. Hence, in the present study, it has been observed that though the macrocyclic ligands prefer deprotonation pathway, the nonmacrocyclic one prefers the $[Cu^{II}-NO]$ intermediate pathway resulting in nitrosation at all the available sites of the ligand as major product. DFT calculations also suggests the facile formation of $[Cu^{II}-NO]$ intermediate for complex **2** which is in good agreement with the experimental observations.

ASSOCIATED CONTENT

Supporting Information

UV−visible, FT-IR, X-band EPR, ^1H NMR, ^{13}C NMR spectra of complexes **1** and **2**, $\mathbf{L_1}'$, $\mathbf{L_2}'$, and $\mathbf{L_2}''$. This material is available free of charge via the Internet at http://pubs.acs.org.

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REFERENCES

(1) (a) *Nitric Oxide: Biology and Pathobiology*; Ignarro, L. J., Ed.; Academic Press: San Diego, CA, 2000. (b) Martin, C. T.; Morse, R. H.; Kanne, R. M.; Gray, H. B.; Malmstrom, B. G.; Chan, S. I. *Biochemistry* **1981**, *20*, 5147.

(2) (a) Cooper, C. E.; Torres, J.; Sharpe, M. A.; Wilson, M. T. *FEBS Lett.* **1997**, *414*, 281. (b) Richter-Addo, G. B.; Legzdins, P. *Metal Nitrosyls*; Oxford University Press: New York, 1992.

(3) (a) Studbauer, G.; Giuffre, P.; Sarti, P. *J. Biol. Chem.* **1999**, *274*, 28128. (b) McCleverty, J. A. *Chem. Rev.* **2004**, *104*, 403.

(4) (a) Chien, J. C. W. *J. Am. Chem. Soc.* **1969**, *91*, 2166. (b) Wayland, B. B.; Olson, L. W. *J. Am. Chem. Soc.* **1974**, *96*, 6037.

(5) (a) Hoshino, M.; Maeda, M.; Konishi, R.; Seki, H.; Ford, P. C. *J. Am. Chem. Soc.* **1996**, *118*, 5702. (b) Hoshino, M.; Ozawa, K.; Seki, H.; Ford, P. C. *J. Am. Chem. Soc.* **1993**, *115*, 9568. (c) Lehnert, N.; Praneeth, V. K. K.; Paulat, F. *J. Comput. Chem.* **2006**, *27*, 1338.
(6) (a) Fernandez, B. O.; Ford, P. C. *J. Am. Chem. Soc.* **2003**, *125*, 10510. (b) Fernandez, B. O.; Lorkovic, I. M.; Ford, P. C. *Inorg. Chem.* **2004**, *43*, 5393.
(7) (a) Ellison, M. K.; Scheidt, W. R. *J. Am. Chem. Soc.* **1999**, *121*, 5210. (b) Linder, D. P.; Rodgers, K. R.; Banister, J.; Wyllie, G. R. A.; Ellison, M. K.; Scheidt, W. R. *J. Am. Chem. Soc.* **2004**, *126*, 14136.
(8) (a) Lim, M. D.; Lorkovic, I. M.; Ford, P. C. *J. Inorg. Biochem.* **2005**, *99*, 151. (b) Shamir, D.; Zilbermann, I.; Maimon, E.; Gellerman, G.; Cohen, H.; Meyerstein, D. *Eur. J. Inorg. Chem.* **2007**, 5029.
(9) (a) Martin, C. T.; Morse, R. H.; Kanne, R. M.; Gray, H. B.; Malmstrom, B. G.; Chan, S. I. *Biochem.* **1981**, *20*, 5147. (b) Gorren, A. C. F.; de Boer, E.; Wever, R. *Biochem. Biophys. Acta* **1987**, *916*, 38.
(10) Torres, J.; Cooper, C. E.; Wilson, M. T. *J. Biol. Chem.* **1998**, *273*, 8756.
(11) (a) Torres, J.; Svistunenko, D.; Karlsson, B.; Cooper, C. E.; Wilson, M. T. *J. Am. Chem. Soc.* **2002**, *124*, 963. (b) Brown, G. C. *Biochim. Biophys. Acta* **2001**, *1504*, 46.
(12) (a) Torres, J.; Sharpe, M. A.; Rosquist, A.; Cooper, C. E.; Wilson, M. T. *FEBS Lett.* **2000**, *475*, 263. (b) Wijma, H. J.; Canters, G. W.; de Vries, S.; Verbeet, M. P. *Biochemistry* **2004**, *43*, 10467.
(13) Miranda, K. M.; Bu, X.; Lorkovic, I. M.; Ford, P. C. *Inorg. Chem.* **1997**, *36*, 4838.
(14) (a) Lorkovic, I. M.; Miranda, K. M.; Lee, B.; Bernhard, S.; Schoonover, J. R.; Ford, P. C. *J. Am. Chem. Soc.* **1998**, *120*, 11674. (b) Lorkovic, I. M.; Ford, P. C. *Inorg. Chem.* **1999**, *38*, 1467.
(15) (a) Lorkovic, I. M.; Ford, P. C. *J. Am. Chem. Soc.* **2000**, *122*, 6516. (b) Laverman, L. E.; Wanat, A.; Oszajca, J.; Stochel, G.; Ford, P. C.; van Eldik, R. *J. Am. Chem. Soc.* **2001**, *123*, 285.
(16) (a) Laverman, L. E.; Ford, P. C. *J. Am. Chem. Soc.* **2001**, *123*, 11614. (b) Kurtikyan, T. S.; Martirosyan, G. G.; Lorkovic, I. M.; Ford, P. C. *J. Am. Chem. Soc.* **2002**, *124*, 10124.
(17) (a) Lim, M. D.; Lorkovic, I. M.; Wedeking, K.; Zanella, A. W.; Works, C. F.; Massick, S. M.; Ford, P. C. *J. Am. Chem. Soc.* **2002**, *124*, 9737. (b) Patterson, J C.; Lorkovic, I. M.; Ford, P. C. *Inorg. Chem.* **2003**, *42*, 4902.
(18) (a) Ford, P. C. *Pure Appl. Chem.* **2004**, *76*, 335. (b) Martirosyan, G. G.; Azizyan, A. S.; Kurtikyan, T. S.; Ford, P. C. *Chem. Commun.* **2004**, 1488.
(19) (a) Kurtikyan, T. S.; Gulyan, G. M.; Martirosyan, G. G.; Lim, M. D.; Ford, P. C. *J. Am. Chem. Soc.* **2005**, *127*, 6216. (b) Ford, P. C.; Fernandez, B. O.; Lim, M. D. *Chem. Rev.* **2005**, *105*, 2439.
(20) (a) Gow, A. J.; Luchsinger, B. P.; Pawloski, J. R.; Singel, D. J.; Stamler, J. S. *Proc. Natl. Acad. Sci. U.S.A.* **1999**, *96*, 9027. (b) Luchsinger, B. P.; Rich, E. N.; Gow, A. J.; Williams, E. M.; Stamler, J. S.; Singel, D. J. *Proc. Natl. Acad. Sci. U.S.A.* **2003**, *100*, 461.
(21) (a) Gladwin, M. T.; Lancaster, J. R. Jr.; Freeman, B. A.; Schechter, A. N. *Nat. Med.* **2003**, *9*, 496. (b) Han, T. H.; Fukuto, J. M.; Liao, J. C. *Nitric Oxide, Biol. Chem.* **2004**, *10*, 74.
(22) (a) Feelisch, M. S.; Rassaf, T.; Manimneh, S.; Singh, N.; Byran, N. S.; Jourd'Heuil, D.; Kelm, M. *FASEB J.* **2002**, *16*, 1775. (b) Bryan, N. S.; Rassaf, T.; Maloney, R. E.; Rodriguez, C. M.; Saijo, F.; Rodriguez, J. R.; Feelisch, M. *Proc. Natl. Acad. Sci., U.S.A.* **2004**, *101*, 4308.
(23) (a) Rassaf, T.; Feelisch, M.; Kelm, M. *Free Radical Biol. Med.* **2004**, *36*, 413. (b) Bryan, N. S.; Fernandez, B. O.; Bauer, S. M.; Garcia-Saura, M. F.; Milsom, A. B.; Rassaf, T.; Maloney, R. E.; Bharti, A.; Rodriguez, J.; Feelisch, M. *Nat. Chem. Biol.* **2005**, *1*, 290.
(24) (a) Tran, D.; Skelton, B. W.; White, A. H.; Laverman, L. E.; Ford, P. C. *Inorg. Chem.* **1998**, *37*, 2505. (b) Tran, D.; Ford, P. C. *Inorg. Chem.* **1996**, *35*, 2411.
(25) Lim, M. D.; Capps, K. B.; Karpishin, T. B.; Ford, P. C. *Nitric Oxide, Biol. Chem.* **2005**, *12*, 244.
(26) Tsuge, K.; DeRosa, F.; Lim, M. D.; Ford, P. C. *J. Am. Chem. Soc.* **2004**, *126*, 6564.
(27) Melzer, M. M.; Mossin, S.; Dai, X.; Bartell, A. M.; Kapoor, P.; Meyer, K.; Warren, T. H. *Angew. Chem., Int. Ed.* **2010**, *49*, 904.
(28) (a) Lim, M. H.; Lippard, S. J. *J. Am. Chem. Soc.* **2005**, *127*, 12170. (b) Lim, M. H.; Xu, D.; Lippard, S. J. *Nat. Chem. Biol.* **2006**, *2*, 375. (c) Lim, M. H.; Kuang, C.; Lippard, S. J. *ChemBioChem* **2006**, *7*, 1571.
(29) (a) Lim, M. H.; Wong, B. A.; Pitcock, W. H. Jr.; Mokshagundam, D.; Baik, M.-H.; Lippard, S. J. *J. Am. Chem. Soc.* **2006**, *128*, 14364. (b) Smith, R. C.; Tennyson, A. G.; Won, C.; Lippard, S. *Inorg. Chem.* **2006**, *45*, 9367. (c) Lim, M. H.; Lippard, S. J. *Inorg. Chem.* **2006**, *45*, 8980.
(30) Pell, S. D.; Armor, J. N. *J. Am. Chem. Soc.* **1973**, *95*, 7625.
(31) Ruggiero, C. E.; Carrier, S. M.; Antholine, W. E.; Whittaker, J. W.; Cramer, C. J.; Tolman, W. B. *J. Am. Chem. Soc.* **1993**, *115*, 11285.
(32) (a) Wayland, B. B.; Olson, L. W. *Chem. Commun.* **1973**, 897. (b) Choi, I.-K.; Liu, Y.; Wei, Z.; Ryan, M. D. *Inorg. Chem.* **1997**, *36*, 3113.
(33) (a) Bohle, D. S.; Hung, C.-H. *J. Am. Chem. Soc.* **1995**, *117*, 9584. (b) Killday, K. B.; Tempesta, M. S.; Bailey, M. E.; Metral, C. J. *J. Agric. Food Chem.* **1988**, *36*, 909.
(34) (a) Trofimova, N. S.; Safronov, A. Y.; Ikeda, O. *Inorg. Chem.* **2003**, *42*, 1945. (b) Vilhena, F. S. D. S.; Louro, S. R. W. *J. Inorg. Biochem.* **2004**, *98*, 459.
(35) Nakagawa, S.; Yashiro, T.; Munakata, H.; Imai, H.; Uemori, Y. *Inorg. Chim. Acta* **2003**, *349*, 17.
(36) (a) Gwost, D.; Caulton, K. G. *J. Chem. Soc., Chem. Commun.* **1973**, *3*, 64. (b) Gwost, D.; Caulton, K. G. *Inorg. Chem.* **1973**, *12*, 2095.
(37) (a) Sarma, M.; Kalita, A.; Kumar, P.; Singh, A.; Mondal, B. *J. Am. Chem. Soc.* **2010**, *132*, 7846. (b) Sarma, M.; Singh, A.; Mondal, B. *Inorg. Chim. Acta* **2010**, *363*, 63. (c) Sarma, M.; Mondal, B. *Inorg. Chem.* **2011**, *50*, 3206.
(38) (a) Suarez-Varela, J.; Moreno, J. M.; Ben, M. I.; Lloret, F.; Mrozinski, J.; Kivekas, R.; Colacio, E. *Cryst. Growth Des.* **2009**, *9*, 4102. (b) Ou, G.-C.; Jiang, L.; Feng, X.-L.; Lu, T.-B. *Dalton Trans.* **2009**, 71. (c) Bharadwaj, P. K.; Potenza, J. A.; Schugar, H. J. *Inorg. Chem.* **1988**, *27*, 3172.
(39) (a) Wang, H.; Chen, Y.; Li, J.; Bai, L. *Inorg. Chim. Acta* **1988**, *148*, 261. (b) Dominguez-Vera, J. M.; Suarez-Varela, J.; Ben, M.; Ikram, C. E. *Eur. J. Inorg. Chem.* **2005**, *10*, 1907. (c) Diaz, C.; Ribas, J.; El Fallah, M. S.; Solans, X.; Font-Bardia, M. *Inorg. Chim. Acta* **2001**, *312*, 1.
(40) (a) Diaz, G.; Bustos, C.; Shepherd, R. E. *Chim. Acta* **1987**, *133*, 23. (b) Freiberg, M.; Meyerstein, D.; Yamamoto, Y. *Dalton Trans.* **1982**, 1137. (c) Liang, B.-F.; Chung, C.-S. *Inorg. Chem.* **1980**, *19*, 572.
(41) (a) Al-Shatti, N.; Segal, M. G.; Sykes, A. G. *Dalton Trans.* **1977**, 1766. (b) Bryan, P. S.; Dabrowiak, J. C. *Inorg. Chem.* **1975**, *14*, 299. (c) Liang, B.-F.; Chung, C.-S. *Dalton Trans.* **1980**, 1349.
(42) (a) Muralidharan, S.; Ferraudi, G. *Inorg. Chem.* **1981**, *20*, 2306. (b) John, E.; Bharadwaj, P. K.; Krogh-Jespersen, K.; Potenza, J. A.; Schugar, H. J. *J. Am. Chem. Soc.* **1986**, *108*, 5015. (c) Siddiqui, S.; Shepherd, R. E. *Inorg. Chem.* **1986**, *25*, 3869.
(43) (a) Endicott, J. F.; Rillema, D. P.; Papaconstantinou, E. *Inorg. Chem.* **1971**, *10*, 1739. (b) Ferraudi, G.; Muralidharan, S. *Inorg. Chem.* **1981**, *20*, 4262. (c) Ronco, S.; Van Vlierberge, B.; Ferraudi, G. *Inorg. Chem.* **1988**, *27*, 3453.
(44) (a) Holwerda, R. A. *J. Inorg. Biochem.* **1988**, *33*, 131. (b) Woodin, K. S.; Heroux, K. J.; Boswell, C. A.; Wong, E. H.; Weisman, G. R.; Niu, W.; Tomellini, S. A.; Anderson, C. J.; Zakharov, L. N.; Rheingold, A. L. *Eur. J. Inorg. Chem.* **2005**, *23*, 4829. (c) Chen, J. W.; Wu, D. S.; Chung, C.-S. *Inorg. Chem.* **1986**, *25*, 1940.
(45) (a) Liang, B.-F.; Tsay, Y. K.; Chung, C.-S. *Dalton Trans.* **1983**, 995. (b) Castellani, C. B.; Fabbrizzi, L.; Licchelli, M.; Perotti, A.; Poggi, A. *Chem. Commun.* **1984**, 806. (c) Rodriguez-Dieguez, A.; Kivekaes, R.; Sillanpaeae, R.; Cano, J.; Lloret, F.; McKee, V.; Stoeckli-Evans, H.; Colacio, E. *Inorg. Chem.* **2006**, *45*, 10537.
(46) *SMART, SAINT and XPREP*; Siemens Analytical X-ray Instruments Inc.: Madison, WI, 1995.

(47) Sheldrick, G. M. *SADABS: software for Empirical Absorption Correction*; Institut fur Anorganische Chemie der Universität, University of Göttingen, , Göttingen, Germany, 1999–2003.
(48) Sheldrick, G. M. *SHELXS-97*; University of Göttingen: Göttingen, Germany, 1997.
(49) Farrugia, L. J. J. *Appl. Crystallogr.* **1997**, *30*, 565.
(50) Delly, B. *J. Chem. Phys.* **1990**, *92*, 508.
(51) Deka, R. C.; Vetrivel, R.; Pal, S. *J. Phys. Chem. A* **1999**, *103*, 5978.
(52) Hay, R. W.; Lawrance, A. G.; Curtis, N. F. *J. Chem. Soc., Perkin Trans.* **1975**, *1*, 59.
(53) Curtis, N. F. *Aust. J. Chem.* **1986**, *39*, 239.
(54) (a) Liang, B.-F.; Chung, C. *Inorg. Chem.* **1981**, *20*, 2152. (b) Chen, J.-W.; Wu, D.-S.; Chung, C.-S. *Inorg. Chem.* **1986**, *25*, 1940.
(55) Clay, R.; Murray-Rust, J.; Murray-Rust, P. *Dalton Trans.* **1979**, 1135.
(56) (a) Addison, A. W.; Hendriks, H. M. J.; Reedijk, J.; Thompson, L. K. *Inorg. Chem.* **1981**, *20*, 103. (b) Sorrell, T. N.; Jameson, D. L. *Inorg. Chem.* **1982**, *21*, 1014.
(57) Olson, D. C.; Vasilevskis, J. *Inorg. Chem.* **1971**, *10*, 463.
(58) Ghachtouli, S. E.; Cadiou, C.; Déchamps-Olivier, I.; Chuburu, F.; Aplincourt, M.; Turcry, V.; Baccon, M. L.; Handel, H. *Eur. J. Inorg. Chem.* **2005**, 2658.
(59) (a) Cabbiness, D. K.; Margerum, D. W. *J. Am. Chem. Soc.* **1969**, *91*, 6540. (b) Woodin, K. S.; Heroux, K. J.; Boswell, C. A.; Wong, E. H.; Weisman, G. R.; Niu, W.; Tomellini, S. A.; Anderson, C. J.; Zakharov, L. N.; Rheingold, A. L. *Eur. J. Inorg. Chem.* **2005**, *23*, 4829. (c) Liang, B.-F.; Chung, C.-S. *Inorg. Chem.* **1980**, *19*, 572.
(60) Khin, C.; Lim, M. D.; Tsuge, K.; Iretskii, A.; Wu, G.; Ford, P. C. *Inorg. Chem.* **2007**, *46*, 9323.
(61) Wright, A. M.; Wu, G.; Hayton, T. W. *J. Am. Chem. Soc.* **2010**, *132*, 14336.
(62) Diaz, A.; Ortiz, M.; Sanchez, I.; Cao, R.; Mederos, A.; Sanchiz, J.; Brito, F. *J. Inorg. Biochem.* **2003**, *95*, 283.