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NMR Evaluation of the Configurational Stability of Cu(I) Complexes

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Association of chiral $[CuL_2]^+$ complexes (L = 2-R-phen, 6-R-bpy, and 2-iminopyridine) with TRISPHAT (tris(tetrachlorobenzenediolato)phosphate(V)) anion leads to NMR enantiodifferentiation, which can be used to determine the kinetics of racemization of the complexes.

1,10-Phenanthrolines (phen, **1**), 2,2′-bipyridines (bpy, **2**), and 2-iminopyridines (**3**) have been widely used as ligands for Cu(I). The derived pseudotetrahedral complexes are sensitive to oxidation, and bulky substituents are usually introduced in positions adjacent to the N-coordinating atoms to provide steric inhibition to the geometric reorganization that occurs upon oxidation. The ligands can be unsymmetrical, always in case of compounds **3**, and their complexation to a copper(I) atom results in the formation of chiral $[CuL_2]^+$ adducts (Figure 1).[1,2] VT-NMR evaluation of the configurational stability of these complexes was previously reported using ligands that evidenced nonequivalent signals upon complex formation.[3,4] Herein, we present another method based on the use of a chiral counterion as the source of NMR differentiation. Simple bpy, phen, and iminopyridine ligands can be used, and the configurational stability of their chiral adducts is compared.

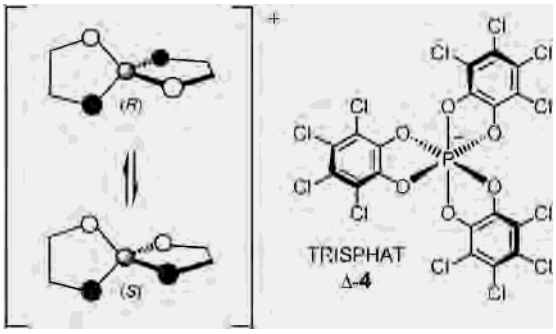

Figure 1. Stereodynamics among diastereoisomeric $[CuL_2][\Delta\text{-}\mathbf{4}]$ ion pairs.

As mentioned, unsymmetrical 2-R-phen, 6-R-bpy, and 2-iminopyridine ligands form chiral bis(diimine)copper(I) complexes (Figure 1),[5] of which the configurational stability can be evaluated by NMR using ligands containing enantiotopic groups.[3,4,6] Upon complex formation, these substituents become diastereotopic, and separated NMR signals are observed when the stereodynamics are slow on the NMR time scale. The determination of the racemization barriers is then performed by VT-NMR ($\Delta G^{\ddagger} \sim 58-64$ kJ·mol^{-1} in $CDCl_3$).[7]

Unfortunately, this efficient method cannot be applied to complexes made of ligands deprived of enantiotopic substituents. For these substrates, it occurred to us that a chiral counterion could be the source of NMR differentiation. The association of chiral cationic $[CuL_2]^+$ complexes with

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(1) Von Zelewsky, A. *Stereochemistry of Coordination Compounds*; John Wiley & Sons: Chichester, U.K., 1996.
(2) (a) Mitchell, D. K.; Sauvage, J. P. *Angew. Chem., Int. Ed. Engl.* **1988**, *27*, 930−931. (b) Chambron, J. C.; Mitchell, D. K.; Sauvage, J. P. *J. Am. Chem. Soc.* **1992**, *114*, 4625−4631. (c) Kaida, Y.; Okamoto, Y.; Chambron, J. C.; Mitchell, D. K.; Sauvage, J. P. *Tetrahedron Lett.* **1993**, *34*, 1019−1022. (d) Riesgo, E. C.; Credi, A.; De Cola, L.; Thummel, R. P. *Inorg. Chem.* **1998**, *37*, 2145−2149.
(3) Van Stein, G. C.; Van Koten, G.; Brevard, C. *J. Organomet. Chem.* **1982**, *226*, C27−C30. Van Stein, G. C.; Van Koten, G.; Debok, B.; Taylor, L. C.; Vrieze, K.; Brevard, C. *Inorg. Chim. Acta* **1984**, *89*, 29−39.
(4) Riesgo, E.; Hu, Y. Z.; Bouvier, F.; Thummel, R. P. *Inorg. Chem.* **2001**, *40*, 2541−2546.
(5) James, B. R.; Williams, R. J. *J. Chem. Soc.* **1961**, 2007−2019. Müller, E.; Piguet, C.; Bernardinelli, G.; Williams, A. F. *Inorg. Chem.* **1988**, *27*, 849−855. Grosshenny, V.; Ziessel, R. *J. Chem. Soc., Dalton Trans.* **1993**, 817−819. Bardwell, D. A.; Thompson, A.; Jeffery, J. C.; Tilley, E. E. M.; Ward, M. D. *J. Chem. Soc., Dalton Trans.* **1995**, 835−841. Bonnefous, C.; Bellec, N.; Thummel, R. P. *Chem. Commun.* **1999**, 1243−1244. Meyer, M.; Albrecht-Gary, A. M.; Dietrich-Buchecker, C. O.; Sauvage, J. P. *Inorg. Chem.* **1999**, *38*, 2279−2287. Riesgo, E. C.; Hu, Y. Z.; Bouvier, F.; Thummel, R. P.; Scaltrito, D. V.; Meyer, G. J. *Inorg. Chem.* **2001**, *40*, 3413−3422.
(6) *R* and *S* correspond to Λ and Δ configurations in the oriented-skew-lines reference system, respectively.
(7) The relationship $\Delta G^{\ddagger} = RT_c(22.96 + \ln(T_c/\sqrt{(\Delta\nu^2 + 6J^2)}))$ was used to determine the activation energy, $\Delta G^{\ddagger}$, from the coalescence temperature, T_c (K), the frequency separation of the peaks, $\Delta\nu$ (Hz), and the coupling constant between the nuclei, J (Hz).

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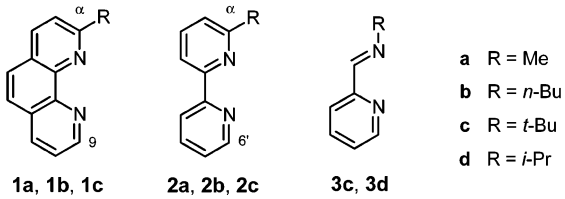

Figure 2. Selected diimine ligands.

enantiopure anions would form diastereoisomeric salts, and distinct NMR signals could thus result from the asymmetric ion pairing.[8] Previously, the synthesis and resolution of tris(tetrachlorobenzenediolato)phosphate(V) or TRISPHAT, **4**, was reported.[9] This chiral anion (Δ and Λ enantiomers) is an efficient NMR chiral shift and resolving agent for organic and organometallic derivatives.[10] Its overall efficiency as an NMR chiral shift agent for chiral cationic derivatives led to its use for the proposed study.

Several unsymmetrical phen and bpy ligands were prepared following previously reported conditions.[11] Nucleophilic addition of alkyl lithium reagents to parent compounds **1** or **2**, followed by the rearomatization in the presence of an excess of manganese dioxide, afforded ligands 2-R-phen (**1a**−**c**) and 6-R-bpy (**2a**−**c**) in low to good yields (16−95%; R = Me (**a**); *n*-Bu (**b**); *t*-Bu (**c**); Figure 2). Formation of the corresponding $[CuL_2][PF_6]$ salts was performed by reaction of the ligands with $[Cu(CH_3CN)_4][PF_6]$ in acetonitrile. Association of these complexes with anion Δ-**4** was realized by chromatography under previously described conditions and afforded ion pairs [Cu(**1a**−**c**)$_2$][Δ-**4**] and [Cu(**2a**−**c**)$_2$]-[Δ-**4**] as the first eluted fractions (SiO_2/CH_2Cl_2, R_f = ∼0.6−0.9, 62−95%).[12,13]

The effect of anion **4** as a chiral shift reagent was simply demonstrated. Solutions of [Cu(**1a**−**c**)$_2$][Δ-**4**] salts were prepared ($CDCl_3$) and analyzed by ^{1}H NMR at room temperature. Because of the presence of TRISPHAT (**4**), the spectra of diastereomeric [(*S*)-Cu(**1a**−**c**)$_2$][Δ-**4**] and [(*R*)-Cu(**1a**−**c**)$_2$][Δ-**4**] complexes showed partial or complete separation of the signals (Figure 3). Of all the split signals, those of higher-frequency H9 protons were particularly easy to monitor. For salt [Cu(**1c**)$_2$][Δ-**4**], proton H8 was better split than H9; this most probably indicates that the steric bulk of the *tert*-butyl groups hinders the approach of the TRISPHAT anion along the C_2-axis of the complex. Rather large differences in chemical shifts ($\Delta\Delta\delta_{max}$ = ∼0.156 ppm) were observed for analogous protons allowing the determination

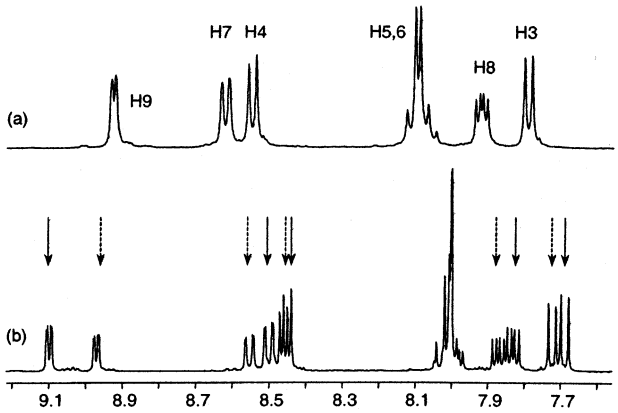

Figure 3. ^{1}H NMR analyses ($CDCl_3$, 400 MHz, 298 K) of salts (a) [Cu(**1b**)$_2$][PF_6] and (b) [Cu(**1b**)$_2$][Δ-**4**]; de 16%.

Table 1. Relevant Data for the Stereodynamics among Diastereoisomeric [CuL_2][Δ-**4**] Ion Pairs

entry	ligand	R	de [%]	$\Delta\Delta\delta^a$	$T_c{}^b$	$\Delta G^{\ddagger\,c}$
1	**1a**	Me	0	0.102^d	>328	>68.0
2	**1b**	*n*-Bu	16	0.156^d	>323	>66.0
3	**1c**	*t*-Bu	0	0.030^e	>328	>71.8
4	**2a**	Me	10	0.036^d	303	65.0
5	**2b**	*n*-Bu	4	0.040^d	313	67.4
6	**2c**	*t*-Bu	7	0.032^e	263	56.8
7^f	**3c**	*t*-Bu	9	0.023^e	285	62.5
8^f	**3d**	*i*-Pr	9	0.026^g	267	58.2

^{a} In ppm. ^{b} In K. ^{c} In kJ·mol^{-1}; $\Delta G^{\ddagger} = RT_c(22.96 + \ln(T_c/\sqrt{(\Delta\nu^2 + 6J^2)}))$. ^{d} Hα. ^{e} H(*t*-Bu). ^{f} In CD_2Cl_2. ^{g} H(imine).

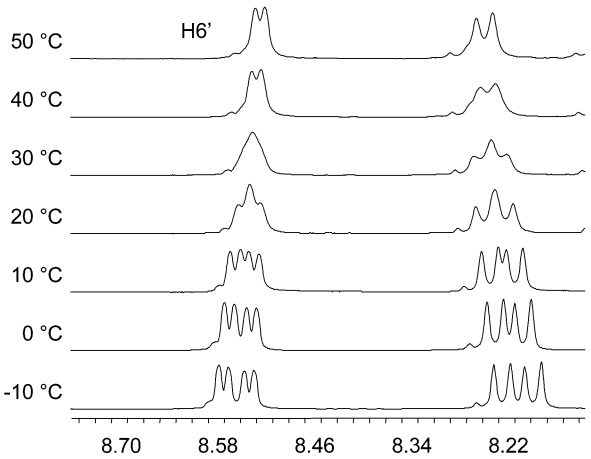

Figure 4. Variable temperature ^{1}H NMR ($CDCl_3$, 400 MHz, δ 8.75−8.10 ppm) of [Cu(**2a**)$_2$][Δ-**4**]. T_c (Hα) = 303 K.

of the asymmetric induction, or the lack of it, by integration of the respective signals (diastereomeric excess (de), Table 1).

However, room temperature NMR analyses of bpy-derived [Cu(**2a**−**c**)$_2$][Δ-**4**] salts revealed broad resonances or lack of signal separation (see Figure 4 and Supporting Information). Rather than consider the presence of Cu(II) species in the medium, we reasoned, in view of the results obtained by Thummel and Van Koten,[3,4] that dynamic processes were occurring and that the spectra were recorded around or above the coalescence temperatures. VT-NMR experiments on salts [Cu(**1a**−**c**)$_2$][Δ-**4**] and [Cu(**2a**−**c**)$_2$][Δ-**4**] were thus performed (253−328 K) and revealed rather different results

(8) Chiral ligands (L*) can also be used to induce an NMR differentiation. However, a high diastereoselectivity is often observed upon complex formation, meaning that only the signals of the major diastereomer appear: see ref 2d.
(9) Lacour, J.; Ginglinger, C.; Grivet, C.; Bernardinelli, G. *Angew. Chem., Int. Ed. Engl.* **1997**, *36*, 608−609. Lacour, J.; Ginglinger, C.; Favarger, F. *Tetrahedron Lett.* **1998**, 4825−4828.
(10) Monchaud, D.; Jodry, J. J.; Pomeranc, D.; Heitz, V.; Chambron, J.-C.; Sauvage, J.-P.; Lacour, J. *Angew. Chem., Int. Ed.* **2002**, *43*, 2317−2319 and references therein.
(11) Dietrich-Buchecker, C. O.; Nierengarten, J. F.; Sauvage, J. P.; Armaroli, N.; Balzani, V.; De Cola, L. *J. Am. Chem. Soc.* **1993**, *115*, 11237−11244. Dietrich-Buchecker, C.; Jiménez, M. C.; Sauvage, J. P. *Tetrahedron Lett.* **1999**, *40*, 3395−3396.
(12) Monchaud, D.; Lacour, J.; Coudret, C.; Fraysse, S. *J. Organomet. Chem.* **2001**, *624*, 388−391.
(13) [Cinchonidinium][Δ−**4**] (dr > 39:1) was used for the ion exchange.

depending upon the nature of the α-substituent and upon the diimine backbone.

For bpy-derived [Cu(**2a**−**b**)$_2$][Δ-**4**] salts, dynamic configurational isomerism was detected as a separation of the NMR signals occurred at lower temperature (coalescence temperature for H6′ protons, T_c = ∼303−313 K, Figure 4, Table 1). Racemization barriers were determined from T_c, $\Delta\nu$, and J values ($\Delta G^{\ddagger}$ = ∼65−67.4 kJ·mol^{-1} in $CDCl_3$)[7] and are similar to those obtained by Thummel et al.[4] For salt [Cu(**2c**)$_2$][Δ-**4**], faster stereodynamics ($\Delta G^{\ddagger}$ = ∼56.5 kJ·mol^{-1}) were monitored as lower coalescence temperatures were measured for the H6′ and *t*-Butyl protons (T_c = ∼263 K). In this particular case, the steric bulk of the *tert*-butyl groups seems to destabilize the Cu(I) complex, enhancing the lability given by the bpy backbone.[14] For phen complexes [Cu(**1a**−**c**)$_2$][Δ-**4**], only reduced differences in chemical shifts ($\Delta\Delta\delta$) for the split signals of protons H9 or H8 were observed at high temperatures demonstrating a higher configurational stability for these derivatives (Table 1, entries 1−3).[15]

Copper(I) complexes of unsymmetrical pyridine imine ligands (**3c**, R = *t*-Bu, and **3d**, R= *i*-Pr) were also prepared and associated with PF_6^- and TRISPHAT anions.[16] Compound [Cu(**3d**)$_2$][PF_6] had been previously studied, and a racemization barrier measured using as NMR probe the diastereotopic methyl groups of the *i*-propyl substituents ($\Delta G^{\ddagger}$ = ∼58.2 kJ·mol^{-1} in $CDCl_3$).[3] For the derived TRISPHAT salt [Cu(**3d**)$_2$][Δ-**4**], well separated signals were observed at low temperature for most of the protons. The racemization barrier was determined using the signals of the imine hydrogen atoms, and a value in complete agreement with the previously reported result was obtained ($\Delta G^{\ddagger}$ = ∼58.2 kJ·mol^{-1} in CD_2Cl_2) demonstrating without ambiguity that TRISPHAT anion does not modify the kinetics of racemization of the Cu(I) complex. A slightly higher barrier was measured for complex [Cu(**3c**)$_2$][Δ-**4**] using the split *tert*-Butyl signals (Table 1, entry 7).

In conclusion, we have shown that TRISPHAT anion **4** is an efficient NMR chiral shift agent for pseudotetrahedral Cu(I) complexes and that the observed NMR enantiodifferentiation can be used as a tool to measure the kinetics of racemization. Rather subtle differences upon the nature of diimine backbone and its substituent were observed that would have been, otherwise, difficult to monitor. We feel that this method is quite general and could be applied to many chiral mono- and polynuclear transition metal complexes.

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Supporting Information Available: VT-NMR spectra of compounds [Cu(**1a**−**c**)$_2$][Δ-**4**], [Cu(**2a**−**c**)$_2$][Δ-**4**], and [Cu(**3c**−**d**)$_2$]-[Δ-**4**]. This material is available free of charge via the Internet at http://pubs.acs.org.

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(14) The lower barrier for exchange of bpy-derived complexes as compared to those derived from phen might be due to the probable stepwise mechanism for the exchange process, which could be better accommodated by the flexible 2,2′-bond of the bpy. We thank the reviews for this suggestion.

(15) For [Cu(**1c**)$_2$][Δ-**4**], the activation energy $\Delta G^{\ddagger}$ is higher than 71.8 kJ·mol^{-1}, considering $T_c \geq$ 328 K and $\Delta\nu$ = 11.4 Hz ($\Delta\delta$ 0.030 ppm for H(*t*-Bu)). See Supporting Information.

(16) [Cu(**3c**−**d**)$_2$][Δ-**4**] were prepared similarly to [Cu(**1a**−**c**)$_2$][Δ-**4**].