SYNTHESIS OF STERICALLY ENCUMBERED 2,9-DIARYL SUBSTITUTED PHENANTHROLINES. KEY BUILDING BLOCKS FOR THE PREPARATION OF MIXED (BIS-HETEROLEPTIC) PHENANTHROLINE COPPER(I) COMPLEXES (1)

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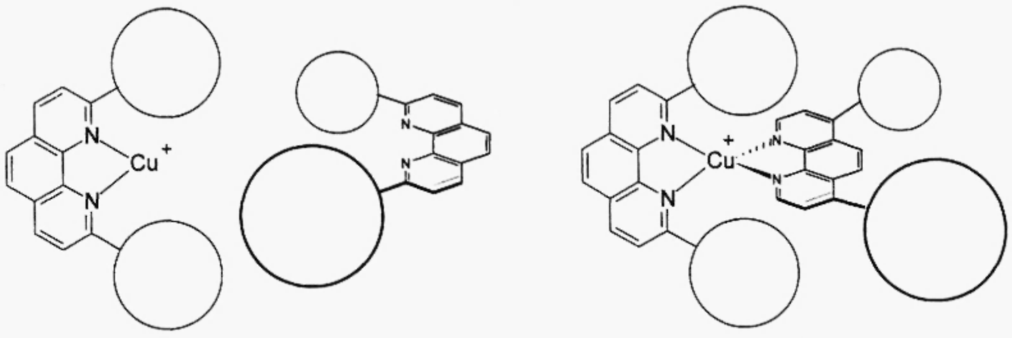
ABSTRACT: The preparation of several novel 2,9-diaryl phenanthrolines is described. Depending on the steric shielding the formation of bis-homoleptic phenanthroline copper(I) complexes can be suppressed and mixed phenanthroline complexes can be prepared.

INTRODUCTION

Metal phenanthroline complexes currently enjoy a renaissance because they find frequent use in exciting molecular structures (2), such as molecular knots (3), rotaxanes (4), dendrimers (5) and catenanes (6), as well as in enantioselective and supramolecular catalysts (7). Unfortunately, bis- and trisphenanthroline complexes have mostly been limited to the general structure $[M(L^1)_n]$ (*e.g.* for Cu(I), Fe(II), Fe(III)) because of rapid ligand exchange processes. Only for Ru(II,III) the combination of different phenanthroline ligands L in mixed (heteroleptic) complexes $[RuL^1{}_2L^2]^{2+/3+}$ and $[RuL^1L^2L^3]^{2+/3+}$ is known since their kinetic exchange is very slow (8). Obviously, many more combinations were possible if we had a strategy at hand to build mixed phenanthroline complexes of metal ions that are prone to rapid ligand exchange, such as copper(I) (9). We have recently shown (10) that the use of sterically encumbered groups in the 2- and 9-position of phenanthrolines, such as in A (scheme 1), prevents formation of complexes of type $[Cu(A_2)]^+$. In contrast, when phenanthroline A is reacted in presence of Cu(I) with a sterically unimpeded phenanthroline B (*e.g.* without any 2,9-substituents) mixed complexes $[Cu(A)(B)]^+$ are afforded in good yield (10). We now want to describe the synthesis of several novel phenanthroline ligands with bulky groups in positions 2 and 9, the steric shielding of which is appropriately tuned to use them for the formation of bis-heteroleptic phenanthroline copper(I) complexes. Of the following 2,9-diaryl phenanthrolines only 3f and 3g have been described before (11).

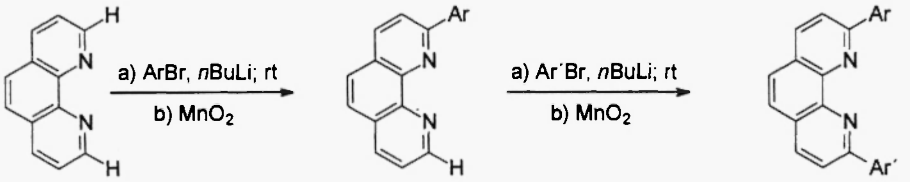


[Cu(A)]+ A [Cu(A)(B)]+

Scheme 1.

Results und Discussion

The synthesis of the 2,9-disubstituted phenanthrolines was undertaken in analogy to the literature procedure (11). However, we found that for introducing sterically demanding groups Ar (scheme 2) the use of toluene, as described for numerous other 2,9-disubstituted phenanthrolines, as well as carrying out the reaction in one step always led to a mixture of mono- and disubstituted products that were difficult to separate.



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2a: Ar = 2,4,6-trimethylphenyl (76%)
2b: Ar = 4-bromo-2,3,5,6-tetramethylphenyl (70%)
2c: Ar = 9-anthracenyl (67%)

3a: Ar = Ar´= 2,4,6-trimethylphenyl (65%)
3b: Ar = Ar´= 4-bromo-2,3,5,6-tetramethylphenyl (51%)
3c: Ar = 9-anthracenyl, Ar´= Phenyl (64%)
3d: Ar = 9-anthracenyl, Ar´= 1-naphthyl (33%)
3e: Ar = Ar´= 9-anthracenyl (21%)
3f: Ar = Ar´= 2,6-dimethylphenyl (ref. 11)
3g: Ar = Ar´= 2,6-dimethoxyphenyl (ref. 11)

Scheme 2.

The yields could be substantially increased by carrying out the substitution in two steps (1 → 2 → 3) and by using diethylether as solvent. Isolation of phenanthrolines 2 was easily accomplished by addition of hexane whereupon 2 readily precipitated. This material was pure enough for a second substitution reaction following the same procedure. For each of the substitution reactions, we first generated the aryllithium species from *n*-butyllithium and the bromoarene in diethyl ether at 0 °C before then adding the phenanthroline in substance. The mixture was stirred overnight (2a-b. 3a-b) or for a few days (2c, 3c-e) at room temperature. After hydrolysis and oxidative rearomatization by MnO_2 the crude product was purified by chromatography. This procedure afforded the desired phenanthrolines in satisfying yields (scheme 2).

To evaluate the steric hindrance of groups Ar in phenanthrolines 2 and 3 we tested whether formation of $[Cu(A)_2]^+$ using A = phenanthrolines 2 and 3 was impeded. Usually, symmetrical copper(I) complexes form quantitatively within seconds by mixing 2 equiv. of the ligand with $[Cu(MeCN)_4]BF_4$ in CH_3CN or CH_2Cl_2 following the general equation:

$$2\,A + [Cu(MeCN)_4]BF_4 \rightarrow [CuA_2]BF_4 + 4\,MeCN$$

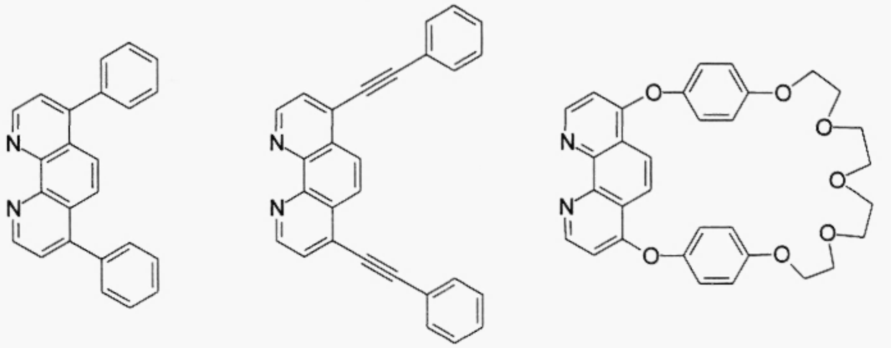
Indeed, when we reacted A = 2a-c, 3c,d with $[Cu(MeCN)_4]BF_4$ the formation of complexes $[CuA_2]BF_4$ was immediately visible by their characteristic red color, indicating that steric shielding in these phenanthrolines is not sufficient. Some of the symmetrical phenanthroline copper(I) complexes were isolated and fully characterized to establish their structure (12).

Table 1. Formation of symmetrical and mixed Cu(I) phenanthroline complexes.

phenanthroline A	$[Cu(A)_2]BF_4$ [a] [b]	$E_{1/2}$ [V *vs.* Fc] [c]	$[Cu(A)(B)]BF_4$ [b]	example of mixed complex [a]	$E_{1/2}$ [V *vs.* Fc] [c]
2a	X (84%)	0.02 V	—		
2b	X [d]		—		
2c	X (78%)	-0.05 V	—		
3a	—		X	$Cu[(3a)(4b)]^+$ (86%) [e]	0.30 V
3b	—		X	$Cu[(3b)(4c)]^+$ (85%)	0.25 V
3c	X [d]		—		
3d	X (85%) [f]	0.56 V	—		
3e	—		X	$Cu[(3e)(4a)]^+$ (95%)	0.16 V
3f	—		X	$Cu[(3f)(4b)]^+$ (86%) [e]	0.36 V
3g	—		X	$Cu[(3g)(4b)]^+$ (97%) [e]	0.04 V
3h	—		X	$Cu[(3h)(4c)]^+$ (65%)	0.22 V
3i	—		X	$Cu[(3i)(4c)]^+$ (60%)	0.20 V

[a] Yields after purification (in brackets). [b] X = Formation possible. [c] Half-wave potentials $E_{1/2}$ (V *vs.* ferrocene/ferrocenium) of copper(I) complexes determined by cyclic voltammetry in dichloromethane at $v = 100$ mV s^{-1} (electrolyte: 0.1 M $NBu^n{}_4PF_6$). [d] Not isolated. [e] See reference 10. [f] As PF_6^- salt.

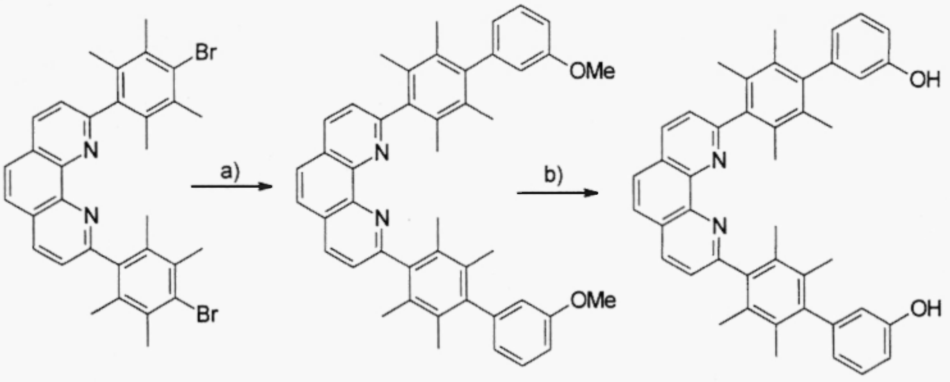
In contrast, with the bulkier phenanthroline ligands A = 3a,b and 3e-g only a yellow solution was obtained under the same conditions, indicative of type $[Cu(A)]^+$ complexes. To acquire some structural information about them they were treated with one equivalent of a 4,7-disubstituted phenanthroline B (*e.g.* 4a-c), which immediately resulted in the formation of a red solution. Therefrom, mixed ligand complexes $[Cu(A)(B)]BF_4$ could be isolated. Their structural assignment is based on several characteristic high field shifts in the ^{1}H-NMR spectra, as in $[Cu(3e)(4a)]^+$ the 2-H and 9-H protons in 4a are shifted to 7.14 ppm from 9.24 ppm in the free ligand (13). Further convincing evidence for mixed complexes was found in the ESI-MS spectra as the corresponding molecular ions $[M]^+$ for $[Cu(A)(B)]^+$ were detected. In addition, collision activated dissociation of the precursor ions led to the formation of characteristic product ions. For example, the molecular ion $[M]^+$ for $[Cu(3e)(4a)]^+$ was detected at *m/z* 927.4; ESI-MS/MS analysis of $[Cu(3e)(4a)]^+$ yielded a product ion at *m/z* 595.4 corresponding to neutral loss of 4a, giving $[Cu(3e)]^+$. This result clearly shows that monosubstituted copper(I) complexes with sterically encumbered phenanthroline ligands (scheme 1) display a much higher stability than the copper adducts of 4,7-disubstituted ligands, and are therefore exclusively obtained in the tandem ESI-MS-experiments.



4a 4b 4c

Scheme 3. 4,7-disubstituted phenanthrolines used for the preparation of mixed complexes $[Cu(A)(B)]^+$ (10,14).

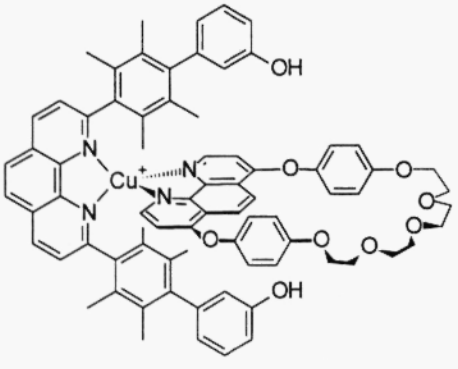
To test whether mixed Cu(I) complexes can be obtained from functionalized phenanthrolines, we coupled 3b with 3-methoxyphenyl boronic acid under Suzuki conditions (15) to yield 78% of phenanthroline 3h. Cleavage of the methyl ether with boron tribromide furnished the bisphenolic ligand 3i in high yield (85%).



3b 3h 3i

Scheme 4. Synthesis of 2,9-disubstituted phenanthrolines 3h,i: a) 3-methoxyphenyl boronic acid, $Pd(PPh_3)_4$ (3 mol-%), Na_2CO_3, toluene, methanol, H_2O, 48 h, 80-90 °C, 78%; b) BBr_3, CH_2Cl_2, 48 h, -78 °C, 85%.

Ligands 3h,i were now reacted in the presence of Cu(I) with the crown-ether phenanthroline 4c (14) following the procedure described above to yield the complexes [Cu(3h)(4c)]BF_4 (65%) and [Cu(3i)(4c)] BF_4 (60%) (scheme 5). Both were characterized by NMR, elemental analysis, ESI-MS as well as cyclic voltammetry. In the ESI-MS spectra the molecular ions $[M]^+$ for the mixed complexes at *m/z* 1273.6 and *m/z* 1245.5 respectively corresponding to $[Cu(A)(B)]^+$ could be detected.



$[Cu(3i)(4c)]^+$

Scheme 5.

Cyclic voltammetry experiments revealed reversible oxidation waves indicative of a reversible redox process Cu(I) $\rightleftharpoons$ Cu(II) despite the fact that both oxidation states of copper prefer different coordination geometries (tetrahedral vs. square planar). In future investigations it is intended to probe whether $[Cu(3i)(4c)]^+$ can act as a redox active host system for the incorporation of artificial or natural guest molecules.

CONCLUSION

It seems obvious from the above results that to impede the formation of the bishomoleptic $[Cu(A_2)]^+$ complexes the two phenyl groups attached to positions 2 and 9 of the phenanthroline need to carry two additional *ortho*-substituents. This is true with the 2,6-dimethylphenyl, 2,6-dimethoxyphenyl, 2,4,6-trimethylphenyl, 2,3,5,6-tetramethylphenyl or alternatively with the anthracenyl but not with the naphthyl group. Hence, all these special ligands can be used for the clean preparation of mixed (bis-heteroleptic) complexes $[Cu(A)(B)]^+$ that are expected to exhibit interesting novel properties.

ACKNOWLEDGEMENTS

Generous financial support from the DFG (Schm 647/5-1, Lu 378/8, He 2599/1-2) and the Fonds der Chemischen Industrie is gratefully acknowledged. We are indebted to Dipl. Chem. M. Hagen (Kiel) and Dr. M. Müller (Freiburg) for the preparation of phenanthrolines 3f,g.

REFERENCES

(1) New building blocks for sensors and supramolecular arrays, part 7; for part 6 see M. Schmittel, H. Ammon, *Synlett* **1997**, 1096.

(2) B. Hasenkopf, J.-M. Lehn, B. O. Kneisel, G. Baum, D. Fenske, *Angew. Chem., Int. Ed. Engl.* **1996**, *35*, 1838.

(3) C. O. Dietrich-Buchecker, J. Guilhem, C. Pascard, J.-P. Sauvage, *Angew. Chem., Int. Ed. Engl.* **1990**, *29*, 1154.

(4) J.-C. Chambron, V. Heitz, J.-P. Sauvage, *Bull. Soc. Chim. Fr.* **1995**, *132*, 340.

(5) E. C. Constable, *Chem. Commun.* **1997**, 1073.

(6) a) C. Dietrich-Buchecker, B. Frommberger, I. Lüer, J.-P. Sauvage, F. Vögtle, *Angew. Chem., Int. Ed. Engl.* **1993**, *32*, 1434; b) D. B. Amabilino, P. R. Ashton, A. S. Reder, N. Spencer, J. F. Stoddart, *Angew. Chem., Int. Ed. Engl.* **1994**, *33*, 433.

(7) *Frontiers in Supramolecular Organic Chemistry and Photochemistry*, Eds. H.-J. Schneider, H. Dürr, VCH, Weinheim, 1991; b) B. Dietrich, P. Viout, J.-M. Lehn, *Macrocyclic Chemistry*, VCH, Weinheim, **1993**.

(8) P. A. Anderson, G. B. Deacon, K. H. Haarmann, F. R. Keene, T. J. Meyer, D. A. Reitsma, B. W. Skelton, G. F. Strouse, N. C. Thomas, J. A. Treadway, A. H. White, *Inorg. Chem.* **1995**, *34*, 6145.

(9) Sauvage and Dietrich-Buchecker have developed an approach to mixed copper(I) complexes using macrocyclic phenanthrolines with *endo*-coordination sites as thereby the formation of symmetrical bisphenanthroline complexes is precluded; see ref. (3).

(10) M. Schmittel, A. Ganz, *Chem. Commun.* **1997**, 999.

(11) U. Lüning, M. Müller, *Chem. Ber.* **1990**, *123*, 643.

(12) Some selected data. Data for complex $[Cu(\underline{2c})_2]BF_4$: red solid, mp. > 300 °C. - ^{1}H-NMR (250 MHz, CD_2Cl_2): $\delta = 6.81$ (d, $J =$ 8.9 Hz, 2H), 7.02-7.24 (m, 6H), 7.07 (dd, $J = 8.1$ Hz, $J = 4.7$ Hz, 2H), 7.38-7.44 (m, 4H), 7.57 (d, $J = 8.5$ Hz, 2H), 7.65 (dd, $J = 4.6$ Hz, $J = 1.5$ Hz, 2H), 7.69 (d, $J = 8.0$ Hz, 2H), 7.78 (d, $J = 8.6$ Hz, 2H), 7.80 (d, $J = 9.2$ Hz, 2H), 7.83 (s, 2H), 7.90 (d, $J = 9.2$ Hz, 2H), 8.25 (dd, $J = 8.3$ Hz, $J = 1.5$ Hz, 2H), 8.33 (d, $J = 8.0$ Hz, 2H). - Elemental analysis: calc. for $C_{52}H_{32}BCuF_4N_4{*}H_2O$ C 70.88% H 3.89% N 6.36%, found: C 70.41% H 4.02% N 5.92%. Data for complex $[Cu(\underline{3d})_2]PF_6$: orange solid, mp. > 300 °C. - ^{1}H-NMR (600 MHz, CD_2Cl_2): $\delta = 6.15$ (m, 2H), 6.64 (d, $J = 8.0$ Hz, 2H), 6.80 (dd, $J = 6.3$ Hz, $J = 6.3$ Hz, 2H), 6.85 (m, 2H), 6.89 (d, $J = 7.6$ Hz, 2H), 6.93 (m, 2H), 7.01 (m, 4H), 7.13-7.17 (m, 4H), 7.27 (d, $J = 8.3$ Hz, 2H), 7.30 (m, 2H), 7.38 (d, $J = 8.6$ Hz, 2H), 7.45 (d, $J = 6.8$ Hz, 2H), 7.60 (d, $J = 8.6$ Hz, 2H), 7.74 (d, $J = 8.7$ Hz, 2H), 7.77 (d, $J = 8.0$ Hz, 2H), 7.87 (d, $J = 8.9$ Hz, 2H), 7.96 (d, $J = 8.9$ Hz, 2H), 7.97 (s, 2H), 8.22 (d, $J = 8.3$ Hz, 2H), 8.42 (d, $J = 8.0$ Hz, 2H). - ESI-MS: calc. for $C_{72}H_{44}N_4Cu^+$: *m/z* 1027.3, found: *m/z* 1027.2.

(13) Data for complex $[Cu(\underline{3e})(4\underline{a})]BF_4$: ^{1}H-NMR (200 MHz, CD_2Cl_2): $\delta = 6.59$ (d, $J = 5.0$ Hz, 2H), 6.92-7.13 (m, 8H), 7.14 (d, $J = 5.0$ Hz, 2H), 7.23 (bd, $J = 8.4$ Hz, 4H), 7.31 (bd, $J = 7.7$ Hz, 4H), 7.41 (s, 2H), 7.45 (s, 2H), 7.57-7.68 (m, 10H), 8.27 (d, $J = 8.0$ Hz, 2H), 8.46 (s, 2H), 8.97 (d, $J = 8.0$ Hz, 2H). - ESI-MS: calc. for $C_{64}H_{40}N_4Cu^+$: *m/z* 927.3, found: *m/z* 927.4; product ions: calcd. for $C_{40}H_{24}N_2Cu^+$: *m/z* 595.1, found: *m/z* 595.4.

(14) M. Schmittel, A. Ganz, *Synlett* **1997**, 710.

(15) J. A. Wytko, E. Graf, J. Weiss, *J. Org. Chem.* **1992**, *57*, 1015.

Received on July 7, 1997