Alternative Demetalation Method for Cu(I)-Phenanthroline-Based Catenanes and Rotaxanes

ARTICLE *in* ORGANIC LETTERS · MARCH 2011

Impact Factor: 6.36 · DOI: 10.1021/ol200304d · Source: PubMed

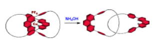
David I Schuster
New York University

Published in final edited form as:
Org Lett. 2011 April 1; 13(7): 1808–1811. doi:10.1021/ol200304d.

An Alternative Demetalation Method for Cu(I)-Phenanthroline-Based Catenanes and Rotaxanes

Jackson D. Megiatto Jr. and **David I. Schuster**
Chemistry Department, New York University, New York City, New York, 10003

Abstract



A new and less hazardous procedure for demetalation of Cu(I)-phenanthroline-based interlocked molecules, using aqueous NH_4OH rather than toxic KCN, has been developed. The conditions are compatible with materials containing nucleophile-sensitive appended groups such as C_{60}, and coordinating moieties such as zinc(II)-porphyrins.

Cu(I)-phenanthroline $[Cu(phen)_2]^+$ complexes have been shown to be useful building blocks in strategies for construction of supramolecular systems such as catenanes, rotaxanes and knots.[1] While the main function of Cu(I) is to hold the two phen-ligands tightly together in the perpendicular arrangement required for the preparation of interlocked molecules, the corresponding MLCT states also act as effective relays in energy transfer (EnT) and electron transfer (ET) processes between photo- and redox-active moieties.[2] These processes can be conveniently monitored spectroscopically by following formation and decay of MLCT excited states.3

It is known from the work of Sauvage and co-workers that removal of Cu(I) from rotaxane and catenane systems results in major conformational changes, which strongly affect the photophysical properties of these supramolecular systems.1b,i The traditional demetalation protocol involves use of KCN in a mixed solvent system (usually, CH_3CN/H_2O), which affords the Cu-free ligands in very high yields.[1b] Although efficient, this method is not general. For example, Sauvage and co-workers reported that $[Cu(phen)_2]^+$-[2]catenanes bearing metaloporphyrins as appended groups could not be demetalated using KCN, presumably due to the complexation of the cyanide anions to the metaloporphyrin moieties.[1e] Another example comes from our own work. We have found that $[Cu(phen)_2]^+$ rotaxanes and catenanes possessing an appended C_{60} moiety are also not compatible with the KCN methodology. Although the loss of copper from the complex can be deteced using by mass-spectrometry,[1b] it is not possible to obtain the original copper-free supramolecular system, presumably due to the well known nucleophilic addition of cyanide anions to the electron deficient fullerene core.[4]

As part of our continuing interest[5] in exploring these $[Cu(phen)_2]^+$ rotaxanes and catenanes as photosynthetic model systems, we have explored alternative demetalation strategies for preparation of copper-free fullereno-rotaxanes and -catenanes, in order to compare their photophysical properties with those of the corresponding $[Cu(phen)_2]^+$ systems. A potential demetalating agent was serendipitously discovered during our attempts to develop a protocol

jackson.megiatto@asu.edu; david.schuster@nyu.edu.

Supporting Information Available: Experimental details for the preparation and spectral characterization of all products and their precursors. This material is available free of charge via the internet at http://pubs.acs.org.

for the synthesis of $[Cu(phen)_2]^+$-[2]catenanes using Huisgen-1,3-dipolar-cycloaddition (CuAAC or "click" chemistry).[5a] In order to remove residual copper catalyst that might bind to coordinating sites in triazole-linked catenanes, we introduced an extra step into the workup procedure. This consisted of dissolving the crude product in dichloromethane (DCM), followed by washing the organic solution with aqueous ammonium hydroxide solution (NH_4OH). To our surprise, the final isolated material after this workup procedure was the Cu-free [2]catenane.

This unexpected result suggested that NH_4OH might be a generally applicable reagent for demetalation of $[Cu(phen)_2]^+$-based interlocked molecules. We therefore decided to systematically investigate the effects of NH_4OH on $[Cu(phen)_2]^+$-based catenanes and rotaxanes. The first system studied was the prototypical [2]catenate **1** (Figure 1).5d,[6] Treatment of an acetonitrile (ACN) solution of **1** with a large excess of NH_4OH resulted in demetalation of **1** after 1h at room temperature to give **2** (for details, see Supporting Information, SI). Since the solution of **1** is dark red and the solution of **2** is colorless, the demetalation process could be easily monitored by eye. The crude product was extracted with DCM, extensively washed with water and purified by column chromatography to afford the Cu-free [2]catenand **2** as a waxy solid in very good yield (88%).

^{1}H NMR analysis (see Figure 2) of the isolated product revealed the well known reorientation of the interlocked rings relative to one another that occurs upon demetalation. 1a-c The phenyl protons (H_o and H_m, Figure 2) attached to the phen moieties move downfield revealing that the two chelates are no longer entwined around the Cu(I) complex. The upfield shifts observed for prorons $H_{4'}$, $H_{5'}$, H_b, and H_d suggest that the triazole-linked phenyl ring is engaged in π-π interactions with the nearby phen moiety, revealing that catenand **2** roughly adopts the configuration depicted in Figure 1. For comparison, catenate **1** was also demetalated with KCN under classical conditions,1a-c and the ^{1}H NMR spectrum of the KCN-demetalated system (Figure not shown) was identical to that shown in Figure 2.

MALDI-TOF spectrometry confirmed the interlocked structure of **2**, showing the molecular ion at *m*/z 1389.06 $(M + H_3O)^+$ (*m*/z 1370.58 calculated for $C_{80}H_{78}N_{10}O_{12}$) and the characteristic fragmentation pattern of catenanes,[1d] namely stepwise fragmentation of the constituent rings.

Inductively-Coupled Plasma Mass Spectrometry (ICP-MS) analysis was used to attest the quality of the Cu-free catenanes. ICP-MS revealed residual copper level of less than 250 ppm for the NH_4OH treated material and of less than 240 ppm for the KCN analog. These data clearly show that both methods are highly effective in removing copper from the $[Cu(phen)_2]^+$ core of catenate **1**.

In order to obtain further insight into the demetalation reaction of **1** with NH_4OH, the progress of the reaction was monitored by UV-Vis spectroscopy (Figure 3) at 440 nm, which is the absorption maximum of the $[Cu(phen)_2]^+$ complex.[3] For comparison, a control experiment using the classical KCN demetalation procedure was performed with catenate **1** (Figure not shown). As can be seen, the absorption in the visible region at 440 nm decreases with time after adding an excess of NH_4OH to an ACN solution of [2]catenate **1** (10^{-5} mol L^{-1}), reaching a steady state after 10 min, indicating successful removal of Cu from most or all of the phen ligands.

The increased absorption in the near infrared region of the spectrum in Figure 3 indicates the formation of a new Cu complex and confirms the successful demetalation of **1**. Absorptions in this region are charcteristic of d-d transitions of Cu(II) complexes (d^9).[7] Since the original $[Cu(phen)_2]^+$ complex (d^{10}) has no *d*-*d* transitions, one can conclude that treatment of **1** with NH_4OH results in **2**, followed by oxidation of Cu(I) to Cu(II) by air[8] and formation of

NIH-PA Author Manuscript

NIH-PA Author Manuscript

$[Cu(L)_x]^{2+}$ complexes, with L = H_2O, OH, NH_3 and/or ACN molecules and x = 4-6. The absorption maxima at 960 and 1040 nm can be accounted for by the existence of a single complex in which two well-separated *d*-orbital transitions are possible, or by two absorbing species, each exhibiting a single band, as expected for copper(II) complexes with square pyramidal (850 – 1000 nm) or flattened tetrahedral (1000 – 1700) geometries.[7]

From the kinetics experiments, it was found that the reaction obeys a pseudo first order rate law and a rate constant $k = 1.6 \times 10^{-3}$ mol^{-1} L s^{-1} was determined. This value revealed that the demetalation reaction of **1** with NH_4OH was about two order of magnitude slower than the KCN reaction under similar conditions, which also obeyed first order kinetics[9] with k = 0.21 mol^{-1} L s^{-1} . Since CN^- is a much stronger nucleophile than NH_3 and OH^-, a faster decomplexation reaction using KCN was expected than with NH_4OH.

Encouraged by these results, we turned our attention to more elaborate interlocked structures (Figure 4) that cannot be efficiently demetalated by the usual KCN procedure,[1e] such as ZnP-[2]catenate **3**. When compound **3** was treated with NH_4OH under the same conditions used for **1** (see SI), the ZnP-[2]catenand **4** was isolated as a purple solid in 79% yield after the usual workup and chromatographic purification.

^{1}H NMR analysis (Figure 5) revealed that NH_4OH treatment of **3** resulted in the Cu-free structure **4**, as revealed by the downfield shift of the protons on the phenyl groups attached to the phen moieties.1a-e MALDI-TOF mass spectrometry revealed a peak at *m/z* 2306.5 corresponding to **4** $[M + H]^+$ (*m/*z 2305.33, calculated for $C_{142}H_{148}N_{14}O_{12}Zn$) and the characteristic fragmentation pattern for catenated species,[1d] revealing that no damage to the interlocked structure of **4** occurred upon treatment with NH_4OH.

The [2]catenate **5**, which possesses a C_{60} moiety (Figure 4) and has proved to be totally incompatible with the nucleophilic character of cyanide ion, constitutes an excellent example to test the general applicability of NH_4OH as a demetalation agent. Another feature of catenate **5** is an ester linkage which is susceptible to hydrolysis under the alkaline conditions of the reaction. Using the same protocol that was applied to decomplexation of **1**, Cu-free [2]catenand **6** was isolated in 64% yield. The other component of the reaction mixture was the starting catenate **5**. No byproducts resulting from ester cleavage were observed.

These findings suggest that the presence of C_{60} on the backbone of catenate **5** prevents to some extent the disengagement of the rings which is necessary for demetalation, reducing the efficiency of the reaction, presumably due to steric constraints imposed by the large carbon cage. The ^{1}H NMR spectrum of **5** showed concentration and temperature dependence, suggesting significant π-π stacking, which is known[1] to protect the metal core against external ligands, contributing to stabilization of the $[Cu(phen)_2]^+$ complex. MALDI-TOF spectrometry revealed the molecular ion for **6** at *m/z* 2219.47 $[M + H]^+$ (*m/*z 2218.30 calculated for $C_{145}H_{82}N_{10}O_{16}$) and *m/z* signals at 1415.87 and 806.01, assigned to the constituent rings of **6** arising from stepwise fragmentation during the ionization process (see SI).

Compound **7** (Figure 4) was chosen to verify if our NH_4OH demetalation procedure could be extended to rotaxane structures. The demetalation of **7** could not be accomplished under precisely the same conditions used for [2]catenate **1** due to the low solubility of **7** in ACN. Instead, **7** was first dissolved in 3 mL of a solvent mixture composed of DCM/ACN (3:7, v/v) to which aq NH_4OH was added following the same protocol as described for **1**. After workup, Cu-free rotaxane **8** was isolated as a purple solid in 90 % yield. For the rotaxane case, the ZnP fluorescence was used as a reliable probe to monitor the demetalation reaction since the Cu-free compound **8** is fluorescent while the analogous metalated rotaxane **7** is not.

As shown in Figure 6, the fluorescence intensity of the ZnP moiety in **8** nearly reaches the level of the tetraphenyl-Zn(II)-porphyrin reference, while in **7** the ZnP excited state is strongly quenched by singlet-singlet energy transfer to the nearby $[Cu(phen)_2]^+$ complex.[5d] Compound **8** was also characterized by MALDI-TOF spectrometry (see SI) which left no doubt about its Cu-free rotaxane structure (*m/z* found 3485.12 $[M + H]^+$, calculated, 3484.70 for $C_{219}H_{234}N_{18}O_{15}Zn_2$).

In conclusion, NH_4OH has been shown to be a convenient, efficient and 'green' demetalating agent for $[Cu(phen)_2]^+$ catenanes and rotaxanes. Although the kinetics of demetalation with NH_4OH are slower than with KCN, the former procedure was shown to be applicable to systems that cannot be successfully demetalated using KCN due to its incompatibility with sensitive subunits, specifically ZnP and C_{60}. We believe that the less hazardous and less toxic NH_4OH procedure will further enhance the usefulness of the metal-template approach pioneered by Sauvage and co-workers for the synthesis of complex supramolecular assemblies.1a-c The easy access to Cu-free catenanes and rotaxanes containing ZnP and C_{60} subunits opens up the possibility of making switchable electron donor-acceptor systems, which allows tuning of the electron transfer dynamics in these materials using external stimuli.

Supplementary Material

Refer to Web version on PubMed Central for supplementary material.

Acknowledgments

The authors are deeply grateful to the National Science Foundation (Grant CHE-0647334) for financial support. This investigation was conducted in part in an instrument facility constructed with support from Research Facilities Improvement Grant Number C06 RR-16572-01 from the National Center for Research Resources, National Institutes of Health.

References

1. a Dietrich-Buchecker CO, Sauvage J-P, Kintzinger J-P. Tetrahedron Lett. 1983; 24:5095–5098. b Dietrich-Buchecker CO, Sauvage J-P, Kern JM. J. Am. Chem. Soc. 1984; 106:3043–3045. c Dietrich-Buchecker CO, Sauvage J-P. Tetrahedron. 1990; 46:503–512. d Weck M, Mohr B, Sauvage J-P, Grubbs HR. J. Org. Chem. 1999; 64:5463–5471. [PubMed: 11674608] e Amabilino DB, Sauvage J-P. New J. Chem. 1998; 22:395–409. f Dietrich-Buchecker CO, Sauvage J-P, Geum N, Hori A, Fujita M, Sakamoto S, Yamaguchi K. Chem. Commun. 2001; 13:1182–1183. g Kang S, Berkshire BM, Xue Z, Gupta M, Layode C, May PA, Mayer MF. J. Am. Chem. Soc. 2008; 130:15246–15247. [PubMed: 18939837] h Sato Y, Yamasaki R, Saito S. Angew. Chem., Int. Ed. 2009; 48:504–507. i Faiz JA, Heitz V, Sauvage J-P. Chem. Soc. Rev. 2009; 38:422–442. [PubMed: 19169458] j Durola F, Sauvage J-P, Wenger OS. Coord. Chem. Rev. 2010; 254:1748–1759. k Share AI, Parimal K, Flood AH. J. Am. Chem. Soc. 2010; 132:1665–1675. [PubMed: 20070081]
2. a Amaroli N, Diederich F, Dietrich-Buchecker CO, Flamigni L, Marconi G, Nierengarten J-F, Sauvage J-P. Chem.-Eur. J. 1998; 4:406–416. b Li K, Schuster DI, Guldi DM, Herranz MA, Echegoyen L. J. Am. Chem. Soc. 2004; 126:3388–3389. [PubMed: 15025442]
3. Scaltrito DV, Thompson DW, O'Callaghan JA, Meyer GJ. Coord. Chem. Rev. 2000; 208:243–266.
4. Hirsch, A.; Brettreich, M. Fullerenes: Chemistry and Reactions. Wiley-VCH; Weinheim, Germany: 2005.
5. a Megiatto JD Jr. Schuster DI. J. Am. Chem. Soc. 2008; 130:12872–12873. [PubMed: 18767850] b Megiatto JD Jr. Schuster DI. Chem.-Eur. J. 2009; 15:5444–5448. c Megiatto JD Jr. Spencer R, Schuster DI. Org. Lett. 2009; 11:4152–4155. [PubMed: 19685862] d Megiatto JD Jr. Schuster DI. New J. Chem. 2010; 34:276–286. d Megiatto JD Jr. Schuster DI, Abwandner S, de Miguel G, Guldi DM. J. Am. Chem. Soc. 2010; 132:3847–3861. [PubMed: 20196597] e Megiatto JD Jr. Li K, Schuster DI, Palkar A, Herranz MA, Echegoyen L, Abwandner S, de Miguel G, Guldi DM. J. Phys.

Chem. B. 2010; 114:14408–14419. [PubMed: 20518479] f Megiatto JD Jr. Spencer R, Schuster DI. J. Mat. Chem. 2011:1544–1550.

6. Sauvage proposed the names catenates for interlocked systems bearing transition-metal-complex (also called metallo-catenanes) and catenand for the corresponding metal-free structure. See refs. 1a-c.
7. a Ray GH. Can. J. Chem. 1966; 44:2165–2171. b Praliaud HA, Mikhailenko S, Chajar Z, Primet M. Appl. Cat., B. 1998; 16:359–374. c Cooper D, Plane RA. Inorg. Chem. 1968; 7:1677–1682. d Elleb M, Meullemeestre J, Schwing-Weill M-J, Vierling F. Inorg. Chem. 1982; 21:1477–1483. e Amuli C, Meullemeestre J, Schwing M-J, Vierling F. Inorg. Chem. 1983; 22:3567–3570.
8. Cu(I) ions are rapidly oxidized to Cu(II) species by air in the presence of nitrogen base ligands. For details see Ref. [6c].
9. Albrecht-Gary M, Saad Z, Dietrich-Buchecker CO, Sauvage J-P. J. Am. Chem. Soc. 1985; 107:3205–3209.
10. Armaroli N, Accorsi G, Cardinali F, Listorti A. Top. Curr. Chem. 2007; 280:69–115.

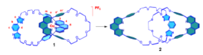


Figure 1.
[2]catenate **1** and the corresponding [2]catenand **2**. After demetalation, a reorientation of the constituent rings results in a molecular conformation with the two phen ligands located away from each other.

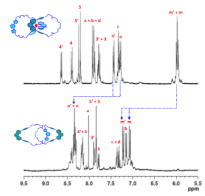


Figure 2.
Partial ^{1}H NMR spectra of catenate **1** and the corresponding catenand **2** (400 MHz, CD_2Cl_2, 298 K). For assignments, see Figure 1.

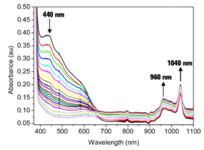


Figure 3.

UV-Vis kinetic study of the demetalation of catenate **1** in acetonitrile (10^{-5} mol L^{-1}) with NH_4OH (3×10^{-4} mol L^{-1}), monitoring the absorbance at 440 nm. Total run time = 10 min, cycle time = 30 s, 298 K (au = arbitrary units).

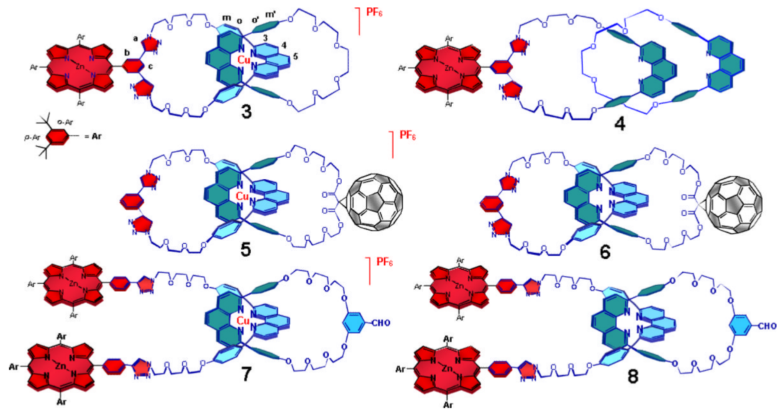


Figure 4.
Chemical structure of Cu-containing interlocked molecules with appended ZnP or C_{60} groups and the corresponding Cu-free materials.

NIH-PA Author Manuscript
NIH-PA Author Manuscript

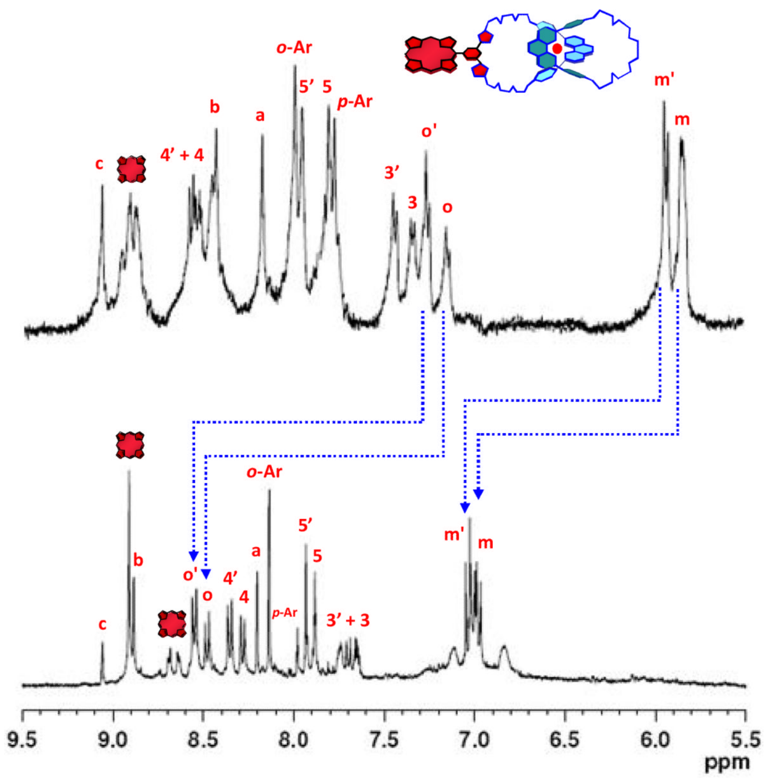


Figure 5.
Partial [1]H NMR spectra (400 MHz, CD_3CN, 298 K) of catenate **4** and catenand **5**.

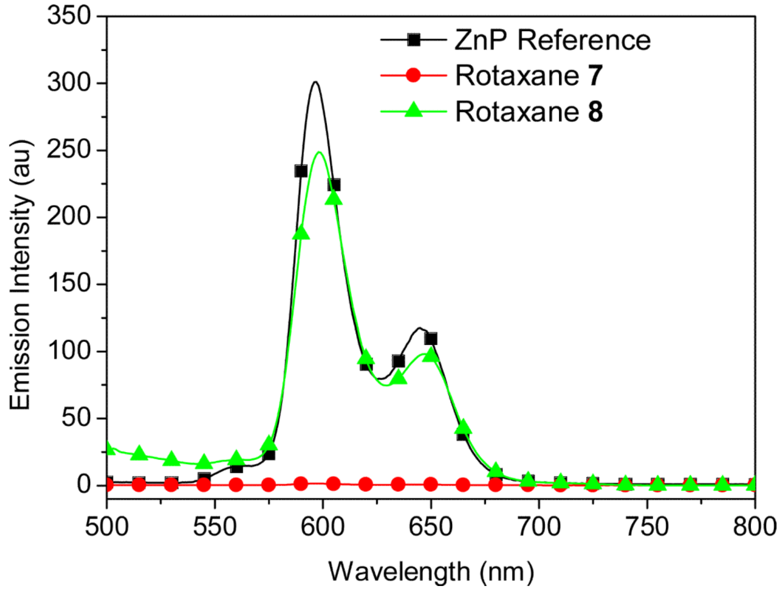


Figure 6.
Fluorescence spectra in CH_2Cl_2 of a ZnP reference, Cu(I) rotaxane **7** and Cu-free rotaxane **8** with O.D. = 0.20, excitation at 424 nm, 298 K (au = arbitrary units).

NIH-PA Author Manuscript
NIH-PA Author Manuscript