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## **SYNTHESIS AND CHARACTERIZATION OF 1-(2*H*-TETRAZOL-5-YL)-1,4,7,10-TETRAAZACYCLODODECANE AND ITS Zn(II), Ni(II), AND Cu(II) COMPLEXES**

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Dedicated to Prof. Dr. Ekkehard Winterfeldt on the occasion of his 75<sup>th</sup> birthday

**Abstract** - As part of an ongoing effort to develop new metal complexes of tetraazamacrocycles with novel properties in coordination or functionalization we report here the synthesis of a new derivative of 1,4,7,10-tetraazacyclododecane (cyclen) with a tetraazole moiety directly bound to the azamacrocycle. The new ligand was obtained by reaction with cyanogen bromide giving the cyanamide, followed by a [2+3] cycloaddition with NaN<sub>3</sub> to yield the tetraazole. The ligand and its Zn(II), Ni(II), and Cu(II) complexes were fully characterized by analytical methods. X-ray structure analysis of the Ni(II) compound shows the formation of a stable dimer by coordination of each of the two tetraazole substituents to the neighboring metal cation. Potentiometric titrations of the metal complexes indicate a possible conversion of the monomer to the dimeric structure in solution and show the p*K*<sub>a</sub> of the NH-atom on the tetraazole substituent to be between 4.03 and 5.3 depending on the metal ion coordinated by cyclen.

## **INTRODUCTION**

Polyamine macrocyclic compounds have attracted great interest in host-guest and supramolecular chemistry due to their intriguing structural and spectroscopic properties.<sup>1</sup> One of their most remarkable properties is their ability to adapt to many metal ion coordination geometries,<sup>2</sup> offering multiple donor sites and being often used as model systems for metalloenzymes or sensors.<sup>3</sup> In addition, tetradentate

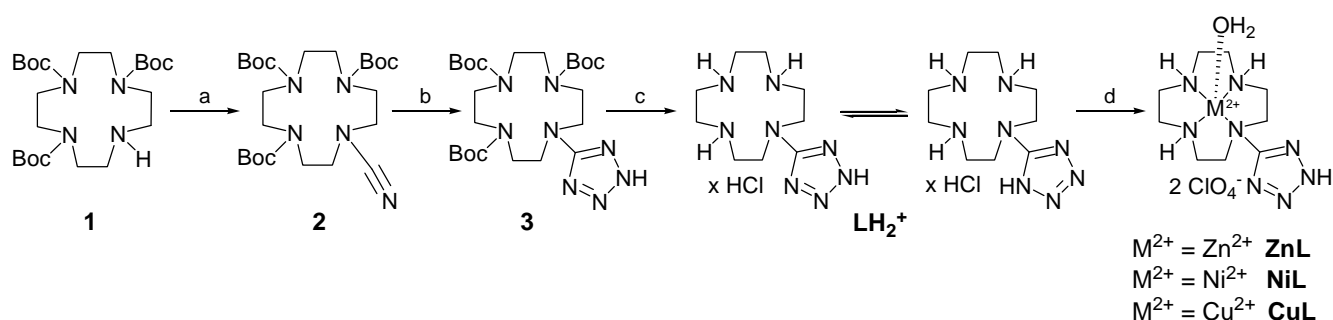
macrocyclic compounds such as tetraazamacrocycles can be easily functionalized<sup>4</sup> on their secondary nitrogen atoms yielding novel properties in coordination, electro- or photochemistry, and catalysis. Tetraazoles, on the other hand are interesting heterocycles<sup>5</sup> with uses in coordination chemistry as ligands, in medicinal chemistry as metabolically stable surrogates for carboxylic acid groups,<sup>6</sup> in pharmaceutical sciences as lipophilic spacers and in various material science applications, including explosives. They are also used as precursors to a variety of nitrogen-containing heterocycles.

As part of an ongoing effort to develop new metal complexes of tetraazamacrocycles with novel properties in coordination or functionalization<sup>7</sup> we report the synthesis of a new derivative of 1,4,7,10-tetraazacyclododecane (cyclen) with the tetraazole moiety directly bound to the azamacrocycle. This is, to the best of our knowledge, the first application of the [2+3] cycloaddition procedure reported by Demko and Sharpless<sup>8</sup> for an azamacrocyclic compound. The ligand and its Zn(II), Ni(II) and Cu(II) complexes were obtained by solution synthesis and not by solvothermal techniques,<sup>9,10</sup> as frequently reported for tetrazol transition metal complexes, and they were fully characterized. X-ray structure analysis of the Ni(II) compound shows the formation of a stable dimer by coordination of each of the two tetraazole substituents to the neighboring metal cation.

## RESULTS AND DISCUSSION

### Syntheses of the macrocyclic tetraazole ligand LH and its metal complexes ZnL, CuL and NiL

The synthesis of the novel ligand, containing the azamacrocyclic moiety bound to a tetraazole unit, starts from the previously reported compound 1,4,7,10-tetraazacyclododecane-1,4,7-tricarboxylic acid tri-*tert*-butyl ester (3-Boc-cyclen) **1**,<sup>11</sup> which was reacted in THF at reflux with cyanogen bromide following a modified literature procedure<sup>12</sup> to yield the monosubstitution product **2**. The reaction does not lead to the expected di(3-Boc-cyclen)methanimine, a precursor of polysubstituted guanidine products, as in previous reports.<sup>12</sup> This could be due to the fact that the electrophilicity of the cyanamide is significantly decreased after reaction with the first cyclen moiety, but also to the lower nucleophilicity of the cyclen. A reaction of **2** with an excess amount of **1** under various reaction conditions did not lead to any new products and showed that **2** is thermally labile as it decomposed completely after 5 hours of reflux. A [2+3] cycloaddition reaction of **2** with NaN<sub>3</sub> following the procedure reported by Demko and Sharpless<sup>8</sup> yielded **3**. The compound was treated with diethyl ether saturated with HCl to remove all Boc protecting groups and Zn<sup>2+</sup> ions giving ligand **LH**<sub>2</sub><sup>+</sup> in the form of the ammonium chloride salt (**Scheme 1**). Other deprotecting methods, such as treatment with TFA, led to a mixture of the desired product with various unidentified decomposition products. The ligand could not be neutralized to the free base form **LH** by passing it through a basic ion exchange resin column due to its decomposition on the basic resin and was therefore neutralized *in situ* in the next reaction step.



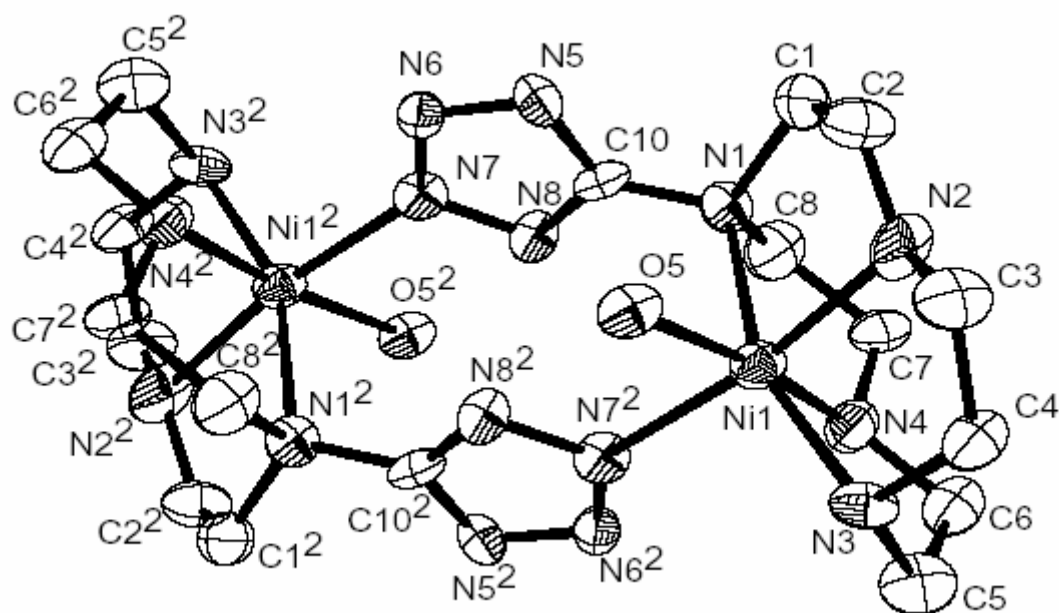
**a:** BrCN (0.52 eq.), K<sub>2</sub>CO<sub>3</sub>, THF, reflux 3h, 82% ; **b:** NaN<sub>3</sub> (1.1 eq.), ZnBr<sub>2</sub>, H<sub>2</sub>O/MeOH 2:1, reflux 20h, 72% ; **c:** Et<sub>2</sub>O/HCl, MeOH, RT, 24h, 99% ; **d:** M(ClO<sub>4</sub>)<sub>2</sub> · 6H<sub>2</sub>O (M = Zn, Ni, Cu) (1.1 eq.), aq. LiOH (pH = 8-9), reflux 4h, quantitative yield.

**Scheme 1.** Synthesis of the azamacrocyclic ligand **LH<sub>2</sub><sup>+</sup>** and its corresponding metal complexes

Metal complexes were isolated in good yields from the reaction of the ligand with metal perchlorate salts in aqueous solutions and were characterized by different analytical methods (<sup>1</sup>H NMR and <sup>13</sup>C NMR for **ZnL**, UV/Vis, IR, ESI, elemental analysis, HRMS) to show a stoichiometry of 1:1 metal cation/ligand.<sup>13</sup> We tried to apply the procedure for the [2+3] cycloaddition reaction of **2** to benzylazide (obtained from benzylbromide following the reported procedure),<sup>14</sup> but no conversion was observed. Use of previously reported other reaction conditions<sup>15</sup> also failed. It has already been shown that nitriles are not sufficient dipolarophiles to react with organic azides in a cycloaddition reaction.<sup>16</sup> At present, only a few highly electron-deficient nitriles are known to undergo this reaction.<sup>17</sup> Sharpless *et al.* have reported the [2+3] cycloaddition of aromatic azides to sulfonyl<sup>16</sup> and acyl cyanides.<sup>18</sup> As can be concluded from these reports, the reaction is favored by strong electron-withdrawing substituents on the nitrile, while in our case the azamacrocyclic substituent acts as an electron donating group. The large substituent may impose steric hindrance on the reaction.

### X-Ray Crystal Structure of the dimer [NiL(H<sub>2</sub>O)]<sub>2</sub>(ClO<sub>4</sub>)<sub>2</sub>.

The heteroarene is directly connected to the macrocycle, without any pendant arm, leading to a rather rigid structure. Pure **NiL** obtained by recrystallization from EtOH, as a pale violet solid, was dissolved in a small amount of water and was left at room temperature. After two weeks pale violet crystals were collected. **Figure 1** shows an ORTEP drawing of the complex with 50% probability thermal ellipsoids. Crystal data and data collection parameters, atomic positional parameters with standard deviations, bond lengths and bond angles are available upon request.<sup>19</sup>



**Figure 1.** ORTEP drawing (50% probability ellipsoids) of  $[\text{NiL}(\text{H}_2\text{O})_2](\text{ClO}_4)_2$ . All hydrogen atoms and the two perchlorate anions are omitted for clarity.

Figure 1 shows the symmetrical structure and geometry of the Ni(II) complex. **NiL** forms a dimer by coordination of the tetraazole substituent to the neighboring metal cation. The coordination takes place through the N2-position on the tetraazole and not N1, minimizing steric constraints.<sup>20</sup>

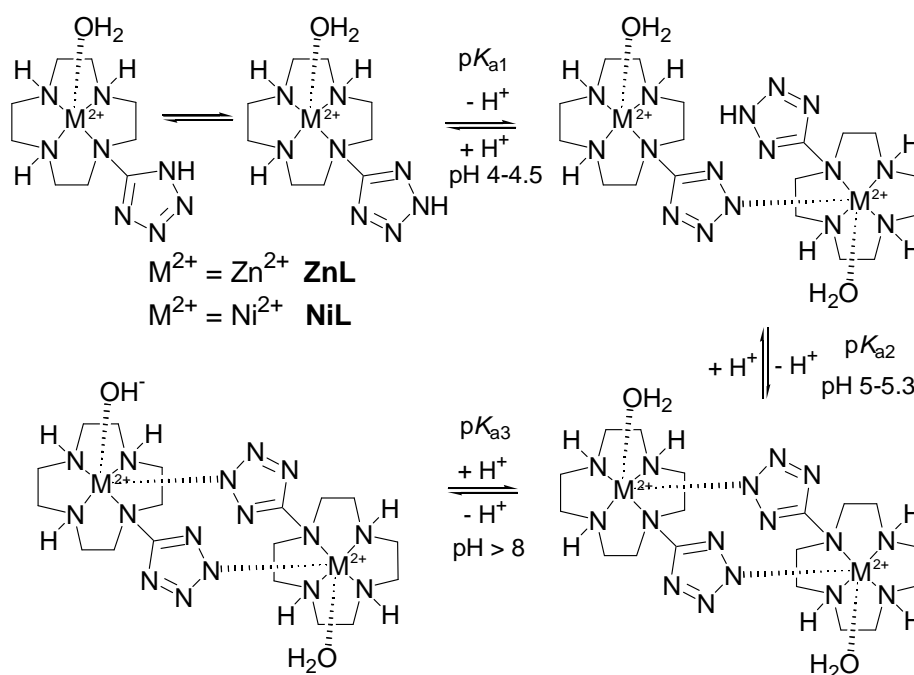
Each Ni(II) ion has a distorted octahedral coordination geometry as previously reported for the  $\text{Ni}([\text{12}] \text{aneN}_4)^{2+}$  complex,<sup>21</sup> with the macrocycle coordinated in a folded configuration to four sites around the central nickel atom (one of which is axial), the other two sites being occupied by a water molecule in an axial position and a deprotonated N-atom (N7 in Figure 1) of the tetraazole.

The distances between the Ni atom and the N atoms of cyclen lie in the range 2.05–2.27 Å, as it is generally reported for Ni–N distances found in octahedral polyamine complexes.<sup>21,22</sup> The longer distance to N(1) is explained by the influence of the tetraazole, which withdraws electron density of the cyclen nitrogen atom thus making the coordination to the metal ion weaker. The tetraazole could also induce a steric constraint as reflected by the short bond length N(1)–C(10). The short distance between the nickel atom and the tetraazole N-atom, comparable to the distance Ni(1)–N(2) and Ni(1)–N(4) indicates a strong interaction and the formation of a stable compound. The two tetraazole bridges are in parallel planes separated by approx. 3 Å, indicating stabilization of the complex by an intramolecular  $\pi$ – $\pi$  stacking interaction. The tetraazole rings are perfectly planar, with almost equal bond lengths in the range 1.318–1.37 Å. C–N and N–N bond lengths are nearly identical, which indicates strong  $\pi$ -electron delocalization in

the tetraazole ring. The angles between the adjacent atoms in the ring lie in the range 103.18-113.83°, close to that expected for a regular pentagon, 108°; the two metal ions are separated by 6 Å. All the data of the tetraazoles coincide to previous reports.<sup>9</sup>

### Deprotonation Constants ( $pK_a$ ) of the metal complexes.

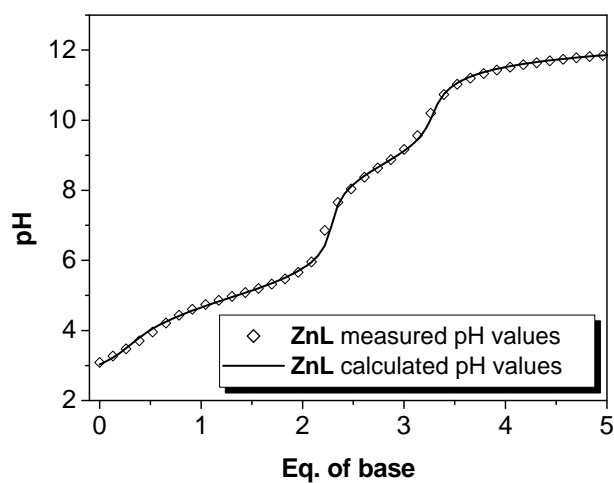
The  $pK_a$  values of **ZnL**, **NiL** and tetraazole (Fluka, contains ~10 % H<sub>2</sub>O) were determined by pH-metric titrations in aqueous solutions under nitrogen at 25 °C and  $I=0.1$  (tetraethylammonium perchlorate TEAP). Various small amounts of HClO<sub>4</sub> 0.1 M (0.2 - 1.2 mL) were added to the titration solution in order to determine values in the pH range of 3 to 8. For each metal complex at least two independent titrations were performed. The proposed model for the deprotonation steps is given in **Scheme 2**; the pH profiles of **ZnL** (**Figure 2**), **NiL** (**Figure 3**) and tetraazole (**Figure 4**) in the following figures. The  $pK_a$  values are summarized in **Table 1**.



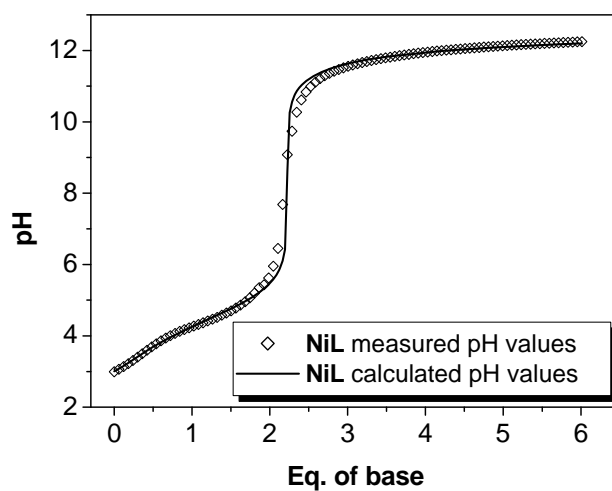
**Scheme 2.** Proposed model for the deprotonation steps of **ZnL** and **NiL**

**Table 1.** Deprotonation constants ( $pK_a$ ) of the metal complexes at 25 °C and  $I = 0.10$  (TEAP)

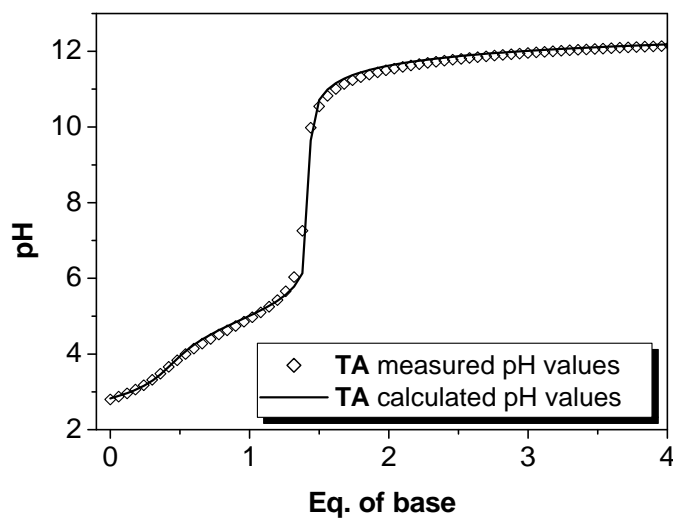
Metal complex	$pK_a$		
	$pK_{a1}$	$pK_{a2}$	$pK_{a3}$
ZnL	$4.54 \pm 0.02$	$5.32 \pm 0.02$	$8.74 \pm 0.02$
NiL	$4.03 \pm 0.02$	$4.9 \pm 0.02$	-
tetraazole	$4.88 \pm 0.02$	-	-



**Figure 2.** Titration curve for the complex  $[\text{ZnL}](\text{ClO}_4)_2$  in aqueous solution (2 eq.  $\text{HClO}_4$ )



**Figure 3.** Titration curve for the complex  $[\text{NiL}](\text{ClO}_4)_2$  in aqueous solution (2 eq.  $\text{HClO}_4$ )



**Figure 4.** Titration curve of tetrazole (TA, Fluka, 10%  $\text{H}_2\text{O}$ ) in aqueous solution (0.2 eq.  $\text{HClO}_4$ )

The obtained  $pK_a$  values indicate a possible conversion in solution from the monomeric to the dimeric structure, as  $pK_{a1}$  and  $pK_{a2}$  of **ZnL** and **NiL** are as shown in **Table 2** to be in the range of that of the tetraazole. Indeed it is known that tetraazoles have  $pK_a$  values in the range of 3 to 5<sup>8</sup> and as there are no other acidic protons in the molecule (cyclen has  $pK_a$  values  $<2$  and  $>10^{23}$  and the water molecules coordinated to the metal centers should have  $pK_a$  values around 8 for **ZnL**<sup>23,24</sup> and  $>11$  for **NiL**<sup>24</sup>) we propose the first two deprotonation steps belong to the two bridging tetraazole units. This would be consistent with the crystallographic structure of **NiL** described earlier. Another support of formation of a dimer in solution is the value of the third  $pK_a$  obtained for **ZnL**,  $pK_{a3} = 8.74$ , which could be attributed to one of the water molecules coordinated on the Zn(II) ion. Its value is in the range reported for water molecules coordinated to a Zn(cyclen) compound.<sup>23,24</sup> For **NiL** no third deprotonation is observed, consistent with the weak Lewis acidic character of nickel leading to coordinated water molecules to be deprotonated at pH values  $>11$ .<sup>24</sup>

From the data obtained by potentiometric titrations, we propose a conversion in solution with increasing pH from the monomeric to the stable dimeric form. From the synthesis, the metal complexes **ZnL** and **NiL** were obtained in their monomeric form as indicated by the analytical data (elemental analysis of **NiL**, mass spectroscopy of **ZnL** and **NiL**, UV and NMR spectra). The IR spectra show bands around 1400 and 1150  $\text{cm}^{-1}$  which are characteristic for the tetraazole moiety,<sup>25</sup> and which are not shifted as expected upon coordination to a metal cation.

Most previously reported metal-tetraazole complexes were obtained by solvothermal techniques<sup>25,10</sup> and analyzed by elemental analysis and crystallographic studies only. So we report one of the first examples of tetraazole metal complexes obtained by solution methods and characterized spectroscopically. The described new azamacrocyclic tetraazole complexes may find use in catalysis or as building blocks for self-assembled supramolecular coordination compounds.

## EXPERIMENTAL

**General information.** UV/VIS spectra were recorded on a Varian Cary BIO 50 UV/VIS/NIR spectrophotometer equipped with a jacketed cell holder using 1-cm cuvettes (quartz or glass) from Hellma. For all UV/VIS measurements the temperature was kept constant at 25 °C ( $\pm 0.1$  °C). IR spectra were recorded on a Bio-Rad FT-IR FTS 155 spectrometer and a Bruker Tensor 27 spectrometer with an ATR unit. Elemental analysis was performed on a Vario EL III. Mass spectra were performed on a ThermoQuest Finnigan TSQ 7000 (ESI) and Finnigan MAT 95 (HRMS). Potentiometric titrations were performed with a Metrohm Dosimat 665. <sup>1</sup>H and <sup>13</sup>C NMR spectra were obtained on the following machines: Bruker AC-250 (<sup>1</sup>H: 250.1 MHz, <sup>13</sup>C: 62.9 MHz, 24 °C), Bruker Avance 300 (<sup>1</sup>H: 300.1 MHz, <sup>13</sup>C: 75.5 MHz, 27 °C), Bruker Avance 400 (<sup>1</sup>H: 400.1 MHz, <sup>13</sup>C: 100.6 MHz, 27 °C), Bruker Avance 600

( $^1\text{H}$ : 600.1 MHz,  $^{13}\text{C}$ : 150.1 MHz, 27 °C). Melting points were determined with a Büchi SMP 20 and are uncorrected.

**Materials and Reagents.** All reagents and solvents used for the synthesis of the metal complexes were of analytical grade. Cyanogen bromide (Fluka), sodium azide (Acros), tetraazole (Fluka) and the various metal salts were purchased from commercial sources and used without any further purification. Cyclen was a generous gift from Schering and was used without further purification.

**Crystallographic Study.** Translucent light blue triclinic crystals of the dimer  $[\text{NiL}(\text{H}_2\text{O})]_2(\text{ClO}_4)_2$  (0.25 x 0.05 x 0.01 mm) were used for data collection at 123 ( $\pm$  1) K with graphite-monochromated Cu-K $\alpha$  radiation ( $\lambda$  = 1.54184 Å) on a Oxford Diffraction Gemini Ultra diffractometer. The structure of the compound  $[\text{NiL}(\text{H}_2\text{O})]_2(\text{ClO}_4)_2$  was solved by direct methods SIR97 and refined by full-matrix least-squares on  $F^2$  using SHELXL-97. The molecular structure is illustrated in **Figure 1** by ORTEP drawing with 50% probability thermal ellipsoids. All crystallographic data have been deposited with the Cambridge Crystallographic Data Centre (CCDC). These data can be obtained free of charge via [www.ccdc.cam.ac.uk/data\\_request/cif](http://www.ccdc.cam.ac.uk/data_request/cif).

**Potentiometric pH Titrations.** The pH titrations were carried out under  $\text{N}_2$  at 25 °C with a computer controlled pH-meter (pH 3000, WTW) and dosimat (Dosimat 665 and 765, Metrohm). Aqueous solutions of the metal complexes (0.05 mM) were titrated with 0.02 M tetraethylammonium hydroxide (TEAOH) aqueous solution. The ionic strength was adjusted to  $I = 0.1$  with tetraethylammonium chloride (TEAC). The TEAOH solutions were calibrated with potassium hydrogen phthalate. A titration of 0.1 M perchloric acid with TEAOH solution was used for calibration and to determine  $\log K_{\text{W}}$ . The Irving-factor ( $A_{\text{I}}$ ) was determined according to  $\text{pH}_{\text{measurement}} = \text{pH}_{\text{real}} + A_{\text{I}}$ . Various small amounts of  $\text{HClO}_4$  0.1 M (0.2 - 1.2 mL) were added to the titration solution in order to determine values in the pH range of 3 to 8. For each metal complex at least two independent titrations were made. Data analysis was performed with the program Hyperquad2000 (Version 2.1, P. Gans) and Origin 6.0.

**Caution:** Although no problems were encountered in this work, metal perchlorate complexes as well as tetraazoles are potentially explosive. They should be handled with care, especially on heating and the complexes should be prepared in small quantities.

**Synthesis of the macrocyclic tetraazole ligand and its metal complexes.** The synthetic intermediate 1,4,7,10-tetraazacyclododecane-1,4,7-tricarboxylic acid tri-*tert*-butyl ester (3-Boc-cyclen) **1**<sup>11</sup> was prepared according to the published method.

#### **10-Cyano-1,4,7,10-tetraazacyclododecane-1,4,7-tricarboxylic acid tri-*tert*-butyl ester (2)**

3-Boc-cyclen **1** (0.4 g, 0.846 mmol) was dissolved in 10 mL of THF and cyanogen bromide (CAUTION!, 0.047 g, 0.440 mmol, 0.52 eq.) was added followed by  $\text{K}_2\text{CO}_3$  (0.117 g, 0.846 mmol). The reaction



mixture was refluxed for 3h. At the end of reaction, the excess of  $K_2CO_3$  was filtered off, the solvent was removed by reduced pressure and the crude mixture (413 mg) was purified by column chromatography (EtOAc/petroleum ether 50:50). The product was obtained as a colorless solid ( $R_f = 0.5$ , EtOAc/petroleum ether, 1:1). Yield: 0.18 g, 82%.

Mp 58 - 60 °C; UV/VIS (MeOH)  $\lambda_{max}$  [nm] ( $\log \epsilon$ ) = 193 (4.524), 203 (3.983), 205 (3.912); IR (KBr):  $\tilde{\nu}$  [ $cm^{-1}$ ] = 2976, 2933, 2361, 2209, 1688, 1463, 1417, 1366, 1249, 1165, 1033, 977, 941, 858, 773;  $^1H$ -NMR (300 MHz,  $CDCl_3$ ):  $\delta$  = 1.39 (bs, 18H,  $COOC(\underline{CH}_3)_3$ ); 1.40 (bs, 9H,  $COOC(\underline{CH}_3)_3$ ); 3.19 (bs, 4H,  $\underline{CH}_2$  cyclen ); 3.33 (bs, 4H,  $\underline{CH}_2$  cyclen ); 3.39-3.44 (m, 8H,  $\underline{CH}_2$  cyclen);  $^{13}C$ -NMR (300 MHz,  $CDCl_3$ ):  $\delta$  = 28.41 ( $COOC(\underline{CH}_3)_3$ ); 28.65 ( $COOC(\underline{CH}_3)_3$ ); 47.92, 49.90, 54.13 ( $\underline{CH}_2$  cyclen); 79.69 ( $COOC(\underline{CH}_3)_3$ ); 80.46 ( $COOC(\underline{CH}_3)_3$ ); 116.98 (N- $\underline{CN}$ ); 155.21 ( $\underline{COOC}(\underline{CH}_3)_3$ ); 156.91 ( $\underline{COOC}(\underline{CH}_3)_3$ ) MS (ESI, MeCN/ $H_2O$ /TFA):  $m/z$  (%) = 498.3 (100) [ $MH^+$ ], 515.3 (80) [( $M + NH_4^+$ ) $^+$ ]. Anal. Calcd for  $C_{24}H_{43}N_5O_6 + 0.5 H_2O$ : C 56.90, H 8.75, N 13.82. Found: C 57.34, H 8.75, N 13.51.

### 10-(2H-Tetrazol-5-yl)-1,4,7,10-tetraazacyclododecane-1,4,7-tricarboxylic acid tri-*tert*-butylester (3)

3-Boc-cyclen-cyanide (0.1 g, 0.2 mmol, 1 eq.),  $NaN_3$  (0.014 g, 0.22 mmol, 1.1 eq.) and  $ZnBr_2$  (45 mg, 0.2 mmol, 1 eq.) were dissolved in water (7 mL). If there were clumps of undissolved nitrile, MeOH,  $i$ PrOH or glycerol was added (no more than 50% v/v). The reaction mixture was refluxed for 20 h under vigorous stirring and the reaction progress was monitored by TLC. The aqueous phase was extracted 3 times with EtOAc (3 x 15 mL). The combined organic layers were evaporated, 8 mL of a 0.25 N aqueous NaOH solution was added and the mixture was stirred for 30 min, until the precipitate was dissolved and a suspension of zinc hydroxide was formed. The suspension was filtered off, the solid was washed with 1 mL 1 N aqueous NaOH. To the filtrate was added a solution of HCl until pH = 5, with vigorous stirring, causing the tetraazole zwitterion to precipitate. The tetraazole was filtered off and dried. If little or no precipitate was formed upon final acidification, the aqueous layer was saturated with NaCl and extracted 3 times with EtOAc, the organic layer was dried over  $Na_2SO_4$  and evaporated to dryness. We obtained 78 mg (72%) of product as a colorless solid ( $R_f = 0.3$ , EtOAc/MeOH, 9:1).

Mp 68 - 70 °C; UV/VIS (MeOH)  $\lambda_{max}$  [nm] ( $\log \epsilon$ ) = 200.9 (4.215), 203.9 (4.123); 316 (2.501); IR (KBr):  $\tilde{\nu}$  [ $cm^{-1}$ ] = 3446, 2977, 2933, 2361, 1693, 1467, 1414, 1367, 1250, 1166, 1039, 974, 947, 857, 777;  $^1H$ -NMR (400 MHz,  $CDCl_3$ ):  $\delta$  = 1.44 (bs, 27H,  $COOC(\underline{CH}_3)_3$ ); 3.29 (bs, 4H,  $\underline{CH}_2$  cyclen); 3.39 (bs, 4H,  $\underline{CH}_2$  cyclen); 3.58 (m, 4H,  $\underline{CH}_2$  cyclen); 3.61-3.62 (m, 4H,  $\underline{CH}_2$  cyclen); 13.5 (very bs, 1H,  $\underline{NH}$  tetraazole);  $^{13}C$ -NMR (400 MHz,  $CDCl_3$ ):  $\delta$  = 28.41 ( $COOC(\underline{CH}_3)_3$ ); 28.56 ( $COOC(\underline{CH}_3)_3$ ); 48.39 ( $\underline{CH}_2$  cyclen); 49.33 ( $\underline{CH}_2$  cyclen); 50.70 ( $\underline{CH}_2$  cyclen); 53.93 ( $\underline{CH}_2$  cyclen); 79.98 ( $COOC(\underline{CH}_3)_3$ ); 80.95 ( $COOC(\underline{CH}_3)_3$ ); 155.61 ( $\underline{COOC}(\underline{CH}_3)_3$ ); 157.01 ( $\underline{COOC}(\underline{CH}_3)_3$ ); 160.40 ( $\underline{C}_{quat}$ . tetraazole); MS (negative ESI,  $CH_2Cl_2$ /MeOH + 10 mmol/l  $NH_4Ac$ ):  $m/z$  (%) = 539.4 (100) [( $M-H^+$ ) $^-$ ]; HRMS

(PI-EI-MS, CH<sub>2</sub>Cl<sub>2</sub>) calculated for (C<sub>24</sub>H<sub>44</sub>N<sub>8</sub>O<sub>6</sub>)<sup>+</sup> 540.3384 found 540.3376 ± 1.44 ppm.

### 1-(2H-Tetrazol-5-yl)-1,4,7,10-tetraazacyclododecane hydrochloride salt (LH<sub>2</sub><sup>+</sup>)

3-Boc-cyclen-tetraazole (0.107 g, 0.198 mmol) was dissolved in MeOH (2 mL) and the solution was cooled in an ice-bath. HCl/Et<sub>2</sub>O (1 mL) was added and the reaction was mixed for 24 h. After reaction completion, the solvent was eliminated under reduced pressure to obtain 69 mg (99%) of the HCl salt as colorless solid (R<sub>f</sub> = 0, CH<sub>2</sub>Cl<sub>2</sub>/MeOH, 9:1).

Mp > 180 °C; UV/VIS (Millipore H<sub>2</sub>O) λ<sub>max</sub> [nm] (log ε) = 220 (3.359); IR (KBr):  $\tilde{\nu}$  [cm<sup>-1</sup>] = 3429, 2985, 2820, 2769, 2664, 2571, 2496, 2393, 1603, 1543, 1443, 1357, 1287, 1251, 1150, 1076, 1005, 957, 760; <sup>1</sup>H-NMR (300 MHz, D<sub>2</sub>O): δ = 3.09-3.21 (m, 12H, CH<sub>2</sub> cyclen); 3.62-3.68 (m, 4H, CH<sub>2</sub> cyclen); <sup>13</sup>C-NMR (300 MHz, D<sub>2</sub>O): δ = 43.56, 44.4, 45.03 (CH<sub>2</sub> cyclen); 49.25 (CH<sub>2</sub> cyclen); 160.53 (C<sub>quat</sub>. tetraazole); MS (positive ESI, H<sub>2</sub>O/MeCN/TFA) : m/z (%) = 241.1 (100) [MH<sup>+</sup>]; HRMS (PI-LSI-MS, MeOH/glycerin) calculated for (C<sub>9</sub>H<sub>21</sub>N<sub>8</sub>)<sup>+</sup> 241.1889 found 241.1888 ± 0.48 ppm.

### 1-(2H-Tetrazol-5-yl)-(zinc-1,4,7,10-tetraazacyclododecane)bisperchlorate (ZnL)

The aqueous solutions of ligand LH<sub>2</sub><sup>+</sup> (0.1 g, 0.28 mmol) and Zn(ClO<sub>4</sub>)<sub>2</sub>•6H<sub>2</sub>O (0.117 g, 0.314 mmol, 1.1 eq.) were added drop wise simultaneously into warm water (5 mL). An aqueous LiOH solution was added until pH = 8-9, and the reaction mixture was refluxed for 4 h. The product was obtained quantitatively as a hygroscopic colorless solid by lyophilization and recrystallization from EtOH.

UV/VIS (Millipore H<sub>2</sub>O) λ<sub>max</sub> [nm] (log ε) = broad band from the lower wavelength region (190 nm) up to 250 nm; IR (KBr):  $\tilde{\nu}$  [cm<sup>-1</sup>] = 3600-3165 (br s), 2945, 2820, 1637, 1492, 1446, 1412, 1357, 1287, 1222, 1141, 1082, 979, 628; <sup>1</sup>H-NMR (400 MHz, D<sub>2</sub>O): δ = 2.82-3.11 and 3.25-3.38 (m, 14H, CH<sub>2</sub> cyclen); 3.51-3.64 (m, 2H, CH<sub>2</sub> cyclen); <sup>13</sup>C-NMR (400 MHz, D<sub>2</sub>O): δ = 43.52, 43.76, 45.03, 51.38 (CH<sub>2</sub> cyclen); 167.79 (C<sub>quat</sub>. tetraazole); MS (positive ESI, H<sub>2</sub>O/MeOH + 10 mM NH<sub>4</sub>Ac): m/z (%) = 339 (100) [M<sup>2+</sup> + Cl<sup>-</sup>]<sup>+</sup>; 363.1 [M<sup>2+</sup> + CH<sub>3</sub>COO<sup>-</sup>]<sup>+</sup>.

### 1-(2H-Tetrazol-5-yl)-(nickel-1,4,7,10-tetraazacyclododecane)bisperchlorate (NiL)

The aqueous solutions of ligand LH<sub>2</sub><sup>+</sup> (0.1 g, 0.286 mmol) and Ni(ClO<sub>4</sub>)<sub>2</sub>•6H<sub>2</sub>O (0.115 g, 0.314 mmol, 1.1 eq.) were added drop wise simultaneously into warm water (5 mL). An aqueous LiOH solution was added until pH = 8-9. The reaction mixture was refluxed for 4 h. The product was recrystallized from EtOH as pale violet solid (94 mg, 66%).

Mp > 180 °C; UV/VIS (Millipore H<sub>2</sub>O) λ<sub>max</sub> [nm] (log ε) = 348 (2.255); 552 (2.024); 964 (2.0); IR (KBr):  $\tilde{\nu}$  [cm<sup>-1</sup>] = 3430, 3324, 3257, 2933, 2364, 1647, 1491, 1443, 1407, 1363, 1103, 1085, 1004, 973, 867, 625; MS (positive ESI, H<sub>2</sub>O/MeOH + 10 mM NH<sub>4</sub>Ac): m/z (%) = 357.1 (100) [M + CH<sub>3</sub>COO]<sup>+</sup>;

Anal. Calcd for  $C_9H_{20}N_8O_8Cl_2Ni$ : C 21.71, H 4.05, N 22.51. Found: C 21.73, H 4.36, N 22.54.

### 1-(2*H*-Tetrazol-5-yl)-(copper-1,4,7,10-tetraazacyclododecane)bisperchlorate (CuL)

The aqueous solutions of ligand  $LH_2^+$  (0.05 g, 0.14 mmol) and  $Cu(ClO_4)_2 \cdot 6H_2O$  (0.058 g, 0.16 mmol, 1.1 eq.) were added drop wise simultaneously into warm water (5 mL). An aqueous LiOH solution was added to adjust to pH = 8-9. The blue reaction mixture was refluxed for 2 h. Then the mixture was allowed to cool to room temp. and EtOH (2 mL) was added. The mixture was left in the refrigerator over-night and the brown residue which appeared was filtered off. The resulting clear blue solution was lyophilized to give the desired product quantitatively as a dark blue hygroscopic solid.

UV/VIS (Millipore  $H_2O$ )  $\lambda_{max}$  [nm] ( $\log \epsilon$ ) = 280 (3.023); 613 (2.022); IR (KBr):  $\tilde{\nu}$  [ $cm^{-1}$ ] = 3600-3200 (br s), 2362, 1635, 1481, 1442, 1282, 1147, 1115, 1085, 985, 626; MS (positive ESI,  $H_2O/MeCN/MeOH$  + 10 mM  $NH_4Ac$ ):  $m/z$  (%) = 338 (45) [ $M^{2+} + Cl$ ] $^+$ ; 362 (100) [ $M^{2+} + CH_3COO$ ] $^+$ .

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### REFERENCES

1. P. D. Beer, N. G. Berry, A. R. Cowley, E. J. Hayes, E. C. Oates, and W. W. H. Wong, *Chem. Commun.*, 2003, 2408; C. Bucher, R. S. Zimmerman, V. Lynch, and J. L. Sessler, *Chem. Commun.*, 2003, 1646; M. Albrecht, S. Schmid, M. de-Groot, P. Weis, and R. Fröhlich, *Chem. Commun.*, 2003, 2526; J. Farkas Jr, S. J. Stoudt, E. M. Hanawalt, A. D. Pajerski, and H. G. Richey Jr, *Organometallics*, 2004, **23**, 423; J. Nelson, M. Nieuwenhuyzen, I. Pál, and R. M. Town, *Dalton Trans.*, 2004, 229; B. Bag and P. K. Bharadwaj, *Inorg. Chem.*, 2004, **43**, 4626; B. Dietrich, P. Viout, and J.-M. Lehn, 'Macrocyclic Chemistry: Aspects of Organic and Inorganic Supramolecular Chemistry', VCH, New York, 1993 and references therein; H.-J. Schneider, and A. Yatsimirsky, 'Principles and Methods in Supramolecular Chemistry,' John Wiley&Sons, New York, 1999 and references therein.
2. Review on thermodynamic and kinetic data for macrocycle interaction with cations, anions and neutral molecules: R. M. Izatt, K. Pawlak, J. S. Bradshaw, and R. L. Bruening, *Chem. Rev.*, 1995, **95**, 2529.

3. For reviews, see: J. Chin, *Acc. Chem. Res.*, 1991, **24**, 145; C. Liu, M. Wang, T. Zhang, and H. Sun, *Coord. Chem. Rev.*, 2004, **248**, 147.
4. M. V. Baker, D. H. Brown, B. W. Skelton, and A. H. White, *J. Chem. Soc., Dalton Trans.*, 2000, 4607; B.-C. Tzeng, W.-C. Lo, C.-M. Che, and S.-M. Peng, *Chem. Commun.*, 1996, 181; P. Planinic, D. Matkovic-Calogovic, and H. Meider, *J. Chem. Soc., Dalton Trans.*, 1997, 3445; L. Burai, É. Tóth, G. Moreau, A. Sour, R. Scopelliti, and A. E. Merbach, *Chem. Eur. J.*, 2003, **9**, 1394; M. E. Padilla-Tosta, J. M. Lloris, R. Martinez-Manez, A. Benito, J. Soto, T. Pardo, M. A. Miranda, and M. D. Marcos, *Eur. J. Inorg. Chem.*, 2000, 741.
5. A. R. Katritzky, C. W. Rees, E. F. V. Scriven, and R. N. Butler, 'Comprehensive Heterocyclic Chemistry', Pergamon, Oxford, UK, 1996, Vol. 4.
6. H. Singh, A. S. Chawla, V. K. Kapoor, D. Paul, and R. K. Malhotra, *Prog. Med. Chem.*, 1980, **17**, 151.
7. M. Subat, H.-C. Gallmeier, A. Fuchs, and B. König, *Synth. Commun.*, 2005, 3003; O. Wiest, B. Christopher, N. J. Saettel, R. Cibulka, M. Sax, and B. König, *J. Org. Chem.*, 2004, **69**, 8183; R. Cibulka, R. Vasold, and B. König, *Chem. Eur. J.*, 2004, **10**, 6223; M. Subat, A. S. Borovik, and B. König, *J. Am. Chem. Soc.*, 2004, **126**, 3185; M. Hechavarría Fonseca, and B. König, *Adv. Syn. Cat.*, 2003, **345**, 1173, R. Reichenbach-Klinke, M. Zabel, and B. König, *J. Chem. Soc., Dalton Trans.*, 2003, 141; R. Reichenbach-Klinke, M. Kruppa, and B. König, *J. Am. Chem. Soc.*, 2002, **124**, 12999; T. Fricke, Š. Chrápavá, and B. König, *Syn. Commun.*, 2002, **32**, 3595.
8. Z. P. Demko and K. B. Sharpless, *J. Org. Chem.*, 2001, **66**, 7945; F. Himo, Z. P. Demko, L. Noodleman, and K. B. Sharpless, *J. Am. Chem. Soc.*, 2002, **124**, 12210; F. Himo, Z. P. Demko, L. Noodleman, and K. B. Sharpless, *J. Am. Chem. Soc.*, 2003, **125**, 9983.
9. R. Das, P. Paul, K. Nag, and K. Venkatsubramanian, *Inorg. Chim. Acta*, 1991, **185**, 221; V. P. Sinditskii, M. D. Dutov, A. E. Fogelzang, T. Y. Vernidub, V. I. Sokol, and M. A. Porai-Koshits, *Inorg. Chim. Acta*, 1991, **189**, 259; R. Guillard, N. Jagerovic, A. Tabard, P. Richard, L. Courthaudon, A. Lonati, C. Lecomte, and K. M. Kadish, *Inorg. Chem.*, 1991, **30**, 16.
10. M. A. M. Abu-Youssef, F. A. Mautner, A. A. Massoud, and L. Oehrstroem, *Polyhedron*, 2007, **26**, 1531; X.-M. Zhang, Y.-F. Zhao, H.-S. Wu, S. R. Batten, and S.W. Ng, *J. Chem. Soc., Dalton Trans.*, 2006, 3170; H. Zhao, Q. Ye, Q. Wu, Y.-M. Song, Y.-J. Liu, and R.-G. Xiong, *Z. Anorg. Allg. Chem.*, 2004, **630**, 1367.
11. M. Brandes, C. Gros, F. Denat, and R. Grilaud, *Bull. Chem. Soc. Chim. Fr.*, 1996, **133**, 3068.
12. S. Thambidurai, K. Jeyasubramanian, and S. K. Ramalingam, *Polyhedron*, 1996, **15**, 4011; J. P. Ferris, C. H. Huang, and W. J. Hagan, *Nucleosides Nucleotides*, 1989, **8**, 407; A. R. Katritzky, B. V.

- Rogovoy, C. Chassaing, and V. Vvedensky, *J. Org. Chem.*, 2000, **65**, 8080; Y.-Q. Wu, S. K. Hamilton, D. E. Wilkinson, and G. S. Hamilton, *J. Org. Chem.*, 2002, **67**, 7553.
13. ZnL and CuL are very hygroscopic solids, which prohibited obtaining accurate elemental analysis or X-ray structure analyses. The small molecular mass with two positive charges did not allow for HRMS.
  14. S. G. Alvarez and M. T. Alvarez, *Synthesis*, 1997, 413.
  15. L. Bosch and J. Vilarrasa, *Angew. Chem. Int. Ed.*, 2007, **46**, 3926.
  16. Z. P. Demko and K. B. Sharpless, *Angew. Chem. Int. Ed.*, 2002, **41**, 2110.
  17. H. Quast and L. Bieber, *Tetrahedron Lett.*, 1976, **18**, 1485; W. R. Carpenter, *J. Org. Chem.*, 1962, **27**, 2085; M. M. Krayushin, A. M. Beskopylnyi, S. G. Slotin, O. A. Lukyanov, and V. M. Zhulin, *Izv. Akad. Nauk. SSSR Ser. Khim.*, 1980, **11**, 2668.
  18. Z.P. Demko and K.B. Sharpless, *Angew. Chem. Int. Ed.*, 2002, **41**, 2113.
  19. Information on crystal data and data collection are given in the experimental section. All crystallographic data for compound  $[\text{NiL}(\text{H}_2\text{O})]_2 (\text{ClO}_4)_2$  have been deposited with the Cambridge Crystallographic Data Centre (CCDC). These data can be obtained free of charge via [www.ccdc.cam.ac.uk/data\\_request/cif](http://www.ccdc.cam.ac.uk/data_request/cif).
  20. H. Gallardo, I. M. Begnini, A. Neves, and I. Vencato, *J. Braz. Chem. Soc.*, 2000, **11**, 274; H. Gallardo, E. Mayer, A. J. Bertoluzzi, F. Molin, and A. S. Mangrich, *Inorg. Chim. Acta*, 2004, **357**, 505 and references therein; W. R. Ellis Jr. and I. W. Purcell, *Inorg. Chem.*, 1982, **21**, 834.
  21. M. Ciampolini, M. Micheloni, N. Nardi, P. Paoletti, P. Dapporto, and F. Zanobini, *J. Chem. Soc., Dalton Trans.*, 1984, 1357; J. H. Coates, D. A. Hadi, S. F. Lincoln, H. W. Dodgen, and J. P. Hunt, *Inorg. Chem.*, 1981, **20**, 707; A. Bencini, A. Bianchi, E. Garcia-Espana, Y. Jeannin, M. Julve, V. Marcelino, and M. Philoche-Levisalles, *Inorg. Chem.*, 1990, **29**, 963.
  22. S. C. Nyburg and J. S. Wood, *Inorg. Chem.*, 1964, **3**, 468.
  23. T. Koike, S. Kajitani, I. Nakamura, E. Kimura, and M. Shiro, *J. Am. Chem. Soc.*, 1995, **117**, 1210.
  24. M. Subat, K. Woinaroschy, S. Anthofer, B. Malterer, and B. König, *Inorg. Chem.*, 2007, **46**, 4336 and references therein.
  25. X.-S. Wang, Y.-Z. Tang, X.-F. Huang, Z.-R. Qu, C.-M. Che, P. W. H. Chan, and R.-G. Xiong, *Inorg. Chem.*, 2005, **44**, 5278; S. Craddock, R. H. Findlay, and M. H. Palmer, *Tetrahedron*, 1973, **29**, 2173.