

## Host–Guest Complex Dependent Regioselectivity in Substitution Reactions of Chlorocyclophosphazene-Containing PNP-Crowns with Alkylenediamines

Krystyna Brandt,<sup>\*,†</sup> Iwona Porwollik,<sup>†</sup> Mariola Siwy,<sup>†</sup> Teobald Kupka,<sup>†</sup> Robert A. Shaw,<sup>‡</sup> David B. Davies,<sup>‡</sup> Michael B. Hursthouse,<sup>§</sup> and Georgia D. Sykara<sup>§</sup>

Institute of Polymer Chemistry  
Polish Academy of Sciences  
34 M. Curie-Sklodowska St., 41-800 Zabrze, Poland  
Department of Chemistry  
Birkbeck College (University of London), Gordon House  
29 Gordon Square, London WC1H 0PP, U.K.  
School of Chemistry & Applied Chemistry  
University of Wales, Cardiff CF1 3TB, Wales, U.K.

Received July 18, 1996

To date there have been no reports on the spontaneous formation of ansa derivatives in the reactions of diamines with chlorocyclophosphazenes having available  $\text{PCl}_2$  sites.<sup>1,2</sup> Spiro-fused derivatives have been obtained exclusively by the reactions of 1,2-diaminoethane with  $\text{N}_3\text{P}_3\text{Cl}_6$  and its geminal bis-*tert*-butylamino- and diphenyltetrachloro derivatives<sup>3,4</sup> and by the reactions of 1,3-diaminopropane with  $\text{N}_3\text{P}_3\text{Cl}_6$ <sup>3,5</sup> and the respective ansa-cyclosubstituted (aminoethyleneoxy)<sup>6</sup> and {[bis(ethylene)oxo]diamino}<sup>7</sup> derivatives. In this paper, we demonstrate that the spiro diaminolysis pattern is not generally valid for all ansa polyether-substituted chlorocyclophosphazenes and can be completely changed (especially marked at lower temperatures, e.g.,  $-25^\circ\text{C}$ ) toward regioselective attack at the chlorine atoms geminal to the ansa arch by the reactions of, for example, 1,2-diaminoethane (**2a**) and 1,3-diaminopropane (**2b**) with the monoansa[(oxytetraethyleneoxy)tetrachlorocyclophosphazene (PNP-crown, **1**), previously reported by us.<sup>8</sup> Together with the ansa-ansa products **5a,b**, the respective doubly (**6a,b**) and singly bridged (**7a,b**) bis(PNP-crowns) are formed (Scheme 1).

<sup>†</sup> Polish Academy of Sciences.

<sup>‡</sup> Birkbeck College.

<sup>§</sup> University of Wales.

(1) Allcock<sup>2</sup> recently obtained the first transannular intramolecularly ansa diamino-bridged 1,3-diaminopropane cyclophosphazene by excluding spiro substitution with an appropriate "blocked" precursor.

(2) Allcock, H. R.; Turner, M. L.; Visscher, K. B. *Inorg. Chem.* **1992**, *31*, 4354–4364 and references therein.

(3) (a) Shaw, R. A. *Phosphorus, Sulfur Silicon Relat. Elem.* **1989**, *45*, 183–136 and references therein. (b) Deutsch, W. F.; Shaw, R. A. *J. Chem. Soc., Dalton Trans.* **1988**, 1757–1763.

(4) (a) Krishnamurthy, S. S.; Ramachandran, K.; Vasudeva Murthy, R. A.; Shaw, R. A.; Woods, M. *J. Chem. Soc., Dalton Trans.* **1980**, *13*, 840–844. (b) Dave, P. R.; Forohar, F.; Axenrod, T.; Bedford, C. D.; Chaykovsky, M.; Rho, M. K.; Gilardi, R.; George, C.; *Phosphorus, Sulfur Silicon Relat. Elem.* **1994**, *90* (1–4), 175–184 and references therein.

(5) (a) Chandrasekhar, V.; Krishnamurthy, S. S.; Vasudeva Murthy, R. A.; Shaw, R. A.; Woods, M. *Inorg. Nucl. Chem. Lett.* **1981**, *17* (5/6), 181–185. (b) Labarre, J.-F. *Top. Curr. Chem.* **1985**, *129*, 173–230 and references therein. (c) Guersch, G.; Graffeuil, M.; Labarre, J.-F.; Enjalbert, R.; Lahana, R.; Sournies, F. *J. Mol. Struct.* **1982**, *95*, 237–244. (d) Vidaud, L.; Labarre, J.-F.; Perly, B. *Inorg. Chim. Acta* **1988**, *147*, 71–75.

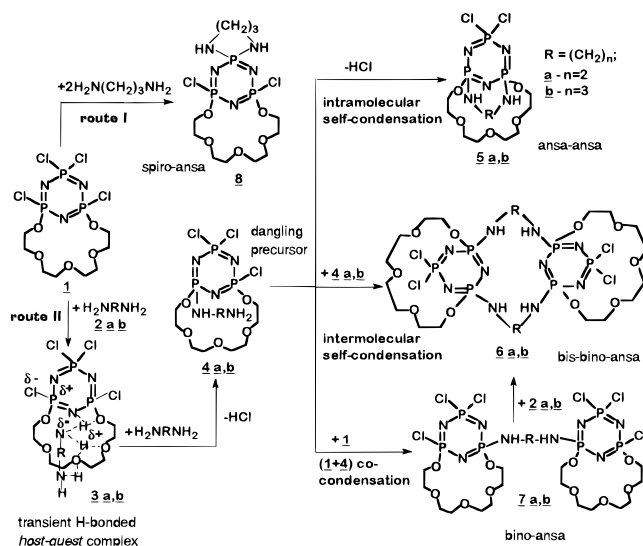
(6) (a) Harris, J. P.; Williams, K. B. *Inorg. Chem.* **1984**, *23*, 1495–1496. (b) Sournies, F.; Labarre, J.-F.; Harris, J.-P.; Williams, K. B. *Inorg. Chim. Acta* **1984**, *90*, L61.

(7) Castera, P.; Faucher, J.-P.; Graffeuil, M.; Labarre, J.-F. *J. Mol. Struct.* **1988**, *176*, 295–301.

(8) (a) Brandt, K.; Kupka, T.; Drozd, J.; van de Grampel, J. C.; Meetsma, A.; Jekel, A. P. *Inorg. Chim. Acta* **1995**, *228*, 187–192. (b) Brandt, K.; Porwollik, I.; Kupka, T.; Olejnik, A.; Shaw, R. A.; Davies, D. B. *J. Org. Chem.* **1995**, *60*, 7433–7438.

(9) Reactions of **1** with **2** (**a,b**) were carried out in dry benzene at  $20^\circ\text{C}$  at a molar ratio for **2/1** greater than or equal to 1:1 full conversion of **1** to **5–7** being achieved in 1–2 h. <sup>31</sup>P NMR investigations of the reactions were performed at  $-25^\circ\text{C}$  in toluene-*d*<sub>8</sub>.

### Scheme 1



According to the mechanism proposed, the reaction starts with complexation of the diamines **2a,b** with the macrocycle **1**, probably due to self-assembly via hydrogen bonding, known to be of key importance in supramolecular chemistry.<sup>10</sup> Many examples of the complexation of neutral guests, like diamines,<sup>11a,b</sup> urea, and thiourea<sup>11c</sup> within suitable macrocyclic receptors have been reported previously. Thus, formation of an intermediate H-bonded "host–guest" complex (e.g., **3a,b**) seems to be a driving force for *gem*-regioselectivity in the respective substitution reactions. Self-assembly may occur through bifurcated hydrogen bonding of the  $\text{N}-\text{H}\cdots\text{O}$ , or  $\text{N}-\text{H}\cdots\text{O}$  type between the  $\text{NH}_2$  group(s) of the complexed *guest* diamine **2a,b** and the lone pairs of electrons of the oxygen and/or nitrogen atoms of the *host* macrocycle **1**, similar to those previously described for the self-assembly Mannich type cyclization of diazacrowns with bis(phenols).<sup>12</sup>

Although it is difficult to detect this H-bonded complex in **3a,b** due to its high reactivity [fast  $\text{Cl}$  (**1**)  $\rightarrow$   $\text{NH}_2$  (**2**) interaction], we obtained MS evidence for complexation of 1,2-diaminoethane (**2a**) with an unreactive tetranaphthoxy-substituted derivative of **1**.<sup>8b,13</sup>

The diamine **2a,b** self-assembled with **1** to form **3a,b** apparently assists the substitution reaction at the macrocycle-bearing P-atom(s) by the favorable combination of its coordinative interaction (hydrogen bonding) with the polyether bridge of **1** and the electrostatic interaction with the negative charge developing on the chlorine atom adjacent to the macrocycle during the activation process.<sup>14</sup> The initial product of aminolysis is an open-chain dangling type intermediate **4a,b**, which has

(10) For example, see: (a) Rebek, J. *Science* **1987**, *235*, 1478–235. (b) Lehn, J.-M. *Angew. Chem., Int. Ed. Engl.* **1988**, *27*, 89. (c) Gokel, G. W. *Crown Ethers & Cryptands, Monographs in Supramolecular Chemistry*; The Royal Society of Chemistry: Cambridge, 1991; pp 83–8.

(11) (a) Danks, I. P.; Sutherland, I. O.; Yap, C. H. *J. Chem. Soc., Perkin Trans. I* **1990**, 421. (b) Vogtle, F.; Hoss, R. *J. Chem. Soc., Chem. Commun.* **1992**, 1584–1585. (c) Scheerder, J.; Engdbernsen, J. F. J.; Casnatio, A.; Ungaro, R.; Reindhoudt, R. *J. Org. Chem.* **1995**, *60*, 6448–6454.

(12) Bordonov, A. V.; Lukyanenko, N. G.; Pastushok, V. N.; Krakowiak, K. E.; Bradshaw, J. E.; Dalley, N. K.; Kou, X. *J. Org. Chem.* **1995**, *60*, 4912–4918.

(13) The molecular ion of the complex (*m/e* 960) has been found in the LSIMS spectrum of the equimolar mixture of  $(\text{C}_{10}\text{H}_8\text{O})_4[\text{O}(\text{CH}_2\text{CH}_2\text{O})_4]-\text{N}_3\text{P}_3$ <sup>8b</sup> (MW = 901) and **2a** (MW = 60).

(14) Similar transition state stabilizing cooperative effects have been previously reported for the various alkali metal cation assisted reactions of functional crowns: (a) Cacciapaglia, R.; Mandolini, L. *Chem. Soc. Rev.* **1993**, 221–231 and references therein. (b) Doddi, G.; Ercolani, G.; La Pegna, P.; Mencarelli, P. *J. Chem. Soc., Chem. Commun.* **1994**, 1239–1240. (c) Brandt, K.; Porwollik, I.; Olejnik, A.; Shaw, R. A.; Davies, D. B.; Hursthouse, M. B.; Sykara, G. *J. Am. Chem. Soc.* **1996**, *118*, 4496–4497.

**Table 1.** MS and  $^{31}\text{P}$  NMR Data of Ansa (**5a,b**) and Spiro (**8**) Diamino-Substituted 1,3-(Oxytetraethyleneoxy) PNP-Crown Derivatives of Formula  $\text{N}_3\text{P}_3\text{Cl}_2[(\text{OCH}_2\text{CH}_2)_4\text{O}][\text{NH}(\text{CH}_2)_n\text{NH}]$  and Their Respective Bis-Bino Cyclam-like Dimers  $\{\text{N}_3\text{P}_3\text{Cl}_2[(\text{OCH}_2\text{CH}_2)_4\text{O}][\text{NH}(\text{CH}_2)_n\text{NH}]\}_2$  (**6a,b**)

compound		$^{31}\text{P}$ NMR <sup>d</sup> A <sub>2</sub> B spin system <sup>e</sup>					
type <sup>a</sup>	<i>n</i> <sup>b</sup>	MS ( <i>m/e</i> ) <sup>c</sup>	$\delta_{\text{P}(\text{OCH}_2)_n\text{NH}}$ [ppm]	$\delta_{\text{PCl}_2}$ [ppm]	$^2J_{\text{P-P}}$ [Hz]	$\delta_{\text{P}(\text{OCH}_2)_4\text{Cl}}$ [ppm]	$\delta_{\text{P}(\text{NH}_2)}$
<b>5a</b>	2	455/455	23.0 <sup>d</sup>	30.5 <sup>t</sup>	60.7		
<b>5b</b>	3	469/469	21.7 <sup>d</sup>	30.6 <sup>t</sup>	54.4		
<b>6a</b>	2	912/910	16.4 <sup>d</sup> <sup>g</sup>	26.6 <sup>t</sup>	56.6		
<b>6b</b>	3	940/938	17.0 <sup>d</sup> <sup>g</sup>	25.1 <sup>t</sup>	57.0		
<b>8</b>	3	469/469			−56.2	23.4 <sup>d</sup> <sup>i</sup>	13.5 <sup>t</sup> <sup>j</sup>

<sup>a</sup> For the respective formula see Scheme 1. <sup>b</sup> Number (*n*) of methylene groups in the polymethylene chain of the diamine unit. <sup>c</sup> Found/calcd – acc. LSI-MS. <sup>d</sup>  $^{31}\text{P}$  NMR spectra obtained at 121 MHz in  $\text{CDCl}_3$  solution at ambient temperature, referenced to  $\text{H}_3\text{PO}_4$ . <sup>e</sup> For A<sub>2</sub>B spin system: doublet (d) corresponds to P<sub>A</sub> (two equally substituted P atoms) and triplet (t) corresponds to P<sub>B</sub>;  $J_{\text{P-P}}$  and  $\delta_{\text{P}}$  values calculated according to ref 17. <sup>f</sup> Pair of doublets, significantly broadened on proton coupling. <sup>g</sup> Doublet, broadened on proton coupling. <sup>h</sup> Triplet unaffected by proton coupling. <sup>i</sup> Doublet, slightly broadened on proton coupling. <sup>j</sup> Triplet, each peak split into three on proton coupling,  $J_{\text{P-H}} = 15.4$  Hz.

been detected by low-temperature  $^{31}\text{P}$  NMR of the reactions of **1** with both **2a** and **2b** and in the mass spectrum of the crude reaction mixture of the reaction of **1** with **2b** (*m/e* 503). A minor side reaction leading to the spirocyclic isomer **8** (route II) has also been found to occur (under the ambient reaction conditions employed<sup>9</sup>) only for 1,3-diaminopropane as a dinucleophile but not when the reaction was carried out at  $-25$  °C. A previous  $^{31}\text{P}$  NMR kinetic study showed the reaction of **2b** with  $\text{N}_3\text{P}_3\text{Cl}_6$  favored the formation of the spiro compound because of the very high stability of a six-membered ring,<sup>5d</sup> and this effect is a minor one compared to the reaction of **1** with **2** due to their H-bonding self-assembly.

The relative ratio of the products formed has been found to depend on the molecular ratio of reactants, concentration, and the molecular size of the dinucleophile (**2a,b**) (Table 1, Supporting Information<sup>15</sup>). In general, at a 1:1 molar ratio of **1/2** formation of singly bridged bino derivatives (**7**) prevailed; whereas, when the diamine **2** was used in excess, the distribution between ansa-cyclosubstituted derivatives (**5**) and doubly bridged bis-bino ones (**6**) (being the main two products formed) could be varied by changing the amount of the solvent used.<sup>9</sup>

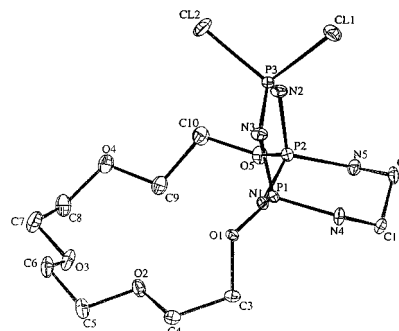
Structural assignments of the products have been based mainly on the respective mass and  $^{31}\text{P}$  NMR spectra<sup>16</sup> (Table 1; Table 3, Supporting Information<sup>15</sup>).  $^1\text{H}$  NMR and elemental analysis data (Table 4, Supporting Information<sup>15</sup>) were used to support the proposed structures. Unambiguous X-ray crystallographic evidence has also been provided for the derivative **5a** which was found to be fully consistent with the MS- and  $^{31}\text{P}$ -NMR-based assignments (Figure 1).<sup>18</sup>

(15) See Supporting Information.

(16) The NMR data combined with the molecular weights by MS were consistent with the proposed structures (Table 1). For singly bridged bino derivatives, the AMX spin pattern found with the A and M parts being affected by proton coupling (Table 3, Supporting Information<sup>15</sup>), together with the respective molecular ions (Table 4, Supporting Information<sup>15</sup>), was consistent with the structures **7a,b**. Detailed results of the  $^{31}\text{P}$  NMR and  $^1\text{H}$  NMR studies of **7a,b** and their higher homologues, as well on the respective intermediates, will be published elsewhere in due course.

(17) Hoffman, R. A.; Forsen, S.; Gestblom, B. In *NMR—Basic Principles and Progress*; Diehl, P., Fluck, E., Kosfeld, R., Eds.; Springer-Verlag: Berlin, Heidelberg, New York, 1971; Vol 5, pp 104–105.

(18) Two aspects of the molecular structure of **5a** are noteworthy: (i) The short span of the ethylenediamino ansa arch has compressed the  $\text{N}_3\text{P}_3$  ring and forced the ring N atom between the ansa arch 0.5 Å out of the plane of the remaining five atoms ( $\text{N}_2\text{P}_3$ ), as previously observed with other short-chain ansa arches.<sup>19</sup> (ii) While the bond length for P(3)—Cl(2) is normal at 2.008 Å, that of P(3)—Cl(7) at 2.033 Å, *cis* to the amino ansa arch, is exceptionally long for a  $\text{PCl}_2$  group, possibly due to the so-called “*cis*-effect”.<sup>20</sup>

**Figure 1.** The molecular structure of *gem*-bisansa{1,3-((oxytetraethyleneoxy)-1,3-(1,2-ethylenediamino))-5,5-dichlorocyclotriphosphatriene (**5a**).

These preliminary results demonstrate that the PNP-crown **1**, and in particular its (Cl)PNP(Cl)[O(CH<sub>2</sub>CH<sub>2</sub>O)<sub>4</sub>] moiety, by virtue of being a bifunctional receptor for diamines represents a useful synthon for the regioselective preparation of unusual diamino-linked transannular (**5a,b**) and/or ladder type doubly bridged (**6a,b**) and/or singly *gem*-bridged (**7a,b**) cyclophosphazene derivatives, which are inaccessible by other synthetic routes. All of the derivatives **5–7**, obtained within this study, may be considered as new multisite macrocyclic ligands. Studies on their complexing abilities are in progress in our laboratories and will be reported in due course.

**Acknowledgment.** This work has been supported by the European Commission (grant CIPA-CT93-0019) and the Polish Committee on Scientific Research (grant 2 P303 068 06). The authors are grateful to the Nippon Fine Chemical Co., Ltd., for a generous gift of hexachlorocyclotriphosphazatriene.

**Supporting Information Available:** Tables giving atom parameters, input data, crystal data and structure refinement, thermal parameters, bond lengths and angles, selected torsion angles, and interatomic contacts for compound **5a**, proton-coupled and -decoupled  $^{31}\text{P}$  NMR spectra of the compounds **5a,b**, **6a,b**, **7a,b**, and **8**, and tables of the reaction conditions and characterization data (26 pages). See any current masthead page for ordering and Internet access instructions.

JA9624883

(19) (a) Contractor, S. R.; Hursthouse, M. B.; Parkes, H. G.; Shaw, L. S.; Shaw, R. A.; Yilmaz, H. *J. Chem. Soc., Chem. Commun.* **1984**, 675–676. (b) Contractor, S. R.; Hursthouse, M. B.; Parkes, H. G.; Shaw, L. S.; Shaw, R. A.; Yilmaz, H. *Phosphorus, Sulfur Silicon Relat. Elem.* **1986**, 28, 267–275.

(20) Keat, R.; Shaw, R. A. *J. Chem. Soc. A* **1966**, 914–961.