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Pyrazolylcyclotriphosphazene Containing Pendant Polymers: Synthesis, Characterization, and Phosphate Ester Hydrolysis Using a Cu(II)-Metalated Cross-Linked Polymeric Catalyst

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A multi-pyrazolyl cyclotriphosphazene containing polymerizable group $N_3P_3(3,5\text{-}Me_2Pz)_5(O\text{–}C_6H_4\text{-}p\text{-}C_6H_4\text{-}p\text{-}CH{=}CH_2)$ (**2**) has been prepared from the corresponding chloro derivative $N_3P_3Cl_5(O\text{—}C_6H_4\text{-}p\text{-}C_6H_4\text{-}p\text{-}CH{=}CH_2)$ (**1**). The X-ray structures of **1** and **2** have been determined. Compound **2** undergoes ready metalation with $CuCl_2$ to afford $N_3P_3(3,5\text{-}Me_2Pz)_5(O\text{—}C_6H_4\text{-}p\text{-}C_6H_4\text{-}p\text{-}CH{=}CH_2)\cdot CuCl_2$ (**3**). Model compound $N_3P_3(3,5\text{-}Me_2Pz)_5(O\text{—}C_6H_4\text{-}p\text{-}CHO)\cdot CuCl_2$ (**6**) has been prepared and characterized by spectroscopy and X-ray crystallography. In this compound, the coordination around copper is distorted trigonal bipyramidal, and the cyclotriphosphazene coordinates in a non-gem N_3 mode. Compound **2** has been copolymerized with divinylbenzene to afford cross-linked multisite coordinating polymer CPPL which is readily metalated with $CuCl_2$ to afford copper-containing polymer CPPL-Cu. The coordination environment around copper in CPPL-Cu has been evaluated by obtaining its EPR, optical, and IR spectra and comparing them with those of model compounds **3** and **6**. The utility of CPPL-Cu as a heterogeneous catalyst has been demonstrated in the phosphate ester hydrolysis involving three model phosphate esters: *p*-nitrophenyl phosphate (pNPP), bis(*p*-nitrophenyl) phosphate (bNPP), and 2-(hydroxypropyl)-*p*-nitrophenyl phosphate (hNPP). In all of these reactions, a significant rate enhancement of ester hydrolysis is observed. Detailed kinetic analyses to evaluate Michaelis–Menten parameters have also been carried out along with experiments to elucidate the effect of pH, solvent, and temperature on the rate of hydrolysis. Recycling experiments on the hydrolysis of pNPP with CPPL-Cu shows that it can be recycled several times over without affecting the rates.

Introduction

Polyphosphazenes, $[N{=}PR_2]_n$, constitute the largest family of inorganic polymers with over 800 different examples.[1] A large majority of these polymers are assembled by a macromolecular nucleophilic substitution on the polydichlorophosphazene $[N{=}PCl_2]_n$.[1a,2] The latter is obtained by a ring opening polymerization[3] of $N_3P_3Cl_6$ or by a condensation polymerization involving $Cl_3P{=}N{-}P(O)Cl_2$[4] or $Cl_3P{=}N\text{-}(SiMe)_3$.[5] Other methods of preparing poly(organophosphazenes) include fluoride-assisted[6] or thermal polymeriza-

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(1) Book and some reviews: (a) Mark, J. E.; Allcock, H. R.; West, R. *Inorganic Polymers*; Prentice Hall: New York, 1992. (b) De Jaeger, R.; Gleria, M. *Prog. Polym. Sci*. **1998**, *23*, 179. (c) Manners, I. *Angew. Chem., Int. Ed. Engl.* **1996**, *35*, 1602. (d) Neilson, R. H.; Wisian-Neilson, P. *Chem. Rev*. **1988**, *88*, 541. (e) Allcock, H. R. *Chem. Eng. News* **1985**, *63*, 22. (f) Allcock, H. R. *Polymer* **1980**, *21*, 673. (g) Allcock, H. R. *Acc. Chem. Res*. **1979**, *12*, 351. (h) Allcock, H. R. *Angew. Chem., Int. Ed. Engl.* **1977**, *16*, 147.

(2) (a) Prange, P.; Reeves, S. D.; Allcock, H. R. *Macromolecules* **2000**, *33*, 5763. (b) Carriedo, G. A.; Alonso, F. J. G.; Gonzalez, P. A.; Gomez-Elipe, P. *Polyhedron* **1999**, *18*, 2853. (c) Allcock, H. R.; Olmeijer, D. L. *Macromolecules* **1998**, *31*, 8036. (d) Allcock, H. R.; Ravikiran, R.; Olshavsky, M. A. *Macromolecules* **1998**, *31*, 5206. (e) Allcock, H. R.; Krause, W. E. *Macromolecules* **1997**, *30*, 5683. (f) Gleria, M.; Minto, M.; Bertani, R.; Facchin, G.; Tondello, E. *Gazz. Chim. Ital.* **1997**, *127*, 343. (g) Carriedo, G. A.; Fernandez-Catuxo, L.; Alonso, F. J. G.; Gomez-Elipe, P.; Gonzalez, P. A. *Macromolecules* **1996**, *29*, 5320. (h) Allcock, H. R.; Kim, Y. B. *Macromolecules* **1994**, *27*, 3933. (i) Allcock, H. R. *J. Polym. Sci., Polym. Symp.* **1983**, *70*, 71.

(3) (a) Allcock, H. R.; Kugel, R. L. *Inorg. Chem*. **1966**, *5*, 1716. (b) Allcock, H. R.; Kugel, R. L.; Valan, K. J. *Inorg. Chem*. **1966**, *5*, 1709. (c) Allcock, H. R.; Kugel, R. L. *J. Am. Chem. Soc*. **1965**, *87*, 4216.

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tion of phosphoranimines.[7,1c] The versatility of polyphosphazenes arises from the fact that the polymer properties can be readily modulated by varying the substituents on phosphorus. Another class of related polymers contains an *intact* cyclophosphazene ring as a pendant group attached at regular intervals to the backbone of an organic polymer.[8] The number of examples of such pendant polymers is limited in comparison to that of the more prolific linear polyphosphazenes. However, in principle, this family also has the same potential in terms of tunability of polymer function and property. This can be accomplished by polymerizing a cyclotriphosphazene monomer $N_3P_3R_5P$ (P = a vinyl containing substituent; R = other substituent).

Polymers containing cyclotriphosphazenes as pendant groups are particularly attractive from the point of view of preparing polymeric ligands. Accordingly, we have prepared a cyclotriphosphazene monomer $N_3P_3(3,5\text{-}Me_2Pz)_5(O{-}C_6H_4\text{-}p\text{-}C_6H_4\text{-}p\text{-}CH{=}CH_2)$ (**2**) that contains five pyrazolyl ligands.[9] This compound is a potential multisite coordinating ligand that possesses pyrazolyl pyridinic nitrogens and cyclotriphosphazene ring nitrogen atoms for coordination to metal ions. This has been used for the preparation of new coordinating cross-linked polymer CPPL and heterogeneous Cu(II)-containing catalyst CPPL-Cu. To test the potential of CPPL-Cu as a heterogeneous catalyst, we have chosen to use it in the hydrolysis of phosphate esters. Phosphate ester hydrolysis plays a very important role in energy metabolism and in various cellular signal transduction pathways in biological systems.[10] A number of phosphoesterases require two or more metal ions for their catalytic activity in these reactions. In recent years, there has been considerable interest in the design of synthetic models that can function as catalysts for this biologically important reaction.[11] Many of these catalysts are homogeneous in nature, and the use of heterogeneous catalysts has been less frequent.[12] In view of this, we have evaluated the utility of CPPL-Cu as a catalyst in the hydrolysis reaction of three substrates: a phosphate monoester (*p*-nitrophenyl phosphate, pNPP), a phosphodiester [bis-(*p*-nitrophenyl) phosphate, bNPP], and an RNA model phosphodiester compound [2-(hydroxypropyl)-*p*-nitrophenyl phosphate, hNPP]. To the best of our knowledge, this is the first time that such studies are reported with this family of polymers. These results are presented in this paper. The X-ray crystal structures of $N_3P_3Cl_5(O{-}C_6H_4\text{-}p\text{-}C_6H_4\text{-}p\text{-}CH{=}CH_2)$ (**1**), $N_3P_3(3,5\text{-}Me_2Pz)_5(O{-}C_6H_4\text{-}p\text{-}C_6H_4\text{-}p\text{-}CH{=}CH_2)$ (**2**), and a copper(II) complex of a model compound $N_3P_3(3,5\text{-}Me_2Pz)_5(O{-}C_6H_4\text{-}p\text{-}CHO)\cdot CuCl_2$ (**6**) have also been determined and are discussed in this paper.

Experimental Section

General. Solvents and other general reagents used in this work were purified according to standard procedures.[13] 4-Hydroxy-4′-vinylbiphenyl,[14] 3,5-dimethylpyrazole,[13] and 2-(hydroxypropyl)-*p*-nitrophenyl phosphate (hNPP)[15] were prepared according to the

(4) (a) Jaeger, R. D.; Potin, Ph. *Phosphorous, Sulfur Silicon Relat. Elem.* **1993**, *76*, 223. (b) D'Halluin, G.; De Jaeger, R.; Chambrette, J. P.; Potin, Ph. *Macromolecules* **1992**, *25*, 1254. (c) Potin, P.; De Jaeger, R. *Eur. Polym. J.* **1991**, *4/5*, 341. (d) Helioui, M.; De Jaeger, R.; Puskaric, E.; Heubel, J. *Makromol. Chem.* **1982**, *183*, 1137.

(5) (a) Allcock, H. R.; Reeves, S. D.; de Denus, C. R.; Crane, C. A. *Macromolecules* **2001**, *34*, 748. (b) Allcock, H. R.; Nelson, J. M.; Prange, R.; Crane, C. A.; de Denus, C. R. *Macromolecules* **1999**, *32*, 5736. (c) Nelson, J. M.; Primrose, A. P.; Hartle, T. J.; Allcock, H. R. *Macromolecules* **1998**, *31*, 947. (d) Allcock, H. R.; Nelson, J. M.; Reeves, S. D.; Honeyman, C. H.; Manners, I. *Macromolecules* **1997**, *30*, 50. (e) Nelson, J. M.; Allcock, H. R. *Macromolecules* **1997**, *30*, 1854. (f) Allcock, H. R.; Reeves, S. D.; Nelson, J. M.; Crane, C. A. *Macromolecules* **1997**, *30*, 2213. (g) Nelson, J. M.; Allcock, H. R.; Manners, I. *Macromolecules* **1997**, *30*, 3191. (h) Allcock, H. R.; Crane, C. A.; Morrissey, C. T.; Nelson, J. M.; Reeves, S. D.; Honeyman, C. H.; Manners, I. *Macromolecules* **1996**, *29*, 7740. (i) Honeyman, C. H.; Manners, I.; Morrissey, C. T.; Allcock, H. R. *J. Am. Chem. Soc.* **1995**, *117*, 7035.

(6) (a) White, M. L.; Montague, R. A.; Matyjaszewski, K. *Polymer* **1995**, *36*, 3493. (b) Matyjaszewski, K.; Franz, U.; Montague, R. A.; White, M. L. *Polymer* **1994**, *35*, 5005. (c) Matyjaszewski, K.; Lindenberg, M. S.; Moore, M. K.; White, M. L.; Kojima, M. J. *Inorg. Organomet. Polym.* **1993**, *3*, 317. (d) Montague, R. A.; Matyjaszewski, K. *J. Am. Chem. Soc.* **1990**, *112*, 6721.

(7) (a) Wisian-Neilson, P.; Neilson, R. H. *J. Am. Chem. Soc.* **1980**, *102*, 2848. (b) Gruneich, J. A.; Wisian-Neilson, P. *Macromolecules* **1996**, *29*, 5511.

(8) (a) Allcock, H. R.; Laredo, W. R.; Kellam, E. C., III; Morford, R. V. *Macromolecules* **2001**, *34*, 787. (b) Allen, C. W.; Brown, E. D.; Worley, S. D. *Inorg. Chem.* **2000**, *39*, 810. (c) Allcock, H. R.; McIntosh, M. B.; Klingenberg, E. H.; Napierala, M. E. *Macromolecules* **1998**, *31*, 5255. (d) Allen, C. W. *MGCN, Main Group Chem. News* **1998**, *6(4)*, 6. (e) Inoue, K.; Sasaki, Y.; Itaya, T.; Tanigaki, T. *Eur. Polym. J.* **1997**, *33*, 841. (f) Selvaraj I. I.; Chandrasekhar, V. *Polymer* **1997**, *38*, 3617. (g) Allen, C. W. *Trends. Polym. Sci.* **1994**, *2*, 342. (h) McNally, L.; Allen, C. W. *Heteroatom Chem.* **1993**, *4*, 159. (i) Allen, C. W. *Stud. Inorg. Chem.* **1992**, *14*, 171. (j) Inoue, K.; Nitta, H.; Tanigaki, T. *Makromol. Chem., Rapid Commun.* **1990**, *11*, 467. (k) Inoue, K.; Nakano, M.; Takagi, M.; Tanigaki, T. *Macromolecules* **1989**, *22*, 1530. (l) Inoue, K.; Takagi, M.; Nakano, M.; Nakamura, H.; Tanigaki, T. *Makromol. Chem., Rapid Commun.* **1988**, *9*, 345. (m) Allen, C. W.; Bright, R. P. *Macromolecules* **1986**, *19*, 571. (n) Allen, C. W. *J. Polym. Sci., Polym. Symp.* **1983**, *70*, 79.

(9) Chandrasekhar, V.; Athimoolam, A.; Vivekanandan, K.; Nagendran, S. *Tetrahedron Lett.* **1999**, *40*, 1185.

(10) (a) Vincent, J. B.; Crowder, M. W.; Averill, B. A. *Trends Biochem. Sci.* **1992**, *17*, 105. (b) Fersht, A. *Enzyme Structure and Mechanism*; W. H. Freeman and Company: New York, 1985.

(11) Reviews: (a) Molenveld, P.; Engbersen, J. F. J.; Reinhoudt, D. N. *Chem. Soc. Rev.* **2000**, *29*, 105. (b) Williams, N. H.; Takasaki, B.; Wall, M.; Chin, J. *Acc. Chem. Res.* **1999**, *32*, 485. (c) Trawick, B. N.; Daniher, A. T.; Bashkin, J. K. *Chem. Rev.* **1998**, *98*, 939. (d) Hegg, E. L.; Burstyn, J. N. *Coord. Chem. Rev.* **1998**, *173*, 133. Recent papers: (a) Gajda, T.; Dupre, Y.; Torok, I.; Harmer, J.; Schweiger, A.; Sander, J.; Kuppert, D.; Hegetschweiler, K. *Inorg. Chem.* **2001**, *40*, 4918. (b) Neverov, A. A.; Brown, R. S. *Inorg. Chem.* **2001**, *40*, 3588. (c) Yamaguchi, K.; Akagi, F.; Fujinami, S.; Suzuki, M.; Shionoya, M.; Suzuki, S. *Chem. Commun.* **2001**, 375. (d) Fritsky, I. O.; Ott, R.; Kramer, R. *Angew. Chem., Int. Ed.* **2000**, *39*, 3255. (e) Yama Kimura, E. *Curr. Opin. Chem. Biol.* **2000**, *4*, 207. (f) Molenveld, P.; Engbersen, J. F. J.; Reinhoudt, D. *J. Org. Chem.* **1999**, *64*, 6337. (g) Williams, N. H.; Lebuis, A.-M.; Chin, J. *J. Am. Chem. Soc.* **1999**, *121*, 3341. (h) Hegg, E. L.; Mortimore, S. H.; Cheung, C. L.; Huyett, J. E.; Powell, D. R.; Burstyn, J. N. *Inorg. Chem.* **1999**, *38*, 2961. (i) Komiyama, M.; Takeda, N.; Shigekawa, H. *Chem. Commun.* **1999**, 1443. (j) Molenveld, P.; Engbersen, J. F. J.; Kooijman, H.; Spek, A. L.; Reinhoudt, D. N. *J. Am. Chem. Soc.* **1998**, *120*, 6726. (k) Suh, J.; Hong, S. H. *J. Am. Chem. Soc.* **1998**, *120*, 12545. (l) Chin, J. *Curr. Opin. Chem. Biol.* **1997**, *1*, 514. (m) Han, M. J.; Yoo, K. S.; Kim, K. H.; Lee, G. H.; Chang, J. Y. *Macromolecules* **1997**, *30*, 5408. (n) Liu, S.; Hamilton, A. M. *Tetrahedron Lett.* **1997**, *38*, 1107. (o) Kalesse, M.; Loos, A. *Liebigs Ann.* **1996**, 935. (p) Bruice, T. C.; Tsubouchi, A.; Dempcy, R. O.; Olson, L. P. *J. Am. Chem. Soc.* **1996**, *118*, 9867. (q) Ruf, M.; Weis, K.; Vahrenkamp, H. *J. Am. Chem. Soc.* **1996**, *118*, 9288. (r) Burstyn, J. N.; Deal, K. A. *Inorg. Chem.* **1993**, *32*, 3585. (s) Kim, J. H.; Chin, J. *J. Am. Chem. Soc.* **1992**, *114*, 9792.

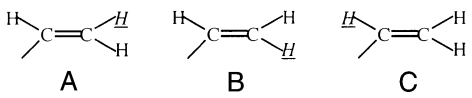
(12) (a) Srivatsan, S. G.; Verma, S. *Chem. Eur. J.* **2001**, *7*, 828. (b) Bodsgard, B. R.; Burstyn, J. N. *Chem. Commun.* **2001**, 647. (c) Srivatsan S. G.; Verma, S. *Chem. Commun.* **2000**, 515. (d) Abraham, A. T.; Zhou, X.; Hecht, S. M. *J. Am. Chem. Soc.* **1999**, *121*, 1981. (e) Menger, F. M.; Tsuno, T. *J. Am. Chem. Soc.* **1989**, *111*, 4903.

(13) *Vogel's Textbook of Practical Organic Chemistry*, 5th ed.; Longman: London, 1989.

reported procedures. *p*-Nitrophenyl phosphate (disodium hexahydrate salt), 4-hydroxy biphenyl (SD Fine Chemicals, India), and anhydrous cupric chloride (Fluka, Switzerland) were used as received. Bis(*p*-nitrophenyl) phosphate (Fluka) was converted into its sodium salt by neutralization with 1 M sodium hydroxide followed by lyophilization. Hexachlorocyclotriphosphazene (Nippon Soda, Japan) and *p*-hydroxy benzaldehyde (SD Fine Chemicals, India) were recrystallized from *n*-hexane before use. Divinylbenzene (Fluka, Switzerland) was treated with 20% sodium hydroxide to remove *tert*-butyl catechol, washed with water, and dried over sodium sulfate prior to use. *N*-Ethyl morpholine and ethylene glycol (Spectrochem, India) were distilled before use.

Instrumentation. ^{1}H and ^{31}P NMR spectra were recorded on a JEOL-JNM LAMBDA 400 model spectrometer operating at 400.0 and 161.7 MHz, respectively. The chemical shifts are reported with respect to internal tetramethylsilane (^{1}H) and external 85% H_3PO_4 (^{31}P). Mass spectra were recorded on a JEOL D-300 (EI/CI) spectrometer in the EI mode or in the FAB mass mode on a JEOL SX 102/DA 6000 mass spectrometer using xenon (6 kV, 10 mA) as the FAB gas. Elemental analyses were carried out on a Carlo-Erba CHNSO 1108 elemental analyzer. The amount of copper present in the polymeric catalyst was determined by atomic absorption spectrometry (AAS) on an Integra XL AAS spectrometer. EPR spectra were recorded on a Varian 109E Line Century Series, X-band spectrometer, at liquid nitrogen temperature. IR spectra were recorded as KBr pellets on a Bruker Vector 22 FTIR spectrophotometer operating from 400 to 4000 cm^{-1}. Optical spectra were recorded on a Shimadzu UV-160 spectrophotometer. TGA was recorded on a Perkin-Elmer, Pyris 6 thermogravimetric analyzer.

Preparation of $N_3P_3Cl_5(O-C_6H_4$-*p*-C_6H_4-*p*-$CH=CH_2)$ (1). The preparation of **1** was carried out by a slightly modified procedure compared to the one reported in the literature.[8l] To a solution of $N_3P_3Cl_6$ (7.0 g, 20.0 mmol) in benzene (60 mL) was added a mixture of 4-hydroxy-4′-vinyl biphenyl (3.9 g, 20.0 mmol) and triethylamine (2.0 g, 20.0 mmol) in benzene (60 mL) dropwise for 30 min. The reaction mixture was stirred for 6 h at room temperature, and the resultant triethylamine hydrochloride was filtered off. Removal of benzene from the filtrate in vacuo afforded an oily liquid. This was chromatographed over a silica gel column using *n*-hexane as the eluent. The first fraction contained unreacted $N_3P_3Cl_6$. The second fraction contained title compound **1**. Yield: 5.8 g, 56% (lit. yield: 40.0%). Mp: 112 °C. ^{1}H NMR ($CDCl_3$): δ 5.3 (d, 1H, J = 10.8 Hz, see structure A for assignment), 5.7 (d, 1H, J = 17.8 Hz, see structure B for assignment), 6.8 (dd, 1H, J = 17.5 and 10.9 Hz, see structure C for assignment), 7.4 (m, 8H, biphenyl). ^{31}P{^{1}H} NMR ($CDCl_3$): δ 22.5 (d, PCl_2), 12.3 (t, P(OR)-Cl), ^2J(P−N−P) = 58.2 Hz. MS(EI): 507 (M^+).



Preparation of $N_3P_3(3,5\text{-}Me_2Pz)_5(O-C_6H_4$-*p*-$C_6H_4$-*p*-$CH=CH_2)$ (2). To a mixture of 3,5-dimethylpyrazole (2.9 g, 30.0 mmol) and triethylamine (3.0 g, 30.0 mmol) in THF (40 mL) was added a solution of **1** (3.0 g, 6.0 mmol) in THF (30 mL) at room temperature over a period of 45 min. This was further stirred at the same temperature for 1 h and was subsequently heated under reflux for 6 h. The reaction mixture was allowed to come to room temperature and filtered and the solvent removed from the filtrate in vacuo to afford a white solid, which was identified as title compound **2**. This was recrystallized by dissolving in hot *n*-hexane and allowing cooling at 5 °C. Yield: 4.2 g, 88%. Mp: 179−181 °C. IR (KBr) cm^{-1}: 3431(s), 3059(s), 3018(s), 2990(s), 2966(s), 2927(s), 1632(w), 1603(w), 1571(s), 1523(w), 1494(s), 1463(m), 1434(m), 1409(s), 1371(m), 1300(s), 1250(vs), 1220(vs), 1169(vs), 1046(s), 1089(s), 1022(m), 964(vs), 913(m), 891(m), 843(m), 825(m), 794(w), 765(w), 752(m), 735(w), 669(w), 638(w), 601(s), 534(s), 519(s), 486(m). ^{1}H NMR ($CDCl_3$): δ 1.97, 2.05, 2.06, 2.07, 2.11 and 2.19 (s, 30 H, *CH*$_3$), 5.19 (d, 1H, J = 10.7 Hz, see structure A for assignment), 5.70 (d, 1H, J = 17.5 Hz, see structure B for assignment), 5.71 and 5.75 (s, 5H, pyrazolyl *CH*), 6.67 (dd, 1H, J = 17.6 and 10.9 Hz, see structure C for assignment), 7.17−7.38 (m, 8H, aromatic). ^{31}P{^{1}H} NMR ($CDCl_3$): δ 3.0 (t, P(OR)-(3,5-Me_2Pz)), 0.2 (d, P(3,5-Me_2Pz)$_2$), ^2J(P−N−P) = 65.5 Hz. MS(FAB): 806 (M^+). Anal. Calcd for $C_{39}H_{46}N_{13}OP_3$ (805.79): C, 58.13; H, 5.75; N, 22.60. Found: C, 57.81; H, 5.63; N, 22.32.

Preparation of $N_3P_3(3,5\text{-}Me_2Pz)_5(O-C_6H_4$-*p*-$C_6H_4$-*p*-$CH=CH_2)\cdot CuCl_2$ (3). To a solution of **2** (1.0 g, 10.0 mmol) in dichloromethane (80 mL) was added anhydrous cupric chloride (0.2 g, 10.0 mmol) at once, and the mixture was stirred for 24 h at room temperature. The solution was filtered, and the solvent was removed from the filtrate in vacuo. A green solid identified as **3** was obtained, and it was purified by reprecipitation by dissolving it in dichloromethane (2 mL) and adding *n*-hexane (20 mL). Yield: 0.80 g, 66.4%. Mp: 186 °C. IR (KBr) cm^{-1}: 3098(w), 2963(w), 2925(m), 1492(s), 1464(s), 1440(m), 1411(s), 1376(w), 1297(s), 1243(vs), 1191(vs), 1085(m), 1049(m), 1022(m), 966(s), 902(m), 830(m), 779(w), 755(w), 735(w), 678(w), 630(m), 594(vs), 540(s), 458(m). EPR (CH_2Cl_2/toluene 1:1 77 K): $g_{||}$ = 2.24; $g_\perp$ = 2.06; $A_{||}$ = 122.0 × 10^{-4} cm^{-1}. UV−vis {$CHCl_3$, [λ_{max}/nm (ϵ_{max}/M^{-1} cm^{-1})]}: 897 (269), 350 (2690), 283 (4470), 232 (4470). MS(FAB): 904 (M^+ − Cl, 25%), 869 (base peak, M^+ − 2Cl), 807 (M^+ − $CuCl_2$). Anal. Calcd for $C_{39}H_{46}N_{13}Cl_2CuOP_3$ (940.24): C, 49.82; H, 4.93; N, 19.37. Found: C, 49.18; H, 4.63; N, 19.15.

Preparation of $N_3P_3Cl_5(O-C_6H_4$-*p*-CHO) (4). $N_3P_3Cl_6$ (3.48 g, 10.0 mmol) was dissolved in THF (30 mL), and to it was added a mixture of *p*-hydroxy benzaldehyde (0.9 g, 10.0 mmol) and triethylamine (1.0 g, 10.0 mmol) taken together in THF (30 mL) dropwise over a period of 30 min. The reaction mixture was stirred for 12 h at room temperature. Triethylamine hydrochloride was filtered off, and the solvent was removed from the filtrate in vacuo to afford viscous oil. This was subjected to column chromatography over a silica gel column. Title compound **4** was obtained in a pure form by elution with a mixture of ethyl acetate and *n*-hexane (5:95). Yield: 2.5 g, 57%. Mp: 52 °C. ^{1}H NMR ($CDCl_3$): 7.86 (d, 2H, J = 8.3 Hz), 7.50 (d, 2H, J = 9.5 Hz, aromatic), 10.02 (s, 1H, *CHO*). ^{31}P{^{1}H} NMR ($CDCl_3$): δ 22.6 (d, PCl_2), 11.8 (t, P(OR)-Cl), ^2J(P−N−P) = 61.5 Hz. MS(EI): 433 (M^+). Anal. Calcd for $C_7H_5N_3Cl_5O_2P_3$ (433.32): C, 19.40; H, 1.16; N, 9.70. Found: C, 19.16; H, 1.40; N, 9.40.

Preparation of $N_3P_3(3,5\text{-}Me_2Pz)_5(O-C_6H_4$-*p*-CHO) (5). To a mixture of 3,5-dimethyl pyrazole (4.8 g, 50.0 mmol) and triethylamine (5.0 g, 50.0 mmol) in THF (50 mL) was added a solution of **3** (4.3 g, 10.0 mmol) in THF (50 mL) dropwise for 15 min at room temperature. The reaction mixture was stirred at room temperature for 1 h and was subsequently heated under reflux for 8 h. The reaction mixture was allowed to come to room temperature and filtered and the filtrate was stripped off the solvent in vacuo to afford a white solid identified as **5**. This was recrystallized from a mixture of dichloromethane and *n*-hexane (1:2) at 0 °C. Yield: 3.7 g, 50%. Mp: 147−148 °C. IR (KBr) cm^{-1}: 3096(m), 2968(m), 2927(s), 1574(vs), 1503(w), 1463(s), 1431(s), 1411(s), 1371(s),

(14) Tanigaki, T.; Shirai, M.; Inoue, K. *Polym. J.* **1987**, *19*, 881.
(15) Brown, D. M.; Usher, D. A. *J. Chem. Soc.* **1965**, 6558.

1319(s), 1295(vs), 1217(vs), 1184(vs), 1164(vs), 1144(s), 1085(vs), 1022(m), 967(s), 901(m), 828(s), 801(s), 756(s), 659(w), 635(s), 609(vs), 577(m), 512(s), 475(vs). ^{1}H NMR ($CDCl_3$): δ 1.93, 2.04, 2.05, 2.06, 2.13, 2.16 (s, 30H, *CH*$_3$), 5.72 and 5.77 (s, 5H, pyrazolyl *CH*), 7.19−7.79 (m, 4H, aromatic), 9.61 (s, 1H, *CHO*). ^{31}P{^{1}H} NMR ($CDCl_3$): δ 2.3 (t, P(OR)(3,5-Me_2Pz)), 0.1 (d, P(3,5-Me_2Pz)$_2$), ^2J(P−N−P) = 65.5 Hz. MS (FAB): 732 (M^+). Anal. Calcd for $C_{32}H_{40}N_{13}O_2P_3$ (731.67): C, 52.53; H, 5.51; N, 24.89. Found: C, 52.31; H, 5.63; N, 24.72.

Preparation of N_3P_3(3,5-Me_2Pz)$_5$(O−C_6H_4-*p*-CHO).$CuCl_2$ (6). To a solution of **5** (1.0 g, 0.1 mmol) in dichloromethane (50 mL) was added anhydrous cupric chloride (0.2 g, 0.1 mmol), and the mixture was stirred for 24 h at room temperature. This was filtered, and the solvent was removed from the filtrate in vacuo. Copper complex **6** was obtained as a green solid, and it was recrystallized by layering *n*-hexane to a solution of **6** in dichloromethane and keeping the mixture at 0 °C. Yield: 1.0 g, 83%. Mp: 161 °C (d). IR (KBr) cm^{-1}: 3095(vs), 2973(vs), 2926(s), 1702(s), 1597(m), 1574(vs), 1503(w), 1463(m), 1440(w), 1410(m), 1377(m), 1298(vs), 1249(vs), 1189(vs), 1154(vs), 1087(w), 1049(w), 965(vs), 887(w), 589(vs), 563(w), 544(s), 463(w). EPR (CH_2Cl_2/toluene, 1:1, 77 K): $g_{||} = 2.28$; $g_\perp = 2.05$; $A_{||} = 130.5 \times 10^{-4}$ cm^{-1}. UV−vis {$CHCl_3$, [λ_{max}/nm (ϵ_{max}/M^{-1} cm^{-1})]}: 905(198), 372(889), 351(488), 262(2398). Anal. Calcd for $C_{32}H_{40}O_2N_{13}P_3CuCl_2$ (866.12): C, 44.38; H, 4.65; N, 21.02. Found: C, 43.78; H, 4.81; N, 21.23.

Preparation of CPPL. To a solution of **2** (1.0 g, 1.2 mmol) in 1,2-dichloroethane (15 mL) was added 1,4-divinylbenzene (80%, mixture of isomers, 0.4 g, 2.5 mmol) and AIBN (30 mg, 0.2 mmol). The solution was purged with argon for 45 min and was subsequently heated at 80 °C for 36 h. The cross-linked polymer obtained was filtered, washed with toluene (3 × 20 mL), dichloromethane (3 × 20 mL), methanol (3 × 20 mL), and acetone (3 × 20 mL), and dried thoroughly under vacuum at 40 °C. Yield: 1.04 g. IR (KBr) cm^{-1}: 3397(s), 2923(s), 1604(s), 1573(s), 1493(s), 1443(s), 1412(s), 1372(m), 1301(s), 1218(vs), 1089(m), 1023(m), 967(m), 902(m), 824(m), 796(m), 711(w), 597(m), 525(m). Anal. Found: C, 64.98; H, 6.2; N, 9.32. From the nitrogen analysis, it is concluded that every gram of the polymer contains 0.54 g of the cyclophosphazene monomer corresponding to 6.7×10^{-4} mol.

Preparation of CPPL-Cu. To a solution of anhydrous cupric chloride (0.09 g, 0.7 mmol) in ethanol was added CPPL (1.0 g, 0.67×10^{-3} mol), and the mixture was stirred for 24 h. The resulting metalated polymer was washed thoroughly with methanol (5 × 20 mL) to remove any unreacted cupric chloride and dried under vacuum at 40 °C. Yield: 1.2 g. IR (KBr) cm^{-1}: 3420(m), 3020(m), 2923(s), 2853(m), 1649(w), 1603(w), 1570(w), 1492(m), 1454(m), 1418(m), 1374(w), 1240(vs), 1187(vs), 1047(m), 964(w), 903(m), 824(m), 795(m), 709(w), 588(w), 540(w). Anal. Found: C, 55.40; H, 5.21; N, 6.39. From the nitrogen analysis, it is concluded that every gram of the polymer contains 0.33 g of the cyclophosphazene monomer corresponding to 4.09×10^{-4} mol. From the AAS analysis, the amount of copper present per gram of CPPL-Cu was found to be 21.7 mg. EPR (solid, 77 K): $g_{||} = 2.27$; $g_\perp = 2.10$; $A_{||} = 130.5 \times 10^{-4}$cm^{-1}. Diffuse reflectance UV−vis [λ_{max}/nm (absorbance)]: λ_{max} = 845 (0.355), 351 (0.294), 318 (0.891), 304 (0.878), 251 (0.920).

X-ray Crystallography. Colorless crystals of **1** and **2** were grown by dissolving these compounds in hot *n*-hexane and allowing the solutions to cool. Crystals of **6** were grown from a mixture of dichloromethane and *n*-hexane (1:1) at room temperature. All hydrogen atoms were included in idealized positions, and a riding model was used. Non-hydrogen atoms were refined with anisotropic displacement parameters. X-ray data for crystals **1** and **6** were collected on Siemens P4S and SMART APEX CCD (Bruker-AXS) diffractometers, respectively. The structures were solved and refined using the SHELXTL program.[16] Disordered carbon atoms of phenyl and vinyl groups in **1** were found with occupancies of 50% each for C2, C3, C5, C6, C8, C9, C11, C12, C14 and C2a, C3a, C5a, C6a, C8a, C9a, C11a, C12a, C14a. X-ray diffraction data for **2** were collected on an Enraf Nonius FR590 CAD-4 diffractometer. The structure of **2** was solved by using WINGX version 1.63, a crystallographic collective package (L. J. Farrugia, WINGX ver 1.63, An integrated Systems of Windows Programs for the solution, refinement and analysis of single-crystal X-ray diffraction data, Department of Chemistry, University of Glasgow). The structure was solved initially with SIR97 and refined with the SHELX-97[17] package incorporated in WINGX. The structure was refined against F^2 with a full-matrix least-squares algorithm. The X-ray data pertaining to data collection, crystal systems, and structure solution for compounds **1**, **2**, and **6** are summarized in Table 1.

Table 1. Crystallographic Data for Compounds **1**, **2**, and **6**

	1	**2**	**6**[a]
empirical formula	$C_{14}H_{11}Cl_5N_3OP_3$	$C_{39}H_{46}N_{13}OP_3$	$C_{34}H_{44}N_{13}O_2P_3CuCl_6$
fw	507.42	805.80	1035.97
space group	$P2_1/c$	$P2_1/c$	$P\bar{1}$
cryst color	colorless	colorless	green
cryst syst	monoclinic	monoclinic	triclinic
a (Å)	23.442(4)	18.882(5)	12.387(3)
b (Å)	7.7938(17)	11.813(5)	13.374(3)
c (Å)	11.619(3)	19.491(5)	14.833(4)
α (deg)	90	90	99.707(4)
β (deg)	99.264(15)	99.352(5)	101.508(4)
γ (deg)	90	90	98.858(4)
V (Å^3)	2095.2 (8)	4290(2)	2328.3(10)
$\rho_{(calcd)}$ (Mg m^{-3})	1.609	1.248	1.478
Z	4	4	2
μ (mm^{-1})	0.931	0.186	0.963
λ (Å)	0.71073	0.71069	0.71073
temp (K)	293(2)	293(2)	150(2)
GOF	1.024	0.813	1.025
total reflns	3898	9585	11765
indep reflns	3690	4806	8059
R_{int}	0.0272	0.1509	0.0183
R1[b] [$I > 2\sigma(I)$]	0.0490	0.0784	0.0503
wR2[b] [$I > 2\sigma(I)$]	0.1078	0.1546	0.1374

[a] Crystallizes with two molecules of dichloromethane. [b] $R = \sum||F_o| - |F_c||/\sum|F_o|$, $R_w = \{[\sum w(|F_o|^2 - |F_c|^2)^2]/[\sum w(|F_o|^2)^2]\}^{1/2}$.

Kinetic Studies. General. Hydrolytic reactions were performed in duplicate in centrifuge tubes containing 3 mL of solution of the substrate prepared in 0.01 M *N*-ethylmorpholine (pH 8.0) in 50% aqueous methanol. Methanol was used in the reaction solvent to ensure optimum wetting of the hydrophobic catalyst. The amount of polymer was 1 mg/mL of the buffer, corresponding to 0.34 mM of copper, if the polymer were to be completely soluble in the buffer. The concentration calculated in this manner was used to estimate k_{cat}. This is quite reasonable as only coordinated copper ions promote phosphate ester hydrolysis and the rest of the polymer matrix merely acts as a scaffold for coordination. In short, this derivation results in *apparent* kinetic parameters. The rate of hydrolysis was followed by monitoring the appearance of *p*-nitrophenolate anion ($\epsilon_{400} = 1.65 \times 10^4$ M^{-1} cm^{-1}). To correct for autohydrolysis of the substrates, the rate of each reaction was measured against a reference cell, which was identical in composi-

(16) Sheldrick, G. M. *SHELXTL, An Integrated System for Solving, Refining and Displaying Crystal Structures from Diffraction Data;* University of Gottingen: Gottingen, Germany, 1991.
(17) Sheldrick, G. M. *SHELX-97, Program for Crystal Structure Refinement;* University of Gottingen: Gottingen, Germany, 1997.

Scheme 1

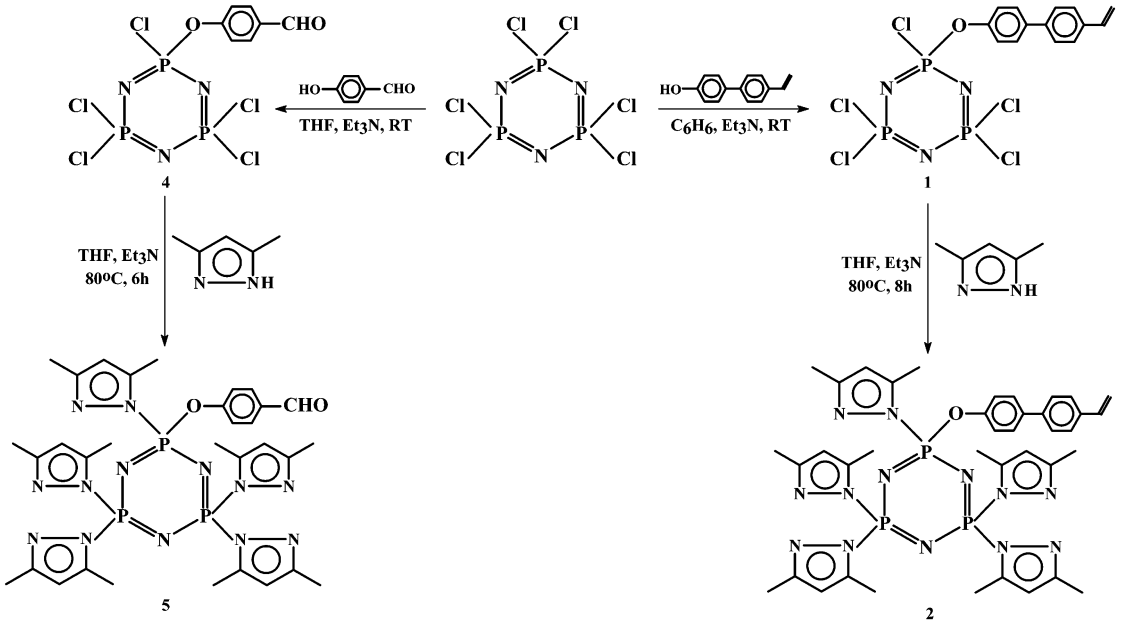


Table 2. Concentrations Used for the Calculation of Michaelis Constants and k_{obs} Values in the Hydrolysis of pNPP, bNPP, and hNPP by CPPL-Cu

substrate	concentration range of the substrate[a]	concentration of the substrate[b]
pNPP	0.10−0.60	2.00
bNPP	0.50−2.00	2.00
hNPP	0.10−0.80	5.00

[a] Used for the calculation of V_{max}, K_m, and k_{cat}, [S] mM. [b] Used for the calculation of k_{obs}, [S] mM.

tion except lacking the catalyst. The hydrolyses of pNPP and bNPP were performed at 30 °C while that of hNPP was performed at 35 °C. The concentrations used for the hydrolysis of the phosphate esters are summarized in Table 2. The initial velocities (V_i's) were determined from concentration versus time plots, and pseudo-first-order rate constants were determined from $\ln A_\infty/A_\infty - A_t$ versus time plots. Michaelis−Menten kinetic parameters such as K_m, k_{cat}, and V_{max} have also been determined from the corresponding Lineweaver−Burk plot ($1/V_i$ vs 1/[S]). Reactions were monitored to less than 10% conversion of substrate to product. In addition to these general kinetic investigations, the hydrolysis of bNPP was carried out under various other conditions. The assay used in these studies is the same as that described vide supra except that the concentration of bNPP was 2.0 mM.

pH and Solvent Dependence on Hydrolysis. Solutions with varying pHs ranging from 7.2 to 8.9 were prepared by using *N*-ethylmorpholine. Pseudo-first-order constants for the hydrolysis of bNPP at these pHs were determined, and a pH versus k_{obs} plot was generated.

Hydrolysis of bNPP by CPPL-Cu was carried out in water, ethylene glycol, and 50% aqueous ethylene glycol at pH 8.0. Initial rates were calculated for each solvent system.

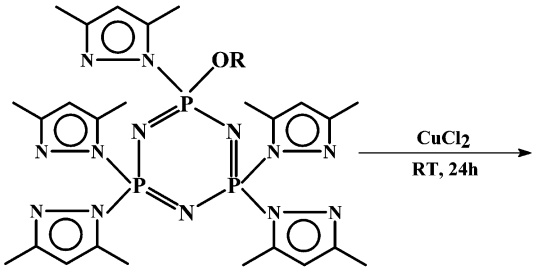
Monitoring of Hydrolysis Products of hNPP by ^{31}P NMR. The hydrolysis of 3.0 mM solutions of hNPP in *N*-ethylmorpholine buffer at pH 8.0 with 0.34 mM of the catalyst was investigated by $^{31}P\{^1H\}$ NMR at 30 °C. The reaction was followed by monitoring the appearance of the signal at 18.5 ppm corresponding to the cyclic phosphate formed after the release of *p*-nitrophenolate anion (this chemical shift value is with respect to 85% H_3PO_4 in 50% aqueous methanol buffer as the external standard).

Results and Discussion

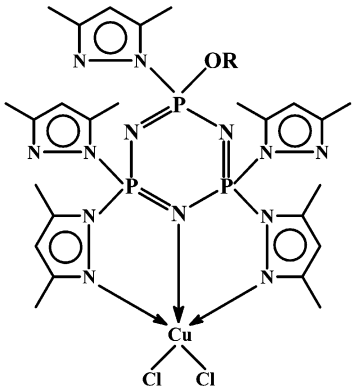
Synthetic and Spectroscopic Aspects of Cyclophosphazene Derivatives 1−6. Hybrid inorganic−organic polymers containing an organic backbone and a cyclophosphazene moiety as the pendant group can be assembled from an appropriate cyclophosphazene monomer, which contains a polymerizable vinyl functional group. Allen and others have shown that the most suitable monomers are those where a spacer separates the vinyl group from the cyclophosphazene.[8d] The spacer minimizes the σ-electron withdrawing effect of the cyclophosphazene ring on the vinyl group as well as enables a reduction of the steric encumbrance about it. Keeping this in view, we have prepared $N_3P_3Cl_5(O{-}C_6H_4\text{-}p\text{-}C_6H_4\text{-}p\text{-}CH{=}CH_2)$ (**1**) which has previously been shown by Inoue[8j−l] and us[8f] to be an excellent monomer in terms of its ease of preparation, hydrolytic stability, and ready polymerizability. An additional advantage of this monomer is the presence of five reactive P−Cl bonds, which can be readily replaced by a variety of nucleophiles. Using this feature, we prepared pyrazolyl derivative $N_3P_3(3,5\text{-}Me_2Pz)_5(O{-}C_6H_4\text{-}p\text{-}C_6H_4\text{-}p\text{-}CH{=}CH_2)$ (**2**) in excellent yield by the reaction of **1** with 3,5-dimethylpyrazole in the presence of triethylamine as the hydrogen chloride scavenger (Scheme 1). Previously, we and others have shown that pyrazolyl cyclophosphazenes such as $N_3P_3(3,5\text{-}Me_2Pz)_6$ or *gem*-$N_3P_3Ph_2(3,5\text{-}Me_2Pz)_4$ are extremely versatile multisite coordination ligands toward several types of transition metal ions as well as metal carbonyls such as $Mo(CO)_6$.[18] In view of this proven coordination behavior of these ligands, we have

(18) (a) Chandrasekhar, V.; Nagendran, S. *Chem. Soc. Rev.* **2001**, *30*, 193. (b) Thomas, K. R. J.; Chandrasekhar, V.; Vivekanandan, K.; Senthil Andavan, G. T.; Nagendran, S.; Kingsley, S.; Teikink, E. R. T. *Inorg. Chim. Acta*. **1999**, *286*, 127. (c) Koo, B. H.; Byun, Y.; Hong, E.; Kim, Y.; Do, Y. *Chem. Commun*. **1998**, 1227. (d) Thomas, K. R. J.; Tharmaraj, P.; Chandrasekhar, V.; Bryan, C. D.; Cordes, A. W. *Inorg. Chem*. **1994**, *33*, 5332. (e) Thomas, K. R. J.; Chandrasekhar, V.; Pal, P.; Scott, S. R.; Hallford, R.; Cordes, A. W. *Inorg. Chem.* **1993**, *32*, 606.

Scheme 2



2 R = -C_6H_4-*p*-C_6H_4-*p*-CH=CH_2
5 R = -C_6H_4-*p*-CHO



3 R = -C_6H_4-*p*-C_6H_4-*p*-CH=CH_2
6 R = -C_6H_4-*p*-CHO

chosen to incorporate the pyrazolyl moiety in monomer **2**. Ligand **2** readily reacts with copper(II) chloride to afford the 1:1 complex N_3P_3(3,5-Me_2Pz)$_5$(O—C_6H_4-*p*-C_6H_4-*p*-CH=CH_2)·$CuCl_2$ (**3**) (Scheme 2). However, we were unable to obtain suitable crystals of this compound. To prove the structure of **3** beyond any reasonable doubt, we prepared structurally analogous compound N_3P_3(3,5-Me_2Pz)$_5$(O—C_6H_4-*p*-CHO)·$CuCl_2$ (**6**) in a three-step synthesis starting from $N_3P_3Cl_6$ (Schemes 1 and 2) and determined its X-ray structure (vide infra). Compounds **1**, **2**, **4**, and **5** show prominent parent ion peaks in their FAB or EI mass spectra. However, compound **3** shows the $M^+ - Cl$ peak as the highest mass peak.

The $^{31}P\{^1H\}$ NMR spectra of $N_3P_3Cl_5$(O—C_6H_4-*p*-C_6H_4-*p*-CH=CH_2) (**1**), N_3P_3(3,5-Me_2Pz)$_5$(O—C_6H_4-*p*-C_6H_4-*p*-CH=CH_2) (**2**), $N_3P_3Cl_5$(O—C_6H_4-*p*-CHO) (**4**), and N_3P_3(3,5-Me_2Pz)$_5$(O—C_6H_4-*p*-CHO) (**5**) are of the AX_2 type consistent with their structures. The structures of **1** and **2** have been further confirmed by X-ray crystallography (vide infra). An interesting feature of the $^{31}P\{^1H\}$ NMR spectra is that both the A and the X region are considerably upfield shifted in the pyrazolyl derivatives in comparison to the chloro precursors. Thus, in compounds **1** and **4**, a doublet is seen corresponding to δ PCl_2 at 22.5 and 22.6 ppm, respectively, while a triplet corresponding to δ PCl(OR) is seen at 12.3 and 11.8 ppm. These chemical shifts move upfield in compounds **2** and **5**: 0.2 and 0.1 ppm (doublet), 3.0 and 2.3 ppm (triplet). Such chemical shift changes have been previously noted in the conversion of $N_3P_3Cl_6$ (singlet, 19.3 ppm) to N_3P_3(3,5-Me_2Pz)$_6$ (singlet, −3.4 ppm).[18e]

Copper complexes **3** and **6** are nonionic in solution, and magnetic moment data are unexceptional. The UV−vis spectra of **3** and **6** show intense high-energy absorptions and weak low-energy absorptions. The latter, which occur at 897 nm for **3** and 905 nm for **6**, are attributed to the d−d transition. These values are comparable to that found for N_3P_3(3,5-Me_2Pz)$_6$·$CuCl_2$.[18e] The high-energy absorptions are due to intra-pyrazole $\pi-\pi^*$ as well as π_1(pyrazole) → Cu(II) and π_2(pyrazole) → Cu(II) charge-transfer bands. In these compounds, the Cl → Cu(II) charge-transfer band is buried in the absorption at 262 and 283 nm for **3** and **6**, respectively. These assignments are based on the pioneering work of Schugar and co-workers and our results on several pyrazolyl cyclophosphazene−metal complexes.[18,19] The infrared spectra of ligands **2** and **5** show strong P=N stretching frequencies at 1220 and 1218 cm^{-1}, respectively. In copper complexes **3** and **6**, the parent P=N stretching frequency is split, and two sets of peaks are seen for each compound: 1243 and 1191 cm^{-1} for **3**, 1249 and 1189 cm^{-1} for **6**, respectively. Metalation or protonation of the ring nitrogen atom of the cyclophosphazene rings is known to cause such a splitting of the P=N stretching frequency.[20]

The EPR spectra of copper complexes **3** and **6** have been recorded in solution at room and liquid nitrogen temperatures. The spectra at room temperature are not informative. However, at 77 K, spectra of axial symmetry are obtained with $g_{\|} > g_{\perp}$. Thus, the $g_{\|}$ values for **3** and **6** are 2.28 and 2.24 while the corresponding $g_{\perp}$ values are 2.05 and 2.06, respectively. The $A_{\|}$ values for these compounds are 130.5 $\times 10^{-4}$ cm^{-1} and 122.0 $\times 10^{-4}$ cm^{-1}, respectively. These EPR parameters are very similar to that observed for N_3P_3(3,5-Me_2Pz)$_6$·$CuCl_2$.[18e] This, along with the similarity of optical spectral features, suggests that in all of these compounds the coordination environment and geometry around Cu(II) are very similar. This estimate has been confirmed by the X-ray structure of **6**.

X-ray Structures of 1 and 2. The X-ray structural determination of compounds **1** and **2** confirms the assignment of their structures from spectroscopic data. The ORTEP diagrams of these compounds along with the important metric parameters are given in Figures 1 and 2. The cyclophosphazene ring in compounds **1** and **2** is nearly planar. The P−N bond lengths in **1** are similar and range from 1.565 to 1.579 Å. The P−N−P angles are about 121° while the angles at phosphorus are slightly smaller. These metric parameters are comparable to those observed in other related monosubstituted cyclophosphazenes such as $N_3P_3Cl_5$($OC_6H_3Cl_2$-2,6).[21] The endocyclic P−N bond lengths in the pyrazolyl derivative **2** are slightly longer than those found for **1** and range from 1.556 to 1.583 Å. The shorter bond length is associated with P−N bonds adjacent to P(3,5-Me_2Pz)(OR) while the longer

(19) Bernarducci, E.; Schwindinger, W. F.; Hughey, J. L., IV; Krogh-Jespersen, J.; Schugar, H. J. *J. Am. Chem. Soc.* **1981**, *103*, 1686.
(20) (a) Krishnamurthy, S. S.; Sau, A. C.; Woods, M. *Adv. Inorg. Chem. Radiochem.* **1978**, *21*, 41. (b) Chandrasekhar, V.; Thomas, K. R. J. *Struct. Bonding (Berlin)* **1993**, *81*, 41. (c) Chandrasekhar, V.; Krishnan, V. *Adv. Inorg. Chem.*, in press.
(21) Allcock, H. R.; Ngo, D. C.; Parvez, M.; Visscher, K. *J. Chem. Soc., Dalton Trans.* **1992**, 1687.

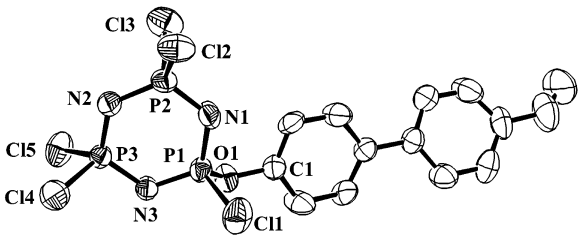


Figure 1. ORTEP diagram of compound **1**. Hydrogen atoms have been omitted for clarity. The important distances (Å) and bond angles (deg) are the following: P(1)−N(1) 1.575(4), P(1)−N(3) 1.574(4), P(2)−N(1) 1.577(4), P(2)−N(2) 1.579(4), P(3)−N(2) 1.565(4), P(3)−N(3) 1.577(4), P(1)−Cl(1) 1.997(2), P(2)−Cl(2) 1.9825(9), P(1)−O(1) 1.571(3), N(1)−P(1)−N(3) 118.4(2), N(1)−P(2)−N(2) 118.6(2), N(2)−P(3)−N(3) 118.6(2), P(1)−N(1)−P(2) 121.4(2), P(2)−N(2)−P(3) 121.1(3), P(1)−N(3)−P(3) 121.0(3), O(1)−P(1)−Cl(1) 103.09(15), Cl(2)−P(2)−Cl(3) 101.43 (8).

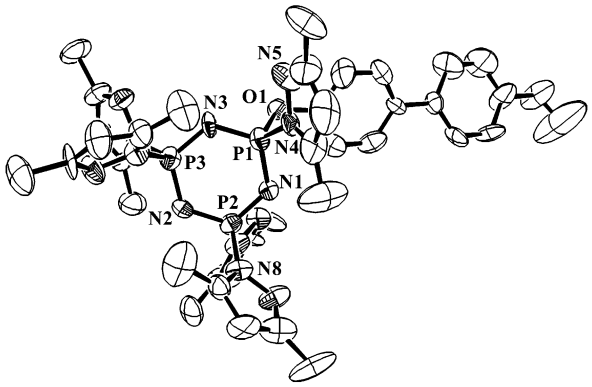


Figure 2. ORTEP diagram of compound **2**. Hydrogen atoms are omitted for clarity. The relevant bond distances (Å) and bond angles (deg) are the following: P(1)−N(1) 1.583(10), P(1)−N(3) 1.588(4), P(2)−N(1) 1.562(4), P(2)−N(2) 1.558(4), P(3)−N(2) 1.582(4), P(3)−N(3) 1.556(11), P(1)−O(1) 1.577(10), P(1)−N(4) 1.667(4), P(2)−N(8) 1.680(12), N(1)−P(1)−N(3) 116.8(6), N(1)−P(2)−N(2) 117.8(6), N(3)−P(3)−N(2) 117.2(7), P(1)−N(1)−P(2) 122.2(2), P(2)−N(2)−P(3) 122.7(8), P(1)−N(3)−P(3) 122.7(8), N(6)−P(2)−N(8) 100.7(6), P(1)−N(4)−N(5) 113.7(11), O(1)−P(1)−N(4) 103.4(6).

bond lengths are associated with P−N bonds adjacent to $P(3,5\text{-}Me_2Pz)_2$. The endocyclic bond angles at nitrogen and phosphorus in **2** are unexceptional.

X-ray Structure of 6. The ORTEP diagram of **6**, along with the important metric parameters, is given in Figure 3. The cyclophosphazene ligand functions in the non-gem N_3 mode.[18d,e] The coordination to Cu(II) occurs through two pyridinic atoms N(5) and N(9) of the nongeminal 3,5-dimethylpyrazolyl substituents on P(1) and P(3) of the cyclophosphazene ring and the ring nitrogen atom N(1). The chlorides take up the other two coordination sites around the metal atom. The geometry around the copper atom is distorted trigonal bipyramidal; the two chlorides and the cyclophosphazene ring nitrogen atom (N(1)) occupy the equatorial positions while the pyrazolyl pyridinic nitrogen atoms (N(5) and N(9)) take up the axial positions. The distortion of geometry around the copper is a result of the steric constraints of the ligand in this coordination mode. Thus, the axial N(9)−Cu(1)−N(5) angle is 161.08(12)° while the equatorial angles N(1)−Cu(1)−Cl(2), N(1)−Cu(1)−Cl(1), and Cl(1)−Cu(1)−Cl(2) are 107.96(8)°, 106.49(7)°, and 145.34(5)°. The Cu(1)−N(1) bond distance is 2.295(3) Å while the Cu(1)−N(5) and Cu(1)−N(9) distances are

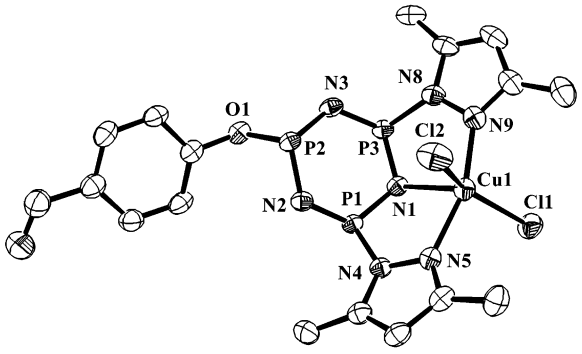


Figure 3. ORTEP diagram of compound **6**. All hydrogen atoms and the 3,5-dimethyl pyrazolyl groups, which are not involved in the coordination, are removed for clarity. The important bond lengths (Å) and bond angles (deg) are the following: Cu(1)−N(9) 1.993(3), Cu(1)−N(5) 2.010(3), Cu(1)−N(1) 2.295(3), Cu(1)−Cl(1) 2.2501(11), Cu(1)−Cl(2) 2.2764 (10), P(1)−N(1) 1.594(3), P(1)−N(2) 1.572(3), P(2)−N(2) 1.580(3), P(2)−N(3) 1.590(3), P(3)−N(1) 1.598(3), P(3)−N(3) 1.569(3), P(2)−O(1) 1.586(2), P(1)−N(4) 1.693(3), P(3)−N(8) 1.685(3), N(9)−Cu(1)−N(5) 161.08(12), N(9)−Cu(1)−Cl(1) 97.40(9), N(5)−Cu(1)−Cl(1) 93.13(8), N(9)−Cu(1)−Cl(2) 91.53(8), N(5)−Cu(1)−Cl(2) 88.64(8), Cl(1)−Cu(1)−Cl(2) 145.34(5), N(9)−Cu(1)−N(1) 81.03(11), N(5)−Cu(1)−N(1) 80.93(11), Cl(1)−Cu(1)−N(1) 106.49(7), Cl(2)−Cu(1)−N(1) 107.96(8), P(1)−N(1)−Cu(1) 110.60(14), P(3)−N(1)−Cu(1) 110.93(14), N(2)−P(1)−N(1) 118.59(14), N(2)−P(2)−N(3) 117.77(15), N(3)−P(3)−N(1) 118.15(15), P(1)−N(1)−P(3) 117.80(17), P(1)−N(2)−P(2) 120.72(15), P(3)−N(3)−P(2) 122.04(18), O(1)−P(2)−N(3) 104.59(14), N(3)−P(2)−N(12) 111.62(15).

2.010(3) and 1.993(3) Å, respectively. The cyclophosphazene ring in **6** is nonplanar with the atoms N(1) and P(1) being displaced from the mean plane of the cyclophosphazene ring by +0.15 and −0.13 Å, respectively. The P−N bond lengths within the cyclophosphazene ring are not equal: thus, the distances flanking the site of coordination P(1)−N(1) and P(3)−N(1) are 1.594(3) and 1.598(3) Å while P(1)−N(2) and P(3)−N(3) are 1.572(3) and 1.569(3) Å. The N−P−N and P−N−P bond angles within the cyclophosphazene ring range from 117° to 122°. The coordination behavior observed in **6** closely resembles that found in other Cu(II) complexes of pyrazolyl cyclophosphazenes including $N_3P_3(3,5\text{-}Me_2Pz)_6 \cdot CuCl_2$.[18a,e]

A closer inspection of the X-ray structure of **6** reveals interesting intermolecular C−H···Cl secondary interactions (Figure 4). The metric parameters involved in these interactions are within the norms for C−H···Cl hydrogen bonds. An analysis of such interactions has been performed recently, and it has been concluded that C−H···Cl−M interactions behave as hydrogen bonds.[22] Thus, the chlorine atom [Cl(1)] is involved in hydrogen bonding to two different hydrogen atoms of two neighboring molecules, viz., to H(27) of the aromatic substituent of a neighboring molecule and H(12) of the pyrazolyl substituent of another neighboring molecule. These interactions lead to the formation of a sheet type structural arrangement in the solid-state. This array comprises two alternating macrocylic rings, a 24-membered ring A and a 12-membered ring B.

Polymeric Ligand CPPL and Metalated Polymer CPPL-Cu. Monomer **2** has been copolymerized in the presence of divinylbenzene to afford cross-linked polymer CPPL (Scheme

(22) Thallapally, P. K.; Nangia, A. *CrystEngComm* **2001**, 27.

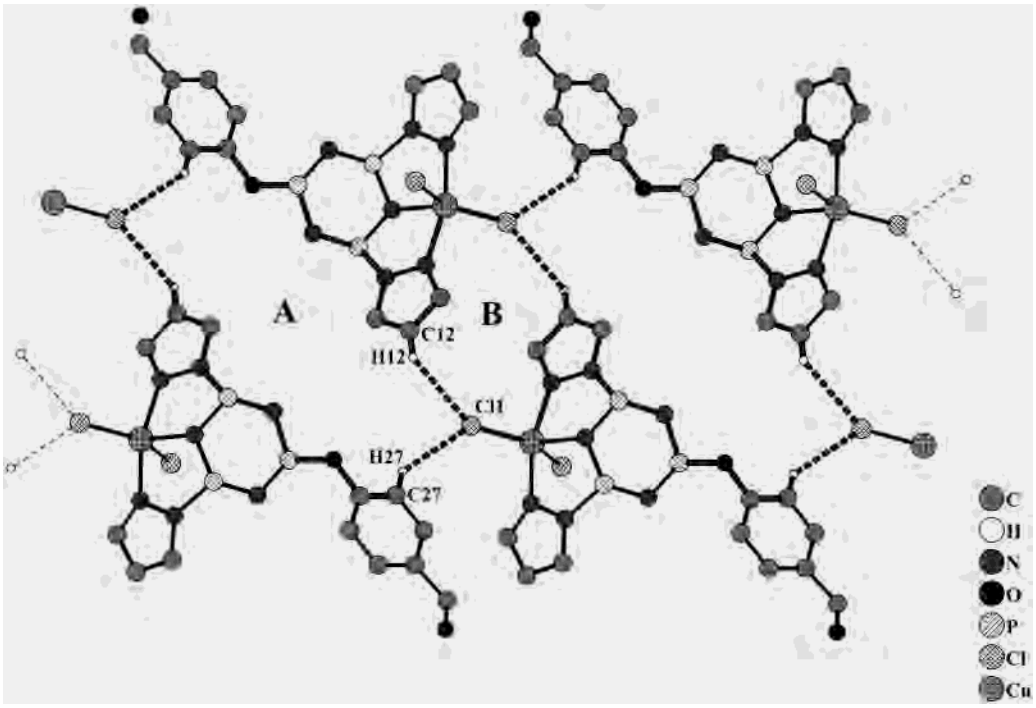


Figure 4. DIAMOND view of hydrogen bonding present in compound **6**. 3,5-Dimethyl pyrazolyl groups, which are not involved in the coordination, have been omitted. Methyl substituents on the *coordinating* pyrazole groups have also been omitted. Also, all hydrogen atoms except those that are involved in C−H···Cl hydrogen bonding have been omitted for clarity. The important bond lengths (Å) and bond angles (deg) are the following: (a) for C(12)−H(12)···Cl(1), C−H 0.950(5), H···Cl 2.842(7), C−Cl 3.525(9), C−H···Cl 129.66(25), and the symmetry is $2 - x, 1 - y, 1 - z$; (b) for C(27)−H(27)···Cl(1), C−H 0.950(5), H···Cl 2.836, C−Cl 3.638(9), C−H···Cl 142.74(24), and the symmetry is $-1 + x, y, z$.

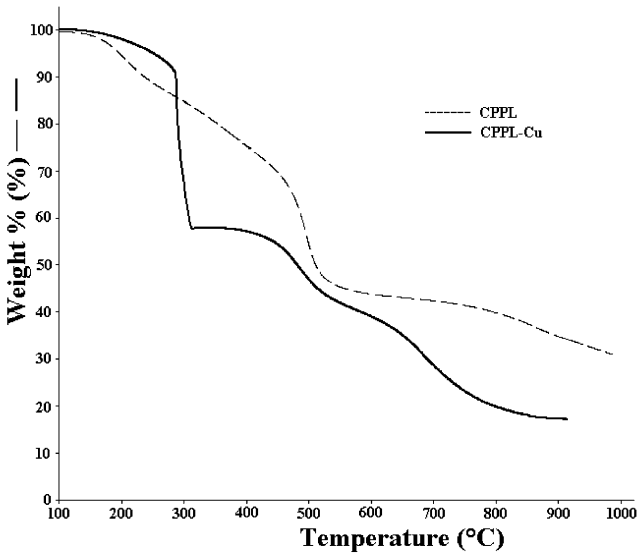
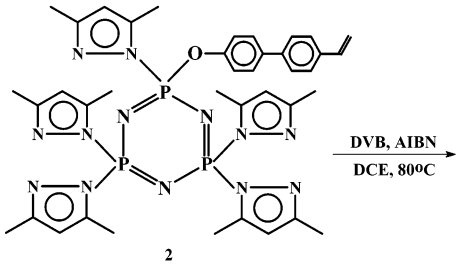


Figure 5. TGA curve for CPPL (- -) and CPPL-Cu (−).

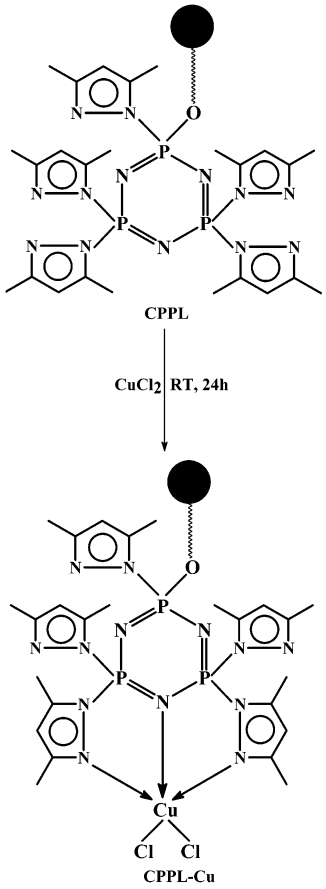
3). From the nitrogen analysis of this polymer, it is concluded that every gram of the polymer contains 0.54 g of the cyclophosphazene moiety. The IR spectrum of CPPL shows the characteristic P═N stretching frequency at 1216 cm^{-1}. This value is relatively unchanged with respect to monomer **2** suggesting that the cyclophosphazene unit remains intact in the cross-linked polymer. The TGA trace of this polymer shows that it gives a char yield of nearly 31% even at 1000 °C (Figure 5). The polymer undergoes a slow degradation from 170 °C up to 474.8 °C. At this point, the char yield is 69.3%. A relatively sharp degradation occurs from 475 °C to 523 °C. After this, the polymer virtually remains unchanged. Metalation of CPPL with copper(II) chloride occurs readily to afford metalated polymer CPPL-Cu (Scheme 3). To ensure that the material does not have any unreacted copper(II) chloride, CPPL-Cu was washed several times with methanol and dried until reproducible and consistent copper analysis could be obtained from atomic absorption spectra. The diffuse reflectance spectrum of CPPL-Cu shows peaks at 845, 351, 318, 304, and 251 nm. Similar to the data for compounds **3** and **6**, the low-energy peak is assigned to the d−d transition while the high-energy peaks correspond to intra-pyrazole $\pi-\pi^*$ and other LMCT transitions. The infrared spectrum of CPPL-Cu shows that the P═N stretching frequency is split and two peaks at 1240 and 1186 cm^{-1} are seen. This is very similar to the changes observed upon metalation of cyclophosphazene ligands **2** and **5** (vide supra). The EPR spectrum of CPPL-Cu at 77 K is of the axial type, and the parameters obtained, viz., $g_{\|} = 2.27$, $g_{\perp} = 2.10$, and $A_{\|} = 130.5 \times 10^{-4}$ cm^{-1}, are very similar to those found for copper(II) complexes **3** and **6**. In view of the close similarity of the IR, optical, and EPR spectra of CPPL-Cu with those of **3** and **6**, we believe that the same type of coordination environment and geometry is present for the copper atoms in all of these systems. The TGA curve of CPPL-Cu shows a final char yield of 17% at 950 °C (Figure 5). The polymer undergoes a three-step degradation. An initial weight loss occurs from 281 to 312 °C followed by a slow and continuous degradation from 437 to 545 °C. The final degradation occurs from 673 to 824 °C. The nature of the degraded products has not been investigated.

Hydrolysis Studies of pNPP, bNPP, and hNPP with CPPL-Cu. To screen the utility of CPPL-Cu on phospho-

Scheme 3

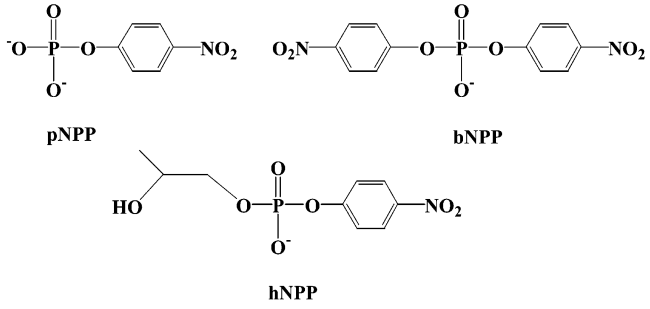


2



esterase activity, the hydrolysis reactions of three model substrates, *p*-nitrophenyl phosphate (pNPP), bis(*p*-nitrophenyl)phosphate (bNPP), and 2-hydroxypropyl-*p*-nitrophenyl phosphate (hNPP), (Scheme 4) were studied. While pNPP is a model for phosphomonoester, bNPP acts as a phosphodiester substrate. Both of these are examples where the hydrolytic reaction is triggered in an intermolecular manner by an external nucleophile. hNPP is a phosphodiester and is also a model for RNA in that the 2′-OH position of the latter is structurally mimicked. Our results on this substrate show an *intramolecular* hydrolytic reaction, through the activation of an internal hydroxyl group (vide infra). The hydrolyses of all the three substrates pNPP, bNPP, and hNPP in the presence of CPPL-Cu were followed in 50% aqueous methanol/0.01 M *N*-ethylmorpholine buffer at pH 8.0 by the time-dependent release of *p*-nitrophenolate anion at 400 nm. Attempts to use copper complex **3** or **6** as homogeneous catalysts for the previous reactions did not succeed as these complexes decomposed during the hydrolysis reaction conditions. The hydrolytic instability of simple cyclophosphazene metal complexes has been documented.[18e,23]

Scheme 4



pNPP bNPP hNPP

Table 3. Pseudo-First-Order Rate Constants and k_{rel} Values for the Hydrolysis of pNPP, bNPP, and hNPP[a]

substrate	k_{obs} (min^{-1})	k_{rel} (k_{obs}/k_{uncat})
pNPP	4.42×10^{-4}	8.98×10^{2}
bNPP	2.19×10^{-4}	2.81×10^{5}
hNPP	5.31×10^{-3}	2.68×10^{3}

[a] Hydrolytic reactions were performed in duplicate containing 3 mL of solution of the substrate prepared in 0.01 M *N*-ethylmorpholine (pH 8.0) in 50% aqueous methanol. The amount of catalyst used was 1 mg/mL of the buffer, corresponding to 0.34 mM of copper, if the polymeric catalyst were to be completely soluble in the buffer. The hydrolyses of pNPP and bNPP were performed at 30 °C while that of hNPP was performed at 35 °C. The concentrations of the phosphate esters used for this study are summarized in Table 2.

Rate constants for the hydrolysis of all these substrates by CPPL-Cu were determined under pseudo-first-order conditions. The hydrolysis proceeds with considerable rate enhancement relative to that of the uncatalyzed[24] reaction for all three substrates. We have carried out control experiments with unmetalated cross-linked polymer CPPL under the same conditions as those described, and no phosphate ester hydrolysis was observed. Further, enhancement in the hydrolytic reaction rates was not observed when the substrates were incubated in the buffer alone in the absence of a catalyst or even in the presence of simple copper(II) chloride.

For the hydrolysis reaction of all the three substrates by CPPL-Cu, pseudo-first-order rate constants (k_{obs}) were determined from $\ln A_\infty/A_\infty - A_t$ versus time plots (Table 3). The k_{obs} values obtained are 4.42×10^{-4}, 2.19×10^{-4}, and 5.31×10^{-3} min^{-1} for pNPP, bNPP, and hNPP, respectively. The k_{rel} values, which represent the actual enhancement of the rate of hydrolysis relative to the uncatalyzed reactions for these substrates, are 8.98×10^2, 2.81×10^5, and 2.68×10^3, respectively. Thus, there is significant rate enhancement for all three substrates with the highest rate enhancement being seen for bNPP hydrolysis. Although for homogeneously catalyzed reactions higher rate enhancements have been observed previously, the data obtained in the present study are comparable with other heterogeneous polymeric systems studied recently.[12] Thus, Verma and co-workers[12a]

(23) Chandrasekaran, A.; Krishnamurthy, S. S.; Nethaji, M. *Inorg. Chem.* **1994**, *33*, 3085.
(24) (a) Vance, D. H.; Czarnik, A. W. *J. Am Chem. Soc.* **1993**, 115, 12165. (b) Breslow, R.; Huang, D. L. *Proc. Natl. Acad. Sci. U.S.A.* **1991**, 88, 4080.

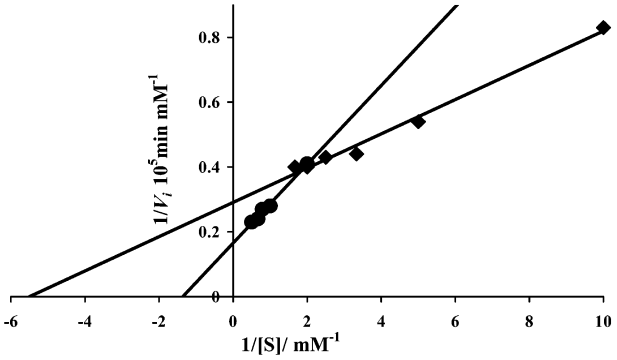


Figure 6. Lineweaver−Burk plots for pNPP (■) and bNPP (●) hydrolysis by CPPL-Cu. These experiments were carried out at pH 8.0 and at 30 °C. The other experimental conditions relating to the data plotted in this figure are summarized in Table 4.

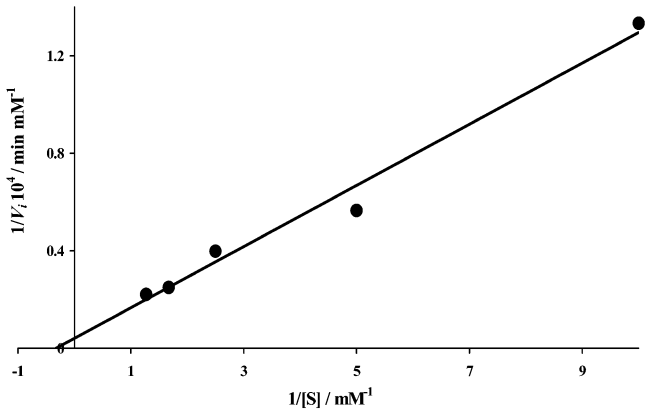


Figure 7. Lineweaver−Burk plot for hNPP hydrolysis by CPPL-Cu. These experiments were carried out at pH 8.0 and at 35 °C. The other experimental conditions relating to the data plotted in this figure are summarized in Table 4.

have shown that an adenine-containing metalated polymeric resin exhibits a rate enhancement (k_{rel}) of 4.8×10^5 for bNPP hydrolysis.

To demonstrate that the catalysis is due to the copper contained in the cross-linked polymer and not because of leached out metal ion species, the following tests were carried out. First, catalyst CPPL-Cu was filtered after 6 h of reaction, and the release of *p*-nitrophenolate anion for the hydrolysis of bNPP in the filtrate was monitored for a further period of 36 h. The reaction was completely arrested, and no further formation of the hydrolytic product was observed (Supporting Information). Second, AAS analysis of *used* and *fresh* CPPL-Cu confirmed that the metal does not leach out during the course of the catalytic reaction as indicated by the invariance of the copper content in both the samples. Third, *used* CPPL-Cu catalyst could be separated from the reaction mixture, washed, dried, and recycled without affecting the rates of hydrolysis (vide infra). Thus, cross-linked polymer CPPL not only provides a multisite coordinating medium for the preparation of a metal complex but also imparts hydrolytic stability to the complex so formed. Although it is speculative, the hydrolytic stability of CPPL-Cu probably arises because of the cross-linked nature of the polymer which shields the P−N (pyrazolyl) bonds effectively.

Detailed kinetic studies were carried out for the purpose of evaluating Michaelis−Menten kinetic parameters K_m, V_{max}, and k_{cat} for all the substrates from the corresponding Lineweaver−Burk plots, ($1/V_i$) versus 1/[S] (Figures 6 and 7). The K_m values obtained are 0.18 (pNPP), 0.74 (bNPP), and 3.11 mM (hNPP), respectively. The corresponding k_{cat} values are 1.02×10^{-4}, 1.76×10^{-4}, and 6.80×10^{-3} min^{-1}, respectively. The V_{max} values found for the hydrolysis of these substrates are 3.44×10^{-5}, 6.05×10^{-5}, and 2.48×10^{-3} mM min^{-1}. All of these parameters are summarized in Table 4.

The effect of temperature on the rate of hydrolysis of bNPP was studied. Pseudo-first-order rate constants were obtained at four different temperatures, viz., 30, 40, 50, and 60 °C. The steady increase in k_{obs} even at higher temperatures is indicative of the stability of CPPL-Cu under these conditions (Table 5). Arrhenius parameters E_a and A were obtained from the plot of ln k_{obs} versus $1/T$ (Figure 8). The energy of activation was found to be 13.71 kcal mol^{-1}, while the frequency factor A was 2.18×10^6 min^{-1}. These parameters are comparable to those obtained from a recently studied heterogeneous Cu(II) catalyst in the hydrolysis of phosphodiester substrates.[12a]

Table 4. Michaelis Constants, Maximal Velocities, and k_{cat} Values for the Hydrolysis of pNPP, bNPP, and hNPP[a]

substrate	K_m (mM)	V_{max} (mM min^{-1})	k_{cat} (min^{-1})
pNPP	0.18	3.44×10^{-5}	1.02×10^{-4}
bNPP	0.74	6.05×10^{-5}	1.76×10^{-4}
hNPP	3.11	2.48×10^{-3}	6.80×10^{-3}

[a] Hydrolysis was performed in duplicate containing 3 mL of solution of the substrate prepared in 0.01 M *N*-ethylmorpholine (pH 8.0) in 50% aqueous methanol. The amount of the polymeric catalyst was 1 mg/mL of the buffer. This corresponds to 0.34 mM of copper, if the polymeric catalyst were to be completely soluble in the buffer. The hydrolyses of pNPP and bNPP were performed at 30 °C, while that of hNPP was performed at 35 °C. Ranges of concentrations of the substrates were used for the hydrolysis, and these are summarized in Table 2.

Table 5. Temperature Dependence on the Hydrolysis of bNPP by CPPL-Cu[a]

T (K)	$k_{obs} \times 10^{-4}$ min^{-1}	relative increase in k_{obs}[b]
303	2.19	
313	7.85	3.59
323	12.26	1.56
333	18.75	1.53

[a] Hydrolytic reactions were performed in duplicate containing 3 mL of solution of bNPP prepared in 0.01 M *N*-ethylmorpholine (pH 8.0) in 50% aqueous methanol. The amount of the polymeric catalyst was 1 mg/mL of the buffer, and the substrate concentration was 2.0 mM. [b] For a 10 °C increase in reaction temperature.

pH Dependence and Solvent Effect Studies. The effect of pH on the hydrolytic activity of CPPL-Cu was investigated using bNPP and hNPP as the substrates in the pH range 7.0−9.0. The pH−rate profile for bNPP is slightly complicated and shows that there is an increase in the rate constant of hydrolysis with an increase in pH up to pH 8.0. The rate constant slightly drops thereafter and becomes nearly constant in the pH range 8.4−9.0 (Figure 9). This kind of a pH profile has also been observed in other instances involving phosphate ester hydrolysis where an increase in the rate of hydrolysis with pH was attributed to the ease of deprotona-

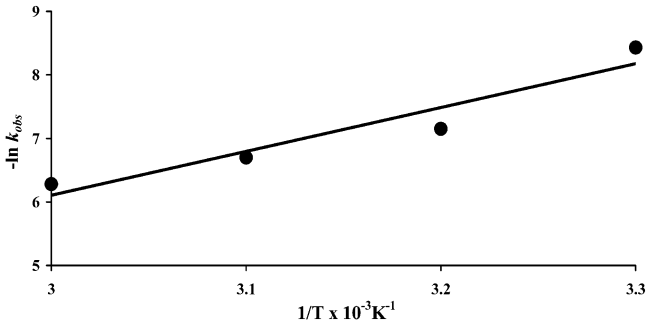


Figure 8. Plot of $-\ln k_{obs}$ versus $1/T$ for the hydrolysis of bNPP by CPPL-Cu. These experiments were carried out at pH 8.0. The other experimental conditions relating to the data plotted in this figure are summarized in Table 5.

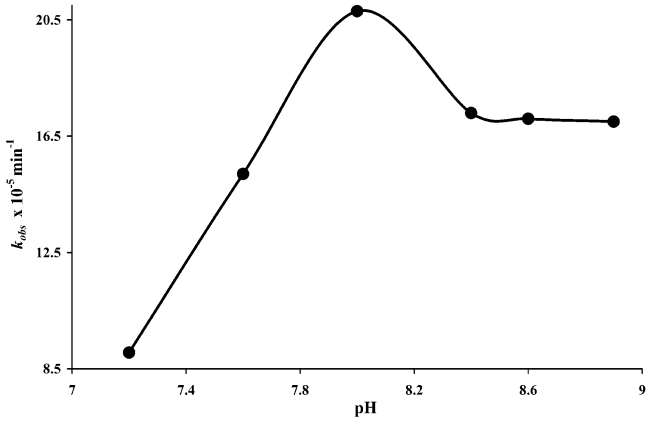


Figure 9. pH versus k_{obs} plot for the hydrolysis of bNPP by CPPL-Cu. These experiments were carried out at 30 °C. The concentration of the substrate used was 2.00 mM. Other experimental conditions are as described in Table 4.

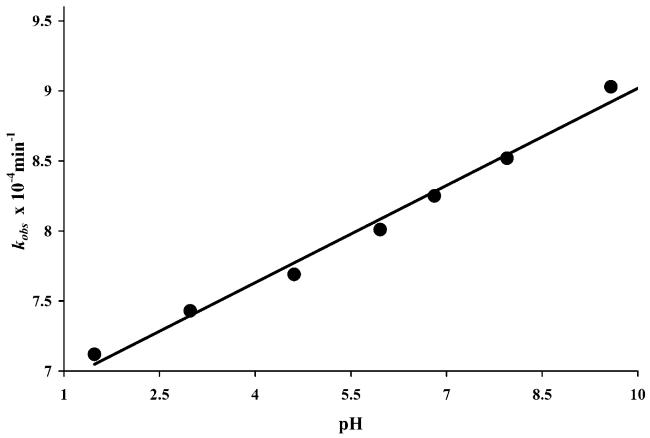


Figure 10. pH versus k_{obs} plot for the hydrolysis of hNPP by CPPL-Cu. These experiments were carried out at 35 °C. The concentration of the substrate was 1.00 mM. Other experimental conditions are as described in Table 4.

tion of water molecules that are bound to the metal ion leading to the formation of metal hydroxide.[11a,f,j] The reasons for the slight drop in the rate constant after pH 8.0 appear to be complex and elude an unequivocal explanation at this stage. However, the pH−rate profile for hNPP hydrolysis is relatively more straightforward where a linear dependence of the rate constant on pH was observed (Figure 10). Such a linear profile has been documented in the literature.[11f,j,k,n]

Table 6. Solvent Dependence on bNPP Hydrolysis by CPPL-Cu[a]

solvent	V_i (mM $min^{-1} \times 10^{-5}$)	k_{rel}[b]
ethylene glycol (100%)	0.36	1.0
water/ethylene glycol (1:1)	1.93	5.4
water (100%)	2.92	8.1

[a] Hydrolysis reactions were performed in duplicate containing 3 mL of solution of the substrate prepared in 0.01 M *N*-ethylmorpholine (pH 8.0) in the corresponding solvent systems at 30 °C. The amount of polymeric catalyst was 1 mg/mL of the buffer, and the substrate concentration was 2.0 mM. [b] Relative rates are reported with respect to k_{obs} obtained for pure ethylene glycol.

To probe the preferential attacking nucleophile on bNPP hydrolysis by CPPL-Cu, viz., Cu−OH or Cu−OR, we have performed solvolytic reactions in water, ethylene glycol, and 50% aqueous ethylene glycol. Ethylene glycol was used instead of methanol because of the insufficient solubility of bNPP (sodium salt) in pure methanol. Initial rates (V_i's) were determined for the three systems (Table 6). Relative to the rate observed for pure ethylene glycol ($V_i = 0.36 \times 10^{-5}$ mM min^{-1}), a 5.4-fold increase in rate for 50% aqueous ethylene glycol ($V_i = 1.93 \times 10^{-5}$ mM min^{-1}) and an 8.1-fold increase in rate for pure water ($V_i = 2.92 \times 10^{-5}$ mM min^{-1}) were observed. From these results, it appears that the deprotonation of coordinated water is preferred over alcohol.

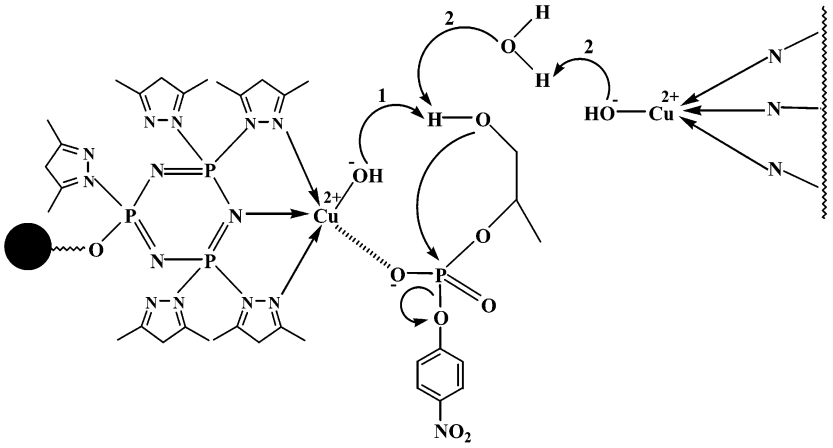
^{31}P NMR Study on the Hydrolysis of hNPP. The hydrolysis of hNPP can proceed either by an intermolecular pathway or an intramolecular pathway. The latter would lead to the formation of a cyclic phosphate while the former would lead to the formation of an acyclic phosphate. The hydrolysis of hNPP was monitored by a time-dependent ^{31}P NMR study. The ^{31}P NMR spectra obtained at various time intervals are given in Figure 11. The chemical shift of hNPP is at −4.65 ppm. As the hydrolysis proceeds, the formation of the cyclic phosphate is observed at +18.53 ppm.[11k] No evidence for the formation of any acyclic phosphates was observed. These results clearly suggest that an intramolecular pathway is preferred. It is possible to envisage two possible mechanisms: (a) a direct activation of the hydroxyl group of hNPP by the metal hydroxide acting as a base or (b) activation of water molecules by the metal hydroxide leading to the eventual deprotonation of the hydroxyl group on hNPP. These possibilities are summarized in Scheme 5.

Recycling Experiments. To evaluate the facile recovery and reusability of the catalyst, we have carried out recycling experiments using pNPP as the substrate. Typically, CPPL-Cu was filtered after the reaction, washed with aqueous methanol (6 × 5 mL), methanol (3 × 5 mL), and acetone (3 × 5 mL), dried in a vacuum at 40 °C for 6 h, and reused. The initial rates (V_i's) obtained show that CPPL-Cu can be recycled several times at different substrate concentrations without affecting the rates of hydrolysis (Table 7).

Conclusion

We have shown for the first time that a polymer containing cyclophosphazene as pendant groups can be designed as a multisite coordinating polymeric ligand for metal ions. Apart

Scheme 5[a]



[a] Pathway 1 represents a *direct* activation of the hydroxyl group of hNPP by metal hydroxide. Pathway (2) represents the activation of water molecules by metal hydroxide followed by the activation of the hydroxyl group on hNPP.

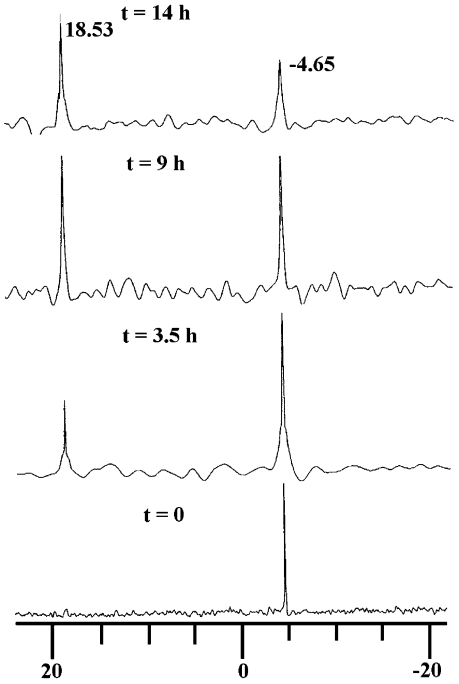


Figure 11. ^{31}P NMR spectra of the product of hNPP hydrolysis by CPPL-Cu at different time intervals (the peak at −4.65 ppm is due to hNPP, and the one at +18.53 ppm is due to cyclic phosphate).

from generating an insoluble polymer, cross-linking of cyclophosphazene monomer **2** with divinyl benzene also provides hydrolytic stability to the metal complex (CPPL-Cu) prepared thereafter. This methodology is quite general and offers a powerful and alternative synthetic route to the traditional approaches based mainly on modification of Merrifield and Wang resins,[25] for the preparation of a variety of polymeric ligands and polymer-bound transition and lanthanide metal complexes. The heterogeneous catalyst CPPL-Cu has been used for the catalysis of an important biological reaction, viz., phosphate ester hydrolysis. This has been accomplished by studying the hydrolysis of three activated substrates, viz., pNPP, bNPP, and RNA model substrate hNPP. The hydrolysis of all of these substrates in the presence of CPPL-Cu proceeds with considerable rate enhancement relative to the uncatalyzed reactions. Further, we have shown that CPPL-Cu is very robust and can be recycled several times. This augurs well for the development of new polymer-bound catalysts and reagents based on polymers containing cyclophosphazenes as pendants.

Table 7. Recycling Experiments[a]

no. cycles	pNPP concentration, [S] (mM)	V_i (mM min^{-1})
2	0.2[b]	1.6×10^{-5}
3	0.4	2.03×10^{-5}
4	0.6	1.84×10^{-5}

[a] Hydrolytic reactions were performed in duplicate containing 3 mL solution of pNPP prepared in 0.01 M *N*-ethylmorpholine (pH 8.0) in 50% aqueous methanol at 30 °C. The amount of polymeric catalyst used for each cycle was 1 mg/mL of the buffer, and the substrate concentration was 2.0 mM. [b] For comparison, initial velocity, V_i, for 0.2 mM substrate concentration at 30 °C using a fresh catalyst was 1.85×10^{-5} mM min^{-1}.

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Supporting Information Available: Additional figure. This material is available free of charge via the Internet at http://pubs.acs.org.

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(25) Merrifield, R. B. *Angew. Chem., Int. Ed. Engl.* **1985**, *24*, 799.