Design and Performance of Rigid Nanosize Multimetallic Cartwheel Pincer Compounds as Lewis-Acid Catalysts

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Design and Performance of Rigid Nanosize Multimetallic Cartwheel Pincer Compounds as Lewis-Acid Catalysts

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Novel strategies for the preparation of rigid cartwheel pincer metal complexes have been developed. The aromatic backbone of these materials ensures a high rigidity, which is expected to be important for a high retention when these multimetallic nanosize complexes are applied as homogeneous catalysts in a nanomembrane reactor. The ligand precursors $C_6[C_6H_3(CH_2Y)_2\text{-}3,5]_6$ (**10**, Y = NMe_2; **11**, Y = SPh; **12**, Y = PPh_2; **13**, Y = pz = pyrazol-1-yl) have been prepared in high yields from the key intermediate $C_6[C_6H_3(CH_2Br)_2\text{-}3,5]_6$ (**9**). The hexakis(pincer) palladium(II) complexes $C_6[(PdX)\text{-}4\text{-}C_6H_2(CH_2Y)_2\text{-}3,5]_6$ (**14**, Y = SPh, L = Cl; **15**, Y = PPh_2, L = Cl; **16**, Y = pyrazol-1-yl, L = OAc; **17**, Y = pyrazol-1-yl, L = Cl) have been prepared via direct electrophilic palladation of the corresponding ligands. The (tris)pincer ligand $C_6H_3[Br\text{-}4\text{-}C_6H_3(CH_2NMe_2)_2\text{-}3,5]_3\text{-}1,3,5$ (**20**) was prepared via a triple-condensation reaction of 4-bromo-3,5-bis[(dimethylamino)methyl]acetophenone (**19**). Reaction of **20** with $Pd(dba)_2$ yielded the tripalladium complex $C_6H_3[(PdBr)\text{-}4\text{-}C_6H_3(CH_2NMe_2)_2\text{-}3,5]_3\text{-}1,3,5$ (**21**). The crystal structure of **21** shows a propeller-like structure with D_3 symmetry and a fixed bromine−bromine distance of 17.4573(4) Å, approximately forming a triangle with a height of 15.2 Å. These nanosize cartwheel pincer metal complexes based on tridentate Y,C,Y′ pincer ligands have been used as homogeneous Lewis-acid catalysts. Moreover, the influence of the donor substituent *Y* on the catalytic activity of cationic mono-Y,C,Y′ Pd^{II} complexes as Lewis-acid catalysts in the double Michael reaction between methyl vinyl ketone and ethyl α-cyanoacetate, as a model reaction, has been investigated. It was found that cationic N,C,N′-type pincer complexes (**1a**, Y = NMe_2; **1b**, Y = pz; **1c**, Y = pz* = 3,5-dimethylpyrazol-1-yl; **23**) were superior to the P,C,P′- and S,C,S′-pincer complexes (**1d**, Y = PPh_2; **1e**, Y = SPh). The nanosize cationic tri-N,C,N′ Pd^{II} complex **23** was found to have a catalytic activity per catalytic site in the double Michael reaction of the same order of magnitude as the monopincer analogue **1a** ($k = 279 \times 10^{-6}$ s^{-1} for **1a** vs $k = 232 \times 10^{-6}$ s^{-1} for **23**). The combination of the nanosize dimensions, the catalytic activity, and the high thermal and air stability makes these complexes excellent candidates for application in a continuous process in a nanomembrane reactor.

Introduction

Within the field of homogeneous catalysis there is currently a great interest in the application of tailored/engineered organic compounds as soluble support materials for anchored, catalytically active metal complexes.[1] These organic materials often have a periphery bearing multidentate ligands or ligand precursors. Their design is usually such that the resulting multimetallic system can easily be recovered for reuse after catalysis from the product-containing solution.[2] Recently, we and others reported the development of nanosize multimetal homogeneous catalysts, which were separable from the reaction mixture by nanomembrane filtration.[2d−g,j] These catalysts are based on metalated phosphine ligands,[2d,e,g] P,O ligands,[2f] or tridentate Y,C,Y′ ligands[2j] (so-called "pincer" ligands) immobilized on large organic frameworks, e.g. carbosilane dendrimers.

In organic synthesis, transition-metal complexes acting as Lewis-acid catalysts have received considerable attention in recent years.[3−7] Tridentate Y,C,Y′ pincer ligands in combination with group VIII metals (**A**;

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[||] Address correspondence pertaining to crystallographic studies to this author. E-mail: A.L.Spek@chem.uu.nl.

(1) For a review on the application of metallodendrimers as homogeneous catalysts, see: Kreiter, R.; Kleij, A. W.; Klein Gebbink, R. J. M.; van Koten, G. *Topics in Current Chemistry, Dendrimers IV* by Prof. Dr. F. Vögtle.

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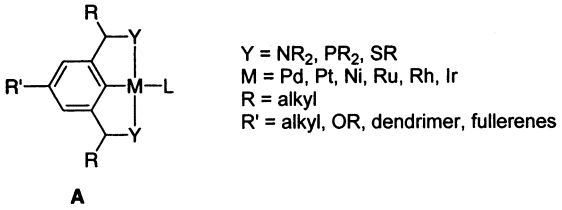


Figure 1.

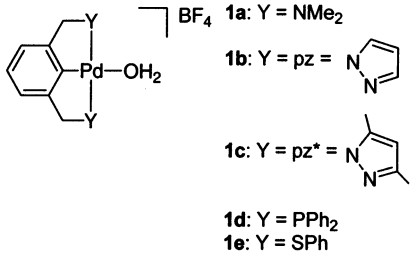


Figure 2.

Figure 1) have been found to be active as homogeneous Lewis-acid catalysts as well.[8−10] Venanzi and Zhang have reported on the use of chiral P,C,P′-type complexes as catalysts in the aldol reaction between benzaldehydes and methyl isocyanoacetate.[8] Zhang has also reported that the palladium complexes exhibit a higher activity than the analogous platinum complexes in this reaction. The use of a chiral palladated 1,3-bis(2-oxazolinyl)-benzene complex in an aldol reaction, as well as in a single and double Michael reaction, has been reported by Stark et al.[9] The same ligand on rhodium has been used by Nishiyama and co-workers in the enantioselective allylation of aldehydes.[10] Although palladated oxazolinyl-based pincer complexes[9] appear to be more active in the aldol reaction than the corresponding P,C,P′ analogue,[8b] a detailed investigation into the influence of the donor group Y on the catalyst activity has not been reported thus far.

The lack of understanding of the influence of the donor substituent Y (Figure 1) on the activity of the Lewis-acid catalyst impedes the rational design of effective catalysts of the form **A**. For the design and synthesis of nanosize homogeneous catalysts based on pincer metal building blocks for organic reactions, knowledge about this aspect is important. Thus, we have undertaken such a study by varying Y in complexes **1a**−**e** (Figure 2) and investigated the catalytic activity of these complexes in the double Michael reaction between methyl vinyl ketone and ethyl α-cyanoacetate as a model reaction. While a direct comparison is not entirely valid, since the substituents attached to the different donor atoms are not equivalent in all cases (e.g. the pincer complex with Y = NPh_2 cannot be prepared), this series can give a good indication of the overall effect of the donor atom (N, P, or S) on the activity of the catalyst. Furthermore, complexes **1b** (Y = pz = pyrazol-1-yl) and **1c** (Y = pz* = 3,5-dimethylpyrazol-1-yl) can also provide additional information about the influence of the electron-donating methyl groups on the activity of the Lewis-acid catalyst. In addition, we report here the application of multipincer complexes as nanosize homogeneous catalysts in the same double Michael reaction. For this study, rigid multipincer benzene complexes **B**[2h] and **C** (Figure 3) were selected incorporating six and three palladated pincer groups, respectively. An obvious difference between **B** and **C** is the lower degree of congestion about the metal centers in the tripalladium cartwheel complex. We expect that a high degree of rigidity in the backbone of these nanosize catalysts is advisable for optimal retention of such materials by nanomembrane filters.

Results and Discussion

Synthesis of Monopincer Complexes. Complexes **1a**−**e** were prepared from the corresponding palladium halide complexes **3a**−**e** by reaction with silver tetrafluoroborate in wet acetone (Scheme 1).[11−13] The palladium chloride complex **3c** was prepared via direct electrophilic palladation, using $Pd(OAc)_2$ in refluxing acetic acid,[14] while complexes **3d**,**e** were prepared according to literature procedures.[15]

Different routes were developed for the synthesis of metalated hexakis(pincer)- and (tris)pincer-substituted benzenes (**B** and **C**, respectively, Figure 3), which are rigid nanosize molecules potentially suitable for recov-

(2) (a) Knapen, J. W. J.; van der Made, A. W.; de Wilde, J. C.; van Leeuwen, P. W. N. M.; Wijkens, P.; Grove, D. M.; van Koten, G. *Nature* **1994**, *372*, 659. (b) Kragl, U.; Dreisbach, C. *Angew. Chem., Int. Ed. Engl.* **1996**, *35*, 642. (c) Reetz, M. T.; Lohmer, G.; Schwickardi, R. *Angew. Chem., Int. Ed.* **1997**, *36*, 1526. (d) Giffels, G.; Beliczey, J.; Felder, M.; Kragl, U. *Tetrahedron: Asymmetry* **1998**, *9*, 691. (e) Brinkmann, N.; Giebel, D.; Lohmer, G.; Reetz, M. T.; Kragl, U. *J. Catal.* **1999**, *183*, 163. (f) Hovestad, N. J.; Eggeling, E. B.; Heidbüchel, H. J.; Jastrzebski, J. T. B. H.; Kragl. U.; Keim, W.; Vogt, D.; van Koten, G. *Angew. Chem., Int. Ed.* **1999**, *38*, 1655. (g) De Groot, D.; Eggeling, E. B.; de Wilde, J. C.; Kooijman, H.; van Haaren, R. J.; van der Made, A. W.; Spek, A. L.; Vogt, D.; Reek, J. N. H.; Kamer, P. C. J.; van Leeuwen, P. W. N. M. *Chem. Commun.* **1999**, 1623. (h) Dijkstra, H. P.; Steenwinkel, P.; Grove, D. M.; Lutz, M.; Spek, A. L.; van Koten, G. *Angew. Chem., Int. Ed.* **1999**, *38*, 2186. (i) Albrecht, M.; Hovestad, N. J.; Boersma, J.; van Koten, G. *Chem. Eur. J.* **2001**, *7*, 1289. (j) Kleij, A. W.; Gossage, R. A.; Klein Gebbink, R. J. M.; Brinkman, N.; Reijerse, E. J.; Kragl, U.; Lutz, M.; Spek, A. L.; van Koten, G. *J. Am. Chem. Soc.* **2000**, *122*, 12112.

(3) (a) Mahrwald, R. *Chem. Rev.* **1999**, *99*, 1095 and references therein. (b) Christoffers, J. *Eur. J. Org. Chem.* **1998**, 1259 and references therein. (c) Drury, W. J.; Ferraris, D.; Cox, C.; Young, B.; Lectka, T. *J. Am. Chem. Soc.* **1998**, *120*, 11006.

(4) Diels−Alder Reactions: (a) Bruin, M. E.; Kündig, E. P. *Chem. Commun.* **1998**, 2635. (b) Kanemasa, S.; Oderaotoshi, Y.; Sakaguchi, S.-I.; Yamamoto, H.; Tanaka, J.; Wada, E.; Curran, D. *J. Am. Chem. Soc.* **1998**, *120*, 3074. (c) Schaus, S. E.; Brånalt, J.; Jacobsen, E. N. *J. Org. Chem.* **1998**, *63*, 403. (d) Davies, D. L.; Fawcett, J.; Garrat, S. A.; Russell, D. R. *Chem. Commun.* **1997**, 1351. (e) Evans, D. A.; Murry, J. A.; von Matt, P.; Norcross, R. D.; Miller, S. J. *Angew. Chem., Int. Ed. Engl.* **1995**, *34*, 798. (f) Kündig, E. P.; Bourdin, B.; Bernardinelli, G. *Angew. Chem., Int. Ed. Engl.* **1994**, *33*, 1856. (g) Corey, E. J.; Imai, N.; Zhang, H.-Y. *J. Am. Chem. Soc.* **1991**, *113*, 728.

(5) Aldol reactions: (a) Fujimura, O. *J. Am. Chem. Soc.* **1998**, *120*, 10032. (b) Evans, D. A.; MacMillan, D. W. C.; Campos, K. R. *J. Am. Chem. Soc.* **1997**, *119*, 10859. (c) Yanagisawa, A.; Matsumoto, Y.; Nakashima, H.; Asakawa, K.; Yamamoto, H. *J. Am. Chem. Soc.* **1997**, *119*, 9319. (d) Evans, D. A.; Murry, J. A.; Kozlowski, M. C. *J. Am. Chem. Soc.* **1996**, *118*, 5814. (e) Mikami, K.; Matsukawa, S. *J. Am. Chem. Soc.* **1994**, *116*, 4077.

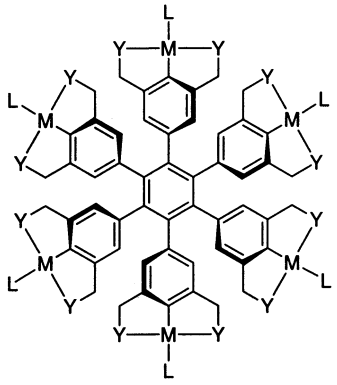
(6) Michael reactions: (a) Blacker, A. J.; Clarke, M. L.; Loft, M. S.; Mahon, M. F.; Williams, J. M. J. *Organometallics* **1999**, *18*, 2867. (b) Sawamura, M.; Hamashima, H.; Ito, Y. *Tetrahedron* **1994**, *50*, 4439. (c) Evans, D. A.; Rovis, T.; Kozlowski, M. C.; Wade Downey, C.; Tedrow, J. S. *J. Am. Chem. Soc.* **2000**, *122*, 9134.

(7) Alkylation reactions: (a) Ferraris, D.; Young, B.; Dudding, T.; Lectka, T. *J. Am. Chem. Soc.* **1998**, *120*, 4548. (b) Yanagisawa, A.; Nakashima, H.; Ishiba, A.; Yamamoto, H. *J. Am. Chem. Soc.* **1996**, *118*, 4723.

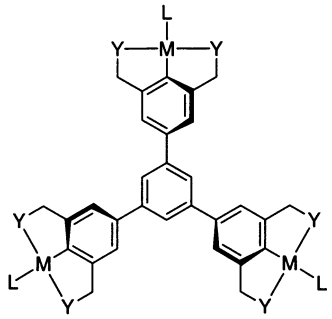
(8) (a) Gorla, F.; Togni, A.; Venanzi, L. M.; Albinati, A.; Lianza, F. *Organometallics* **1994**, *13*, 1607. (b) Longmire, J. M.; Zhang, X.; Shang, M. *Organometallics* **1998**, *17*, 4374.

(9) (a) Stark, M. A.; Richards, C. J. *Tetrahedron Lett.* **1997**, *38*, 5881. (b) Stark, M. A.; Jones, G.; Richards, C. J. *Organometallics* **2000**, *19*, 1282.

(10) Motoyama, Y.; Narusawa, H.; Nishiyama, H. *Chem. Commun.* **1999**, 131.



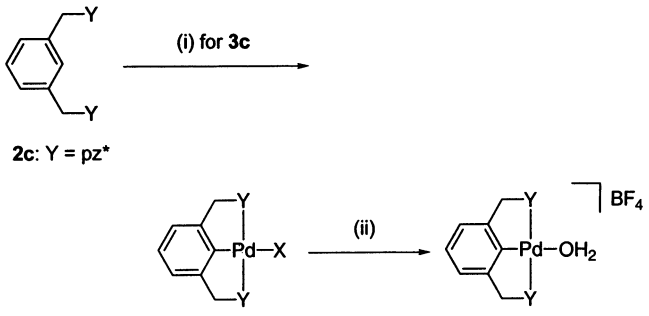
B



C

Figure 3.

Scheme 1[a]



[a] Conditions: (i) $Pd(OAc)_2$, acetic acid, reflux, 18 h, followed by LiCl, acetone, room temperature, 2 h; (ii) $AgBF_4$, acetone/water, room temperature, 1 h.

ery by nanomembrane filtration. Recently, we reported the first synthesis of a fully palladated hexakis(pincer) complex (**B**, M = Pd, Y = SPh, L = Cl; Figure 3) and its molecular geometry in the solid state.[2h] In this study, the preparation of palladated hexakis(pincer) complexes having a variety of different coordinative ligands and the synthesis of novel tripalladated pincer complexes have been carried out.

Synthesis of Hexakis(pincer) Compounds. The various hexakis(pincer) ligands $C_6[C_6H_3(CH_2Y)_2\text{-}3,5]_6$ (**10**−**13**) can be prepared using dodecabromide $C_6[C_6H_3(CH_2Br)_2\text{-}3,5]_6$ (**9**) as the key synthetic intermediate. The synthesis of **9** was first reported by Duchêne and Vögtle,[16] but this route involved a number of time-consuming and expensive column chromatography techniques. Therefore, we developed an improved route to **9**, as outlined in Scheme 2, which involves the trimerization of the bis(pincer)acetylene species **7** to hexakis-[3,5-bis(methoxymethyl)phenyl]benzene (**8**), which can easily be converted to **9**.

Compound **7** was prepared in a one-pot Pd/Cu catalyzed cross-coupling reaction starting from iodoarenes **6** and gaseous acetylene (Scheme 2).[17] This procedure afforded **7** in 90% overall yield, which is a significant improvement over the four-step procedure reported earlier (22% overall yield for **7**).[16]

Conversion of the bis(pincer)acetylene **7** in two steps to the key intermediate **9** and subsequent introduction of the different donor substituents Y via nucleophilic substitution reactions resulted in the formation of the different hexakis(pincer) ligands **10**−**13** (Scheme 3).

Metalation of Hexakis(pincer) Ligands. Direct electrophilic palladation of dodecasulfide **11** and dodecaphosphine **12** with a small excess of $[Pd(MeCN)_4](BF_4)_2$ in acetonitrile,[18] followed by addition of LiCl, gave the hexakis(chloropalladium) complexes **14** and **15** in 90 and 89% yields, respectively (Scheme 4). The reaction time needed for complete metalation of **11** (3 h), however, was considerably shorter than the time needed for **12** (110 h). Thus far, the hexapalladium(II) complex **15** has been analyzed by ^1H, ^{13}C, and ^{31}P NMR spectroscopy only; no product found to be pure by elemental analysis has yet been obtained. The analogous dodecasulfide **14** has been characterized by X-ray crystallography, and its molecular structure showed a cartwheel-like structure with C_3 symmetry and diametrically opposed Pd−Pd separations of 15.340(2) Å.[2h]

Treatment of dodecapyrazole **13** with $Pd(OAc)_2$ in acetic acid resulted in the formation of $C_6[(PdOAc)\text{-}4\text{-}C_6H_2(CH_2pz)_2\text{-}3,5]_6$ (**16**), which was isolated in 53% yield. Reaction of **16** with LiCl gave the corresponding hexakis(chloropalladium) complex **17**, which upon reaction with $AgBF_4$ in wet acetone afforded the hexakis(aquapalladium) complex $C_6[\{Pd(OH_2)\}\text{-}4\text{-}C_6H_2(CH_2Pz)_2\text{-}3,5]_6$ (**18**) in 70% yield (Scheme 4).

Complete palladation of hexakis(pincer) ligand **10** was not feasible via direct electrophilic palladation. Therefore, the palladium centers were introduced via a lithiation−transmetalation method using *t*-BuLi as the lithiation agent and $PdCl_2(SEt_2)_2$ as the palladium source. Although complete lithiation occurred, as shown by a deuteration reaction with D_2O and subsequent analysis by ^1H and ^{13}C NMR spectroscopy, complete palladation via this route also could not be achieved.

(11) For the synthesis of **3a** see: Alsters, P. L.; Baesjou, P. J.; Janssen, M. D.; Kooijman, H.; Sicherer-Roetman, A.; Spek, A. L.; van Koten, G. *Organometallics* **1992**, *11*, 4124.

(12) For the synthesis of **1b** and **3b** see: Canty, A. J.; Honeyman, R. T.; Skelton, B. W.; White, A. H. *J. Organomet. Chem.* **1990**, *389*, 277.

(13) For the synthesis of **1a** from **3a** see: Grove, D. M.; van Koten, G.; Louwen, J. N.; Noltes, J. G.; Spek, A. L.; Ubbels, H. J. C. J. *J. Am. Chem. Soc.* **1984**, *104*, 6609.

(14) Hartshorn, C. M.; Steel, P. J. *Organometallics* **1998**, *17*, 3487.

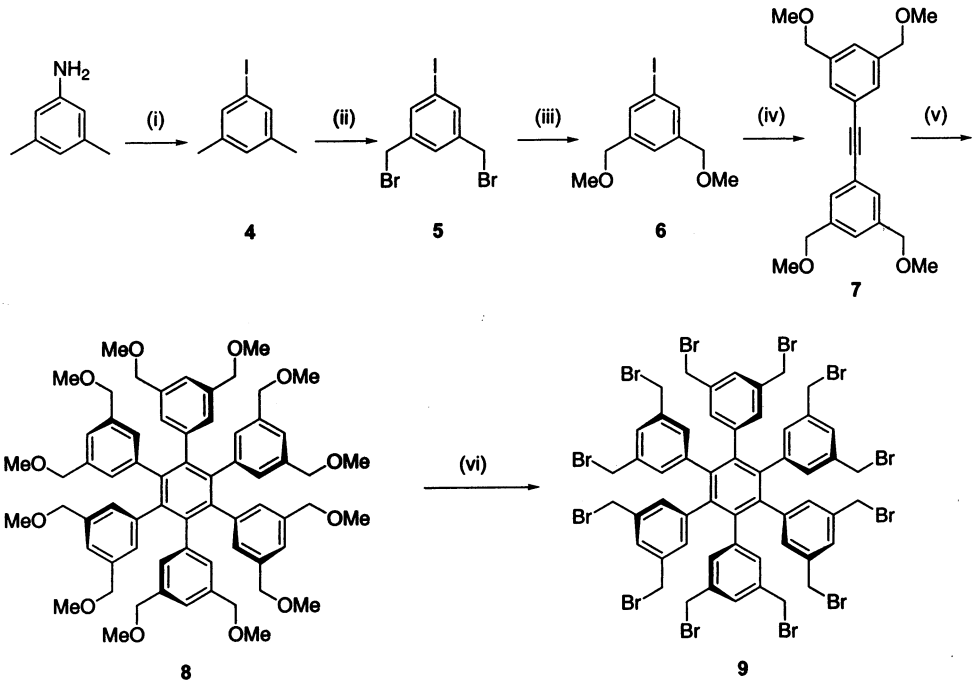
(15) (a) For the synthesis of **3d** see: Rimml, H.; Venanzi, L. M. *J. Organomet. Chem.* **1983**, *259*, C6. (b) For the synthesis of **3e** see: Lucena, N.; Casabo, J.; Escriche, L.; Sanchez-Castello, G.; Teixidor, F.; Kivekäs, R.; Sillanpää, R. *Polyhedron* **1996**, *15*, 3009.

(16) Duchêne, K.-H.; Vögtle, F. *Synthesis* **1986**, 659.

(17) Sonogashira, K.; Tohda, Y.; Hagihara, N. *Tetrahedron Lett.* **1975**, 4467.

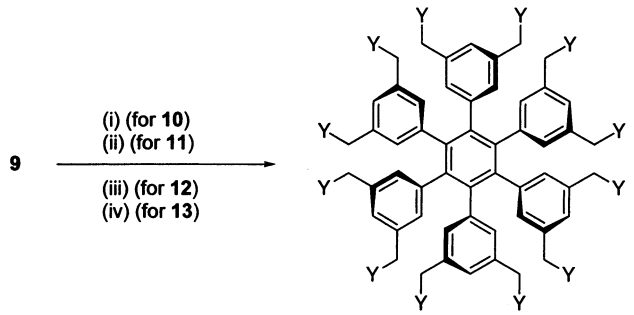
(18) Procedure reported by: (a) Loeb, S. J.; Shimizu, G. K. H. *J. Chem. Soc., Chem. Commun.* **1993**, 1396. (b) Kickham, J. E.; Loeb, S. J. *Inorg. Chem.* **1994**, *33*, 4351.

Scheme 2. Synthesis of $C_6[C_6H_3(CH_2Br)_2\text{-}3,5]_6$ (9) from 3,5-Dimethylaniline[a]



[a] Conditions: (i) 25% H_2SO_4(aq), $NaNO_2$(aq), −10 °C, 30 min, followed by KI(aq), −10 → 90 °C, 2 h; (ii) *N*-bromosuccinimide, AIBN, MeOAc, reflux, *hν*, 12 h; (iii) NaOMe, MeOH, reflux, 18 h; (iv) HC≡CH, $[PdCl_2(PPh_3)_2]$, CuI, Et_2NH, 18 h, room temperature; (v) $[PdCl_2(PhCN)_2]$, benzene, reflux, 6 h; (vi) AcBr, $BF_3{\cdot}OEt_2$, CH_2Cl_2, reflux, 24 h.

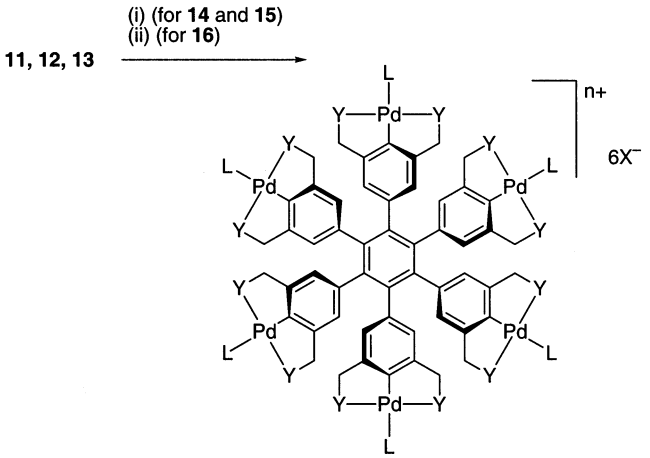
Scheme 3[a]



10: Y = NMe_2
11: Y = SPh
12: Y = PPh_2
13: Y = pz

[a] Conditions: (i) $HNMe_2$, CH_2Cl_2, room temperature, 3 h; (ii) PhSH, K_2CO_3, DMF, room temperature, 18 h; (iii) $HPPh_2{\cdot}BH_3$, *n*-BuLi, THF, −30 °C → room temperature, 18 h, followed by $HBF_4{\cdot}OEt_2$, Et_2O, room temperature, 2 h; (iv) pyrazole, K, THF, reflux, 1.5 h, followed by addition of **9**, THF, reflux, 15 h.

Scheme 4. Palladation Routes for Various $C_6(C_6H_3(CH_2Y)_2\text{-}3,5)_6$ Ligands[a]



14: Y = SPh; L = Cl; n = 0 (no X^-)
15: Y = PPh_2; L = Cl; n = 0 (no X^-)
16: Y = pz; L = OAc; n = 0 (no X^-)
17: Y = pz; L = Cl; n = 0 (no X^-)
18: Y = pz; L = H_2O; X = BF_4; n = 6

[a] Conditions: (i) $[Pd(NCMe)_4](BF_4)_2$, MeCN, reflux, 5−110 h, followed by LiCl, acetone, room temperature, 1 h; (ii) $Pd(OAc)_2$, AcOH, reflux, 15 h; (iii) LiCl, acetone, room temperature, 15 h; (iv) $AgBF_4$, acetone, room temperature, 3 h.

On average, four to five pincer groups were palladated by this method.

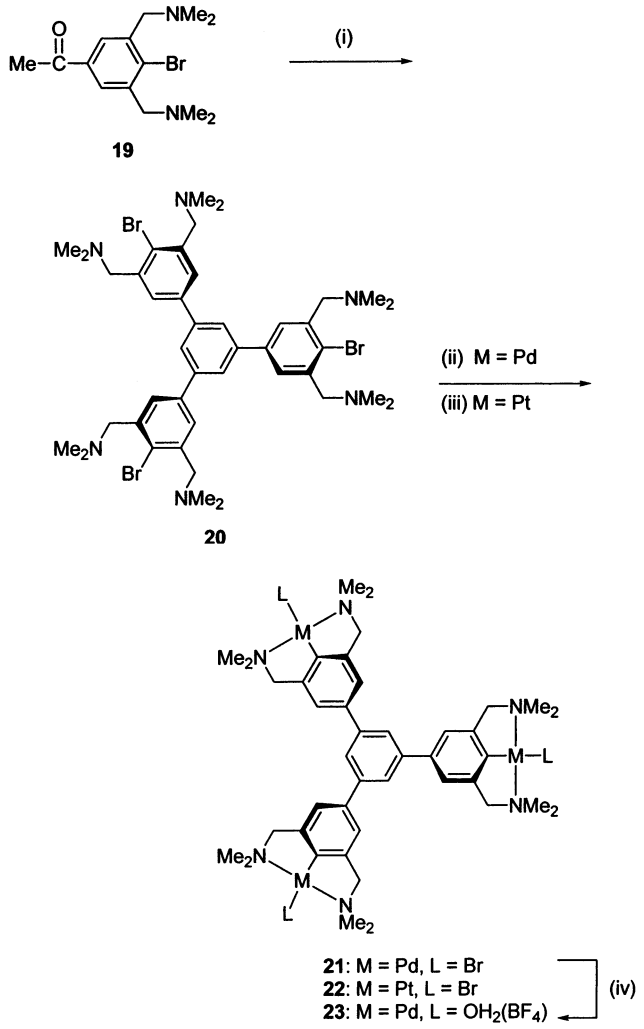
Synthesis of Tris(pincer) Compounds. The synthesis of the tris(pincer) ligand $C_6H_3[Br\text{-}4\text{-}C_6H_3(CH_2\text{-}NMe_2)_2\text{-}3,5]_3\text{-}1,3,5$ (**20**) started from substituted acetophenone **19** (Scheme 5), prepared according to a previous literature procedure.[19] A triple condensation reaction of **19** with tetrachlorosilane in ethanol afforded **20** in 70% yield.[20] Palladation of this tris(pincer) ligand was achieved via an oxidative addition reaction with $Pd(dba)_2$, resulting in the formation of palladated tris(pincer) complex **21** in 70% yield. The corresponding triplatinum(II) compound **22** was obtained in 73% yield by reaction of **20** with $[Pt(tol)_2SEt_2]_2$, a method previously reported.[21] The neutral complex **21** can easily be

(19) Van de Kuil, L. A.; Luitjes, H.; Grove, D. M.; Zwikker, J. W.; van der Linden, J. G. M.; Roelofsen, A. M.; Jenneskens, L. W.; Drenth, W.; van Koten, G. *Organometallics* **1994**, *13*, 471.

(20) Modification of a reported method was used: Elmorsy, S. S.; Pelter, A.; Smith, K. *Tetrahedron Lett.* **1991**, *32*, 4175.

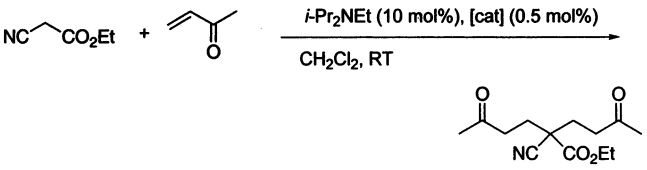
(21) Canty, A. J.; Patel, J.; Skelton, B. W.; White, A. H. *J. Organomet. Chem.* **2000**, *599*, 195.

Scheme 5[a]



[a] Conditions: (i) $SiCl_4$, EtOH, reflux, 18 h; (ii) $Pd(dba)_2$, benzene, room temperature, 18 h; (iii) $[Pt(tol)_2SEt_2]_2$, benzene, reflux, 3 h; (iv) $AgBF_4$, wet acetone, room temperature, 2 h.

Scheme 6



converted to the corresponding triionic aqua complex **23** in 76% yield by treatment with silver tetrafluoroborate in wet acetone (Scheme 5).

Brownish crystals of **21** suitable for a crystal structure determination were obtained by slow diffusion of diethyl ether into a concentrated solution of **21** in methylene chloride. The molecular geometry of **21** shows a central benzene ring substituted at the 1-, 3-, and 5-positions with diorganoamine moieties each cyclopalladated at the intraannular position between the CH_2NMe_2 groups (Figure 4). This affords square-planar Pd^{II} centers with a ligand environment comprised of tridentate N,C,N′ coordination by the organic moiety with a bromo ligand trans to the metal-bonded aromatic carbon. Compound **21** crystallizes in the trigonal space group $R\bar{3}c$ with the molecule on a special position with crystallographic 32 symmetry. This leads to an exact molecular symmetry

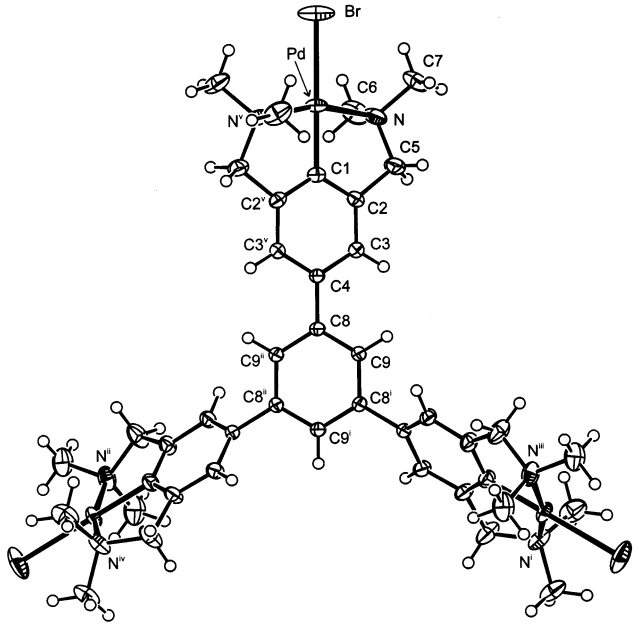


Figure 4. Displacement ellipsoid plot (50% probability level) of **21**. Symmetry operations: (i) $1 - y, x - y, z$; (ii) $1 - x + y, 1 - x, z$; (iii) $^1/_3 + y, -^1/_3 + x, ^1/_6 z$; (iv) $^4/_3 - x, ^2/_3 - x + y, ^1/_6 - z$; (v) $^1/_3 + x - y, ^2/_3 - y, ^1/_6 - z$.

of D_3. The "pincer" systems are therefore tilted in the same direction with respect to the central benzene ring (twist angle 47.31°). The size of the molecule is probably best defined by the fixed bromine−bromine distance of 17.4573(4) Å. If we approximate the molecular shape as a triangle, the height of the triangle would be 15.2 Å. The molecules are stacked on top of each other in the direction of the crystallographic *c* axis with six molecules in one unit cell. We can thus roughly approximate the thickness of the molecule in the crystal with $c/6 = 5.9$ Å.

Although these hexakis- and tris(pincer) complexes have fairly low molecular weights, especially in comparison with dendrimers, the rigid structures result in their true nanoparticle dimensions. These properties make them appropriate catalysts for retention by nanomembrane filters.

Catalysis. Complexes **1a**−**e** were tested as Lewis-acid catalysts in the double Michael reaction between ethyl α-cyanoacetate and methyl vinyl ketone (Scheme 6) as a model reaction, and the results are summarized in Table 1.

From Table 1 it is clear that pincer complexes based on N,C,N′-type ligands (**1a**−**c**, **23**, entries 1−3 and 6) are the most active catalysts in this reaction. The P,C,P′ pincer complex **1e** (entry 5) shows rather low activity, while the reaction catalyzed by the S,C,S′ pincer complex **1d** (entry 4) is hardly faster than the blank reaction (entry 7). It was also found that the catalytic activity of **1c** was considerably higher than the activity of **1b** (entries 2 and 3, respectively). The only difference between the two catalysts is that **1c** contains two methyl substituents in the pyrazolyl group (pz*), making **1c** a weaker Lewis acid than **1b**. The effect of the methyl group substitution can be seen by comparing the pK_a value of 1-Mepz ($pK_a = 1.19$) with that of 1,3,5-Me_3pz

Table 1. Catalytic Activities of the Various Pincer Catalysts in the Double Michael Reaction between Methyl Vinyl Ketone and Ethyl α-Cyanoacetate

entry	catalyst	k (10^{-6} s^{-1})[a]	$t_{1/2}$ (min)[b]
1	**1a**	279	41
2	**1b**	134	86
3	**1c**	348	33
4	**1d**	4.18	2800
5	**1e**	9.48	1200
6	**23**	232	50
7	blank	3.78	3056

[a] Determined by ^{1}H NMR by comparison of the integration of the CH_2 protons of ethyl α-cyanoacetate to the combined integration of the ethyl ester CH_2 protons of the reactant and product. The reactions are first order in CN (CN = ethyl α-cyanoacetate); the rate constant k was determined by plotting $-\ln([CN]/[CN]_0)$ versus time (in seconds). [b] $t_{1/2} = \ln 2/(60k)$.

(pK_a = 2.90).[22] Thus, although **1c** is a weaker Lewis acid than **1b**, it is the most active catalyst tested in this series and also the most active catalyst of the pincer type reported in the literature so far for this particular reaction. Although the mechanism of this reaction is not yet fully established, this probably means that not a deprotonation step but rather the dissociation of the product or an intermediate from the metal center determines the rate of this reaction, as such a step is expected to be faster for weaker Lewis acids.

Unfortunately, the hexakis(pincer) complex **18** is not soluble under the reaction conditions used for the double Michael reaction. Nevertheless, **18** did show catalytic activity (70% after 22 h), despite the heterogeneous nature of the reaction. Complex **23**, on the other hand, is soluble under the reaction conditions, and from Table 1 it is clear that the catalytic activity per palladium center of tris(pincer) complex **23** is almost the same as that of the corresponding monopincer analogue **1a** (in all reactions the total numbers of Pd^{II} centers were kept equal). Although three catalytic sites are located in a single catalyst particle, this has no significant influence on the catalytic activity of the independent catalytic sites. Thus, with the tris(pincer) systems we have a system in hand which is soluble in common organic solvents and is quite heat- and air-stable.

Conclusions

New routes have been developed for the synthesis of rigid nanosize organometallic materials based on an aromatic backbone. Hexametallic complexes **14**−**18** and trimetallic complexes **21**−**23** have been prepared in good yields and have been fully characterized (except for **15**). The molecular structure of **21** shows a propeller-like structure with a molecular symmetry of D_3 and a bromine−bromine distance of 17.4573(4) Å.

The cationic N,C,N′ palladium(II) complexes are the most active Lewis-acid catalysts of the pincer-type series in the double Michael reaction between ethyl α-cyanoacetate and methyl vinyl ketone reported thus far. Comparison of the catalytic activities of **1b** and **1c** demonstrates that the weaker Lewis acid (**1c**) gives a higher activity in this particular reaction, which may mean that dissociation of the product or an intermediate from the metal center appears as a unique step in the rate law of this reaction. Furthermore, the hexakis(pincer) complex **18** was also active in the double Michael reaction, despite the fact that the catalyst did not dissolve under the reaction conditions. These solubility issues also explain the much lower activity of **18** relative to its monopincer analogue **1b**. In contrast, the catalytic activity of the soluble nanosize tricationic catalyst **23** was found to be similar to that of its monopincer analogue **1a**.

As separation of the catalyst will be important in the final catalytic process, we are currently investigating to what extent nanosize pincer catalysts, such as **23**, are retained by nanomembranes. Preliminary results have already shown that the platinum analogue **22** exhibits a retention of approximately 94% by the MPF-60 membrane, which is quite efficient for such a small molecule.[23] For continuous processes, however, higher retentions are needed. Thus, we are currently also investigating the synthesis of larger nanosize pincer complexes with rigid cores for use as homogeneous catalysts in continuous nanomembrane reactor processes.[23]

Experimental Section

Solvents were purified and dried according to standard procedures, stored under a nitrogen atmosphere, and freshly distilled prior to use. NMR solvents were purchased and used without further purification. The complexes **1b**,[12] **3a**,[11] **3b**,[12] **3d**,[15a] **3e**,[15b] and $[PdCl_2(cod)]$[24] were prepared according to literature procedures. All other reagents were purchased and used without further purification. NMR spectra were recorded with a Varian Unity Inova 400 WB spectrometer (^{1}H NMR, 399.716 MHz; ^{13}C NMR, 100.6 MHz), a Varian 300 spectrometer (^{1}H NMR, 300.1 MHz; ^{13}C NMR, 75.5 MHz; ^{31}P NMR, 121.5 MHz), or a Varian Gemini 200 spectrometer (^{1}H NMR, 200.1 MHz; ^{13}C NMR, 50.3 MHz; ^{31}P NMR, 81.0 MHz). Mikroanalyses were determined by either Dornis and Kolbe, Microanalytisches Laboratorium, Mülheim, Germany, or the Central Science Laboratory, University of Tasmania.

Synthesis of 1,3-Bis[(3,5-dimethylpyrazol-1-yl)methyl]-benzene (2c). To a stirred suspension of finely cut potassium (1.12 g, 29.9 mmol) in THF (60 mL) under an argon atmosphere was added 3,5-dimethylpyrazole (2.88 g, 29.9 mmol). The mixture was heated to reflux and maintained at this temperature until beads of molten potassium were no longer evident (∼3 h). The solution was cooled to ambient temperature, and 2,6-bis(bromomethyl)benzene (3.59 g, 13.6 mmol) was added in one portion. The reaction mixture was allowed to stand at reflux overnight, quenched by addition of water (0.1 mL), and filtered and the solvent removed in vacuo. The product, 1,3-(3,5-Me_2pz$CH_2)_2C_6H_4$ (**2c**), was purified by distillation. Yield: 3.27 g (82%). Mp: 68−71 °C. ^{1}H NMR ($CDCl_3$, 300 MHz): δ 7.24 (t, ^3J = 7.7 Hz, 1H, Ar H), 6.94 (d, ^3J = 7.8 Hz, 2H, Ar H), 6.76 (s, 1H, Ar H), 5.85 (s, 2H, H4−3,5-Me_2pz), 5.18 (s, 4H, CH_2), 2.25 (s, 6H, CH_3), 2.12 (s, 6H, CH_3). ^{13}C NMR ($CDCl_3$, 75 MHz): δ 147.5, 139.1, 137.9, 129.0, 125.5, 124.6, 105.5, 52.2, 13.4, 11.0. Anal. Calcd for $C_{18}H_{22}N_4$: C, 73.44; H, 7.53; N, 19.03. Found: C, 73.25; H, 7.39; N, 19.10.

Synthesis of 1-(Chloropalladium)-2,6-bis[(3,5-dimethylpyrazol-1-yl)methyl]benzene (3c). A solution of $Pd(OAc)_2$ (0.10 g, 0.45 mmol) and **2c** (0.15 g, 0.49 mmol) in acetic acid

(22) Canty, A. J.; Lee, C. V. *Organometallics* **1982**, *1*, 1063.

(23) Dijkstra, H. P.; Kruithof, K.; Ronde, N.; Vogt, D.; van Klink, G. P. M.; van Koten, G. To be submitted for publication. SelRo nanofiltration membranes (MPF-60) were purchased from Koch Membrane Systems Inc., Düsseldorf, Germany; further product information may be found at http://www.kochmembrane.com.

(24) Drew, D.; Doyle, J. R.; Shaver, A. G. *Inorg. Synth.* **1972**, *13*, 47.

(10 mL) was heated to 120 °C and maintained at this temperature for 2 h. The solvent was removed by rotary evaporation and the residue dissolved in CH_2Cl_2 (50 mL). The resultant solution was washed with water (3 × 50 mL). The solvent was removed by rotary evaporation and the product dissolved in acetone (50 mL) along with LiCl (0.24 g). The mixture was stirred overnight and then centrifuged and the solution decanted to leave a tan solid. The product was washed with water (20 mL), acetone (20 mL), and CH_2Cl_2 (5 mL) and dried in vacuo. Yield: 0.18 g (90%). ^{1}H NMR ($CDCl_3$, 300 MHz): δ 6.39 (s, 3H, Ar H), 5.82 (s, 2, H4 3,5-Me_2pz), 5.65 (d, ^3J = 14.1 Hz, 2H, CH_2), 4.90 (d, ^3J = 13.8 Hz, 2H, CH_2), 2.65 (s, 6H, CH_3), 2.34 (s, 6H, CH_3). ^{13}C NMR ($CDCl_3$, 75 MHz): δ 152.3, 145.8, 140.0, 137.0, 125.0, 124.2, 107.0, 54.3, 15.5, 11.7. Anal. Calcd for $C_{18}H_{21}ClN_4Pd$: C, 49.67; H, 4.86; N, 12.87. Found: C, 49.78; H, 4.92; N, 12.80.

Synthesis of 1-(Aquapalladium)-2,6-bis[(3,5-dimethylpyrazol-1-yl)methyl]benzene Tetrafluoroborate (1c). To a stirred suspension of **3c** (110 mg, 0.24 mmol) in acetone (10 mL) was added a solution of $AgBF_4$ (47 mg, 0.24 mmol) in water (1.0 mL). The solution was stirred in the absence of light for 10 min and then filtered through Celite. The solvent was removed in vacuo and the residue extracted with acetone (15 mL). The solution was filtered, and a tan solid precipitated on addition of diethyl ether. Yield: 80 mg (66%). ^{1}H NMR (acetone-d_6, 300 MHz): δ 7.20 (d, ^3J = 7.5 Hz, 2H, Ar H), 7.03 (t, ^3J = 7.5 Hz, 1H, Ar H), 6.08 (s, 2H, H4 3,5-Me_2pz), 5.68 (d, ^3J = 14.4 Hz, 2H, CH_2), 5.40 (d, ^3J = 14.7 Hz, 2H, CH_2), 2.50 (s, 6H, CH_3), 2.25 (bs, 6H, CH_3). ^{13}C NMR (acetone-d_6, 75 MHz): δ 150.5, 142.6, 136.8, 126.1, 125.1, 106.8, 53.7, 12.9, 10.7. Anal. Calcd for $C_{18}H_{23}BF_4N_4OPd$: C, 42.84; H, 4.54; N, 11.10. Found: C, 42.71; H, 4.65; N, 10.98.

Synthesis of 1-(Aquapalladium)-2,6-bis[(diphenylphosphino)methyl]benzene Tetrafluoroborate (1d). $AgBF_4$ (0.21 g, 1.1 mmol) dissolved in wet acetone (1 mL) was added to a solution of **3d** (0.68 g, 1.1 mmol) in wet acetone (15 mL). This mixture was stirred in the absence of light at room temperature for 1 h. Subsequently, the reaction mixture was filtered and the filtrate was reduced to a volume of 10 mL. Et_2O (10 mL) was added, resulting in the precipitation of a white solid, which was collected, washed with Et_2O (2 × 10 mL), and dried in vacuo. Yield: 0.69 g (92%). ^{1}H NMR (acetone-d_6, 200 MHz): δ 7.93−7.83 (m, 8H, Ar H), 7.72−7.63 (m, 12H, Ar H), 7.28−7.17 (3H, Ar H), 4.24 (pseudo t, $^2J_{P,H}$ and $^4J_{P,H}$ = 4.8 Hz, 4H, CH_2). ^{31}P NMR (acetone-d_6): δ 47.9.

Synthesis of 1-(Aquapalladium)-2,6-bis[(phenylsulfido)methyl]benzene Tetrafluoroborate (1e). $AgBF_4$ (0.21 g, 1.1 mmol) in wet acetone (1 mL) was added to a solution of **3e** (0.51 g, 1.1 mmol) in wet acetone (15 mL). This mixture was stirred in the absence of light at room temperature for 1 h. Subsequently, the reaction mixture was filtered and the filtrate was reduced to a volume of 10 mL. Et_2O (10 mL) was added, resulting in the precipitation of a light yellow solid, which was collected, washed with Et_2O (2 × 10 mL), and dried in vacuo. Yield: 0.55 g (94%). ^{1}H NMR (acetone-d_6, 200 MHz): δ 7.90−7.96 (m, 4H, Ar H), 7.52−7.59 (m, 6H, Ar H), 7.10−7.13 (m, 3H, Ar H), 4.91 (bs, 4H, CH_2).

Synthesis of 3,5-Dimethyliodobenzene (4). A solution of $NaNO_2$ (30.0 g, 435 mmol) in H_2O (100 mL) was added dropwise over a period of 15 min to a solution of 3,5-dimethylaniline (50.0 g, 413 mmol) in aqueous H_2SO_4 (650 mL, 4.5 M) at −10 °C. The resulting reaction mixture was stirred at −10 °C for an additional 15 min, after which a solution of KI (80 g, 482 mmol) in H_2O (100 mL) was slowly added over a period of 5 min, while the temperature was maintained at −10 °C. The reaction mixture was warmed and stirred for 2 h each at 0, 20, and 90 °C. The resulting dark brown reaction mixture was cooled to room temperature and subsequently extracted with Et_2O (3 × 200 mL). The combined organic extracts were washed successively with aqueous Na_2SO_3 (100 mL, 1 M), aqueous NaOH (100 mL, 4 M), and brine (100 mL) and were then dried with K_2CO_3. After filtration, the filtrate was reduced in vacuo to leave a brown oily residue. This residue was flame-distilled from solid KOH (10 g) to afford $C_6H_3I(Me)_2$-3,5 (**4**) as a light orange oil. Yield: 67.1 g (70%). ^{1}H NMR (C_6D_6, 200 MHz): δ 7.18 (s, 2H, Ar H), 6.57 (s, 1H, Ar H), 1.90 (s, 6H, CH_3). ^{13}C NMR (C_6D_6, 50 MHz): δ 140.0, 135.4, 129.6, 94.9, 21.0.

Synthesis of 3,5-Bis(bromomethyl)iodobenzene (5). $C_6H_3IMe_2$-3,5 (**4**; 55.0 g, 237 mmol), *N*-bromosuccinimide (95.0 g, 534 mmol), and AIBN (azobis(isobutyronitrile); 2.63 g, 16 mmol) were mixed in methyl acetate (400 mL). This mixture was photolytically heated to reflux by irradiation of the flask with a 100 W IR bulb for 12 h (no additional heating source was used). The reaction mixture was then cooled to room temperature, followed by evaporation of the volatiles. This resulted in the formation of a solid residue, which was washed with cold hexanes (0 °C, 2 × 200 mL) and subsequently extracted with boiling hexanes (4 × 400 mL). The combined hexanes extract was heated to reflux to redissolve all solids, and the solution was cooled to room temperature over a period of 18 h. Crystals of pure **5** that had formed during this time were collected by filtration, washed with cold hexanes (0 °C, 2 × 200 mL), and dried in vacuo. Yield: 43.5 g (47%). Mp: 110−113 °C (lit.[16] mp 112−114 °C). ^{1}H NMR ($CDCl_3$, 200 MHz): δ 7.67 (s, 2H, Ar H), 7.38 (s, 1H, Ar H), 4.38 (s, 4H, CH_2). ^{13}C NMR ($CDCl_3$, 50 MHz): δ 140.3, 137.8, 129.0, 94.4, 31.4.

Synthesis of 3,5-Bis(methoxymethyl)iodobenzene (6). Synthesis as described by Duchêne and Vögtle[16] using **5** (75.9 g, 194 mmol) as the starting material. Yield: 54.0 g (95%). ^{1}H NMR ($CDCl_3$, 200 MHz): δ 7.58 (s, 2H, Ar H), 7.22 (s, 1H, Ar H), 4.35 (s, 4H, CH_2), 3.35 (s, 6H, OMe); ^{13}C NMR ($CDCl_3$, 50 MHz): δ 140.7, 135.6, 125.8, 94.5, 73.6, 58.4.

Synthesis of Bis[3,5-bis(methoxymethyl)phenyl]acetylene (7). Solid [$PdCl_2(PPh_3)_2$] (2.60 g, 3.7 mmol) and CuI (0.35 g, 1.85 mmol) were added to a stirring solution of 3,5-bis(methoxymethyl)iodobenzene (**6**; 54.0 g, 185 mmol) in Et_2NH (500 mL) at room temperature in a 1 L round-bottomed Schlenk tube. After stirring of the reagents, a slow stream of acetylene was passed through the stirred solution for 16 h at room temperature. The color of the reaction mixture gradually turned to dark red and after 16 h a two-phase system had formed. After in vacuo evaporation of the volatiles, the residue was extracted with hexanes (2 × 200 mL) and the combined organic extracts were stored at −25 °C for 24 h. The precipitated white solid which formed during this time was filtered off, washed with cold hexanes (−25 °C, 100 mL) and dried in vacuo to afford **7** as a white solid. Yield: 29.5 g (90%). Mp: 37−39 °C (lit.[16] 38−41 °C). ^{1}H NMR ($CDCl_3$, 200 MHz): δ 7.42 (s, 4H, Ar H), 7.28 (s, 2H, Ar H), 4.44 (s, 8H, CH_2), 3.39 (s, 12H, OMe). ^{13}C NMR ($CDCl_3$, 50 MHz): δ 136.6, 129.9, 126.7, 123.4, 89.3, 74.1, 58.3.

Synthesis of Hexakis[3,5-bis(methoxymethyl)phenyl]benzene (8). Synthesis was as described by Duchêne and Vögtle[16] using **7** (27.3 g, 77.0 mmol) and [$PdCl_2(NCPh)_2$] (12.1 g, 47.3 mmol) in benzene (150 mL). The workup was performed as follows: after evaporation of the volatiles, the solid residue was extracted with boiling hexanes (3 × 250 mL). The combined hexane extract was cooled to room temperature over a period of 20 h after which pure **8** had separated from the solution as colorless crystals, which were collected by filtration, washed with hexanes (2 × 100 mL) and dried in vacuo. Yield: 16.4 g (60%). ^{1}H NMR ($CDCl_3$, 200 MHz): δ 6.70 (s, 12H, Ar H), 6.61 (s, 6H, Ar H), 3.99 (s, 24H, CH_2), 2.83 (s, 36H, OMe). ^{13}C NMR ($CDCl_3$, 50 MHz): δ 140.4, 139.6, 136.6, 130.0, 124.3, 73.8, 56.8.

Synthesis of Hexakis[3,5-bis(bromomethyl)phenyl]benzene (9). Synthesis was as described by Duchêne and Vögtle[16] using **8** (16.4 g, 15.4 mmol), $BF_3{\cdot}Et_2O$ (80 mL, 635 mmol), and acetyl bromide (55 mL, 740 mmol) in CH_2Cl_2 (1200 mL). The workup was performed as follows: the reaction

mixture was cooled with an ice bath and aqueous Na_2CO_3 (25%, 400 mL) was slowly added. After complete addition the mixture was stirred for 15 min at room temperature. The CH_2Cl_2 layer was then collected, dried with $MgSO_4$, filtered, and concentrated to ca. 300 mL. Hexane was slowly added to the resulting solution, resulting in the separation of pure hexasubstituted benzene **9** as white crystals. The crystals were collected by filtration, washed with hexanes (2 × 100 mL), and dried in vacuo. Yield: 23.5 g (93%). ^{1}H NMR ($CDCl_3$, 200 MHz): δ 6.90 (s, 6H, Ar H), 6.83 (s, 12H, Ar H), 4.17 (s, 24H, CH_2). ^{13}C NMR ($CDCl_3$, 50 MHz): δ 140.4, 139.4, 137.6, 131.9, 127.1, 32.9.

Synthesis of Hexakis{3,5-bis[(dimethylamino)methyl]phenyl}benzene (10). Neat $HNMe_2$ (10 mL, 150 mmol) was added in one portion to a solution of **9** (1.65 g, 1.00 mmol) in CH_2Cl_2 (100 mL) at 0 °C. The reaction mixture was warmed to room temperature over a period of 1 h and was stirred for an additional 3 h. Aqueous NaOH (40 mL, 4 M, 160 mmol) was then added, the CH_2Cl_2 layer was collected, and the water layer was extracted with Et_2O (4 × 50 mL). The combined organic fraction was washed with saturated aqueous NaCl (50 mL), dried with $MgSO_4$ and filtered. Evaporation of the filtrate in vacuo afforded crude **10** as a pale yellow solid, mp 51−54 °C. Pure **10** was obtained by recrystallization of the corresponding HBF_4 salt, $[C_6\{C_6H_3(CH_2N(H)Me_2)_2\text{-}3,5\}_6](BF_4)_{12}$ (**10′**), which was prepared by addition of aqueous HBF_4 (35%, excess) to a solution of crude **10** in H_2O (20 mL). Addition of MeOH (150 mL) followed by warming of the mixture to ca. 60 °C afforded a clear solution, from which upon cooling to room temperature analytically pure white crystals (mp 161−163 °C) of the dodecakis(tetrafluoroborate) salt **10′** separated. The crystals were filtered off, washed with MeOH (2 × 30 mL) and dried in vacuo. Dissolution of crystalline **10′** in H_2O afforded a clear solution which was neutralized with aqueous NaOH (2 M, excess), followed by extraction of the desired product **10** with CH_2Cl_2 (3 × 60 mL). The combined CH_2Cl_2 extracts were dried with $MgSO_4$, filtered, and evaporated in vacuo to afford pure **10**. Yield: 0.96 g (79%).

10: ^{1}H NMR (C_6D_6, 200 MHz) δ 6.97 (s, 6H, Ar H), 6.94 (s, 12H, Ar H), 3.10 (s, 24H, CH_2), 1.98 (s, 72H, Me); ^{13}C NMR (C_6D_6, 50 MHz): δ 141.3, 140.5, 137.9, 131.5, 126.9, 64.5, 45.4.

10′: ^{1}H NMR (D_2O, 300 MHz) δ 7.37 (s, 12H, Ar H), 7.17 (s, 6H, Ar H), 4.05 (s, 24H, CH_2), 2.46 (s, 72H, $HNMe_2$); ^{13}C NMR (D_2O, 75 MHz) δ 141.8, 138.7, 134.9, 130.9, 130.6, 59.1, 41.9. Anal. Calcd for $C_{78}H_{126}B_{12}F_{48}N_{12}$ (**10′**): C, 41.21; H, 5.59; N, 7.39. Found: C, 41.19; H, 5.55; N, 7.35.

Synthesis of Hexakis{3,5-bis[(phenylsulfido)methyl]phenyl}benzene (11). Thiophenol (2.5 mL, 24.4 mmol) was added in one portion to a solution of **9** (1.65 g, 1.00 mmol) in degassed DMF (50 mL) under nitrogen at room temperature. Solid K_2CO_3 (7.9 g, 50 mmol) was added and the resulting mixture was stirred for 48 h at 50 °C. The volatiles were evaporated in vacuo and the residue was extracted with CH_2Cl_2 (3 × 50 mL). The combined organic fraction was washed with brine (50 mL), dried with $MgSO_4$ and filtered. Evaporation of the filtrate in vacuo afforded crude **11** as a pale yellow waxy solid. The hexasubstituted benzene **11** was purified by slow diffusion of pentane into a concentrated solution of crude **11** in CH_2Cl_2. This resulted in the formation of off-white crystals, which were collected by filtration, washed with pentane (50 mL), and dried in vacuo. Yield: 1.66 g (83%). ^{1}H NMR ($CDCl_3$, 300 MHz): δ 7.22−7.10 (m, 60H, Ar H), 6.96 (s, 12H, Ar H), 6.64 (s, 6H, Ar H), 3.67 (s, 24H, CH_2). ^{13}C NMR ($CDCl_3$, 75 MHz): δ 146.1, 140.9, 139.8, 137.2, 136.0, 130.8, 128.8, 126.9, 125.9, 38.4. MALDI-TOF-MS: *m*/*z* 1999.78 ($[M]^+$, calcd 2000.97), 1891.49 ($[M - SPh]^+$, calcd 1891.80), 1781.47 ($[M - 2\ SPh]^+$, calcd 1782.63). Anal. Calcd for $C_{126}H_{102}S_{12}$: C, 75.63; H, 5.14; S, 19.23. Found: C, 75.85; H, 5.29; S, 19.23.

Synthesis of Hexakis{3,5-bis[(diphenylphosphino)methyl]phenyl}benzene (12). *n*-BuLi (3.62 mL, 5.79 mmol) was added to $HPPh_2{\cdot}BH_3$ (1.08 g, 5.40 mmol) in THF (30 mL) at −70 °C. The temperature was allowed to rise to room temperature, and stirring was continued for 2 h. Next, this solution was added to a solution of **9** (0.50 g, 0.30 mmol) in THF (30 mL) at −40 °C. The temperature was allowed to rise to room temperature, and the mixture was stirred for another 18 h. All volatiles were evaporated, CH_2Cl_2 (75 mL) was added, and this mixture was washed with H_2O (3 × 50 mL) and dried over $MgSO_4$. The CH_2Cl_2 was evaporated, and the white solid was washed with hot EtOH (2 × 50 mL) and hexanes (3 × 50 mL) and dried in vacuo to give **12**·12BH_3 as a white air-stable powder. Yield: 0.87 g (94%). ^{1}H NMR (toluene-d_8, 300 MHz): δ 8.17 (pseudo t, $^3J_{H,H}$ and $^3J_{P,H}$ = 9 Hz, 24H, *o*-H Ar−P), 7.87 (pseudo t, $^3J_{H,H}$ and $^3J_{P,H}$ = 9 Hz, 24H, *o*-H Ar−P), 7.42−7.15 (m, 72H, Ar H), 6.55 (s, 12H, Ar H), 6.21 (s, 6H, Ar H), 4.07 and 3.39 (pseudo t, ABX, $^2J_{H,H}$ and $^2J_{P,H}$ = 12.5 Hz, 24H, CH_2), 1.61 (br s, 36H, BH_3). ^{13}C NMR ($CDCl_3$, 75 MHz): δ 32.38 (d, $^1J_{P,C}$ = 34.0 Hz), 128.4−140.5 (9 different Ar−C). ^{31}P NMR ($CDCl_3$, 121 MHz): δ 17.78. Anal. Calcd for $C_{198}H_{198}P_{12}B_{12}$: C, 77.23; H, 6.48; P, 12.07; B, 4.21. Found: C, 77.17; H, 6.64; P, 11.95; B, 4.16.

Removal of BH_3 from 12·12BH_3. $HBF_4{\cdot}OEt_2$ (1.98 mL, 6.60 mmol) was added dropwise to a solution of **12**·12BH_3 (0.31 g, 0.10 mmol) in CH_2Cl_2 (25 mL) at 0−5 °C. The temperature was allowed to rise to room temperature, and stirring was continued for 2 h. Next, a saturated $NaHCO_3$(aq) solution (50 mL) was added dropwise at 0 °C, resulting in considerable gas evolution. After complete addition the reaction mixture was stirred for 1 h at room temperature. The organic layer was collected, the water layer was washed with CH_2Cl_2 (2 × 25 mL), and the combined organic layer was dried ($MgSO_4$). After evaporation of all volatiles **12** was obtained as a white solid in quantitative yield. This product was used without further purification. ^{1}H NMR (C_6D_6, 200 MHz): δ 7.29−6.94 (m, 72H), 6.13 (s, 6H), 3.21 (br s, 24H). ^{13}C NMR (C_6D_6, 50 MHz): δ 139.6 (d, $^1J_{P,C}$ = 11.3 Hz), 136.4, 133.2 (d, $^2J_{P,C}$ = 12.1 Hz), 128 4, 128.3, 128.2, 127.9, 127.6, 36.3. ^{31}P NMR (C_6D_6, 54 MHz): δ −7.95 (s).

Synthesis of Hexakis{3,5-bis[(pyrazol-1-yl)methyl]phenyl}benzene (13). To a stirred suspension of finely cut potassium (0.16 g, 4.18 mmol) in dry THF (40 mL) was added pyrazole (0.30 g, 4.36 mmol). The mixture was heated to reflux and maintained at this temperature until the beads of molten potassium were no longer evident (±1 h). The resulting white suspension was cooled to ambient temperature, and **9** (0.50 g, 0.30 mmol) was added in one portion. The reaction mixture was heated at reflux for 15 h and then quenched by addition of H_2O (0.1 mL) and filtered; the solvent was removed in vacuo. The product was dissolved in CH_2Cl_2 (20 mL), the mixture was filtered, and the filtrate was reduced to ∼1 mL. The product precipitated as a white solid on addition of Et_2O and was finally crystallized from CH_2Cl_2/Et_2O, giving **13** as small white crystals. Yield: 0.40 g (89%). ^{1}H NMR ($CDCl_3$, 300 MHz): δ 7.46 (d, 12H, ^3J = 1.80 Hz, pz-H3), 6.80 (d, 12H, ^3J = 2.10, pz-H5), 6.65 (s, 6H, Ar H), 6.38 (s, 12H, Ar H), 6.15 (t, 12H, pz-H4), 4.84 (s, 24H, CH_2). ^{13}C NMR ($CDCl_3$, 75 MHz): δ 140.46, 139.28, 135.97, 130.05, 128.95, 125.20, 105.78, 55.09. Anal. Calcd for $C_{90}H_{78}N_{24}$: C, 72.27; H, 5.26; N, 22.47. Found: C, 72.35; H, 5.28; N, 22.36.

Synthesis of Hexakis{4-(chloropalladium)-3,5-bis[(phenylsulfido)methyl]phenyl}benzene (14). A solution of $[Pd(NCMe)_4](BF_4)_2$ (1.41 g, 3.2 mmol) in degassed MeCN (10 mL) was added over a period of 2 min to a solution of the hexasubstituted benzene $C_6\{C_6H_3(CH_2SPh)_2\text{-}3,5\}_6$ (**11**; 1.0 g, 0.50 mmol) in degassed MeCN (40 mL). A red-brown solution formed immediately and was heated at reflux for 5 h. The resulting solution was evaporated to ∼15 mL, and Et_2O (50 mL) was slowly added. This resulted in the precipitation of $[C_6(\{Pd(NCMe)\}C_6H_2(CH_2SPh)_2\text{-}3,5)_6](BF_4)_6$ as a pale yellow solid, which was collected, washed with Et_2O, and dried in vacuo. Yield: 1.56 g. Subsequently, this solid was dissolved in MeCN (80 mL), and LiCl (large excess) was added in one

portion. This resulted in a suspension which was stirred for an additional 15 h. Subsequently, the solid material was filtered off and washed with H_2O (100 mL) and Et_2O (2 × 100 mL), giving a yellow solid. This solid was dissolved in DMSO (80 mL), and THF (140 mL) was added, resulting in a white precipitate. This procedure was repeated three times, and the solid was collected and dried in vacuo, affording **14** as a light yellow solid. Yield: 1.28 g (90%). Yellow crystals suitable for X-ray analysis were obtained by suspension of **14** in toluene and addition of CH_2Cl_2 until all solids were dissolved, followed by slow evaporation of the solvent in air.[2h] ^{1}H NMR (DMSO-d_6, 200 MHz): δ 7.60−7.56 (m, 24H, Ar H), 7.44−7.31 (m, 36H, Ar H), 6.33 (s, 12H, Ar H), 4.20 (br s, 24H, CH_2). ^{13}C NMR (DMSO-d_6, 50 MHz): δ 161.06, 148.22, 139.38, 136.80, 132.09, 130.60, 130.28, 130.20, 125.65, 49.76. MALDI-TOF-MS: *m*/*z* 2811.52 ([M − Cl]$^+$, calcd. 2810.71). Anal. Calcd for $C_{126}H_{96}Cl_6Pd_6S_{12}$: C, 53.26; H, 3.48; S, 13.37. Found: C, 53.17; H, 3.40; S, 13.52.

Synthesis of Hexakis{4-(chloropalladium)-3,5-bis[(diphenylphosphino)methyl]phenyl}benzene (15). [Pd(NCMe)$_4$](BF$_4$)$_2$ (0.16 g, 0.38 mmol) dissolved in degassed MeCN (5 mL) was added to a suspension of **12** (0.18 g, 63 mmol) in degassed MeCN (15 mL), immediately resulting in a yellow solution. This mixture was heated at reflux for 110 h and then cooled to room temperature. The mixture was filtered over Celite and washed with MeCN (20 mL), and the filtrate was concentrated to ∼5 mL. Subsequently, Et_2O (10 mL) was added, resulting in a yellow precipitate, which was collected, washed with Et_2O (2 × 15 mL), and dried in vacuo. Yield: 0.25 g. The yellow solid was dissolved in acetone (15 mL), and LiCl (54 mg, 1.26 mmol) dissolved in H_2O (1 mL) was added. This mixture was stirred for 1 h at room temperature, resulting in the precipitation of a yellow solid. This solid was collected, washed with H_2O (2 × 15 mL), acetone (3 × 20 mL), and Et_2O (3 × 20 mL), and dried in vacuo, affording a brownish solid. Yield: 0.21 g (89%). ^{1}H NMR ($CDCl_3$, 200 MHz): δ 7.90−6.97 (br m, 120H, Ar H), 6.45 (br s, 12H, Ar H), 3.16 (br s, 24H, CH_2). ^{13}C NMR ($CDCl_3$, 75 MHz): δ 128.5−146.1 (9 different Ar C), 41.7. ^{31}P NMR ($CDCl_3$, 81 MHz): δ 34.29.

Synthesis of Hexakis{4-(acetatopalladium)-3,5-bis[(pyrazol-1-yl)methyl]phenyl}benzene (16). A solution of Pd(OAc)$_2$ (0.34 g, 1.53 mmol) and **13** (0.36 g, 0.24 mmol) in AcOH (20 mL) was heated to 120 °C and maintained at this temperature for 3 h. The resulting brown solution was cooled to ambient temperature. Dropwise addition of Et_2O eventually produced a precipitate. The mixture was centrifuged and the solution decanted. Et_2O was added a second time until a precipitate formed, and the mixture was again centrifuged and decanted. Et_2O (100 mL) was added to the resultant pale brown solution, and the product precipitated as a tan solid. The solution was decanted and the product immediately washed with Et_2O (2 × 50 mL) and then dried in vacuo, affording **16** as an off-white solid. Yield: 0.32 g (53%). ^{1}H NMR ($CDCl_3$, 300 MHz): δ 7.86 (br s, 12H, pz H), 7.15 (br s, 12H, pz H), 6.49 (br s, 12H, pz H), 6.12 (s, 12H, Ar H), 4.54 (br s, 24H, CH_2), 2.02 (s, 18H, CH_3CO). ^{13}C NMR ($CDCl_3$, 75 MHz): δ 142.28, 135.10, 130.92, 129.14, 107.30, 57.81. Anal. Calcd for $C_{102}H_{90}N_{24}O_{12}Pd_6$: C, 49.35; H, 3.65; N, 13.54. Found: C, 49.09; H, 3.75; N, 13.38.

Synthesis of Hexakis{4-(chloropalladium)-3,5-bis[(pyrazol-1-yl)methyl]phenyl}benzene (17). A solution of **16** (0.10 g, 40 mmol) was prepared by dissolution of the complex in acetone (30 mL) and addition of H_2O (3 mL). LiCl (17 mg, 0.4 mmol) was added to this solution, and the mixture was stirred at ambient temperature for 15 h. After this time a brown precipitate had formed, the mixture was centrifuged, and the solution was decanted. The solid residue was washed with H_2O (50 mL), acetone (50 mL), and Et_2O (50 mL) and then dried in vacuo, giving **17** as a brown solid. Yield: 70 mg (74%). Because the product was insoluble in common organic solvents, no NMR data were obtained and the product was derivatized as the corresponding aqua complex **18**.

Synthesis of Hexakis{4-(aquapalladium)-3,5-bis[(pyrazol-1-yl)methyl]phenyl}benzene Hexakis(tetrafluoroborate) (18). A solution of $AgBF_4$ (82 mg, 0.42 mmol) in H_2O (0.5 mL) was added to a stirred suspension of **17** (0.16 g, 70 mmol) in acetone (50 mL). The solution was stirred in the absence of light for 1 h. The solvent was removed in vacuo, the residue was extracted with acetone (50 mL), and the product **18** was precipitated as a white-tan powder on addition of Et_2O. Yield: 0.17 g (89%). ^{1}H NMR (acetone-d_6, 300 MHz): δ 8.10 (d, $^3J_{H,H}$ = 2.10 Hz, 12H, pz H), 7.53 (s, 12H, pz H), 6.81 (s, 12H, Ar H), 6.49 (t, 12H, pz H), 5.18 (s, 24H, CH_2). ^{13}C NMR (acetone-d_6, 75 MHz): δ 141.34, 137.59, 132.94, 129.19, 107.01, 56.52. Anal. Calcd for $C_{90}H_{84}B_6F_{24}N_{24}O_6Pd_6$: C, 39.21; H, 3.07; N, 12.19. Found: C, 39.06; H, 3.17; N, 12.11.

Synthesis of 1,3,5-Tris{4-bromo-3,5-bis[(dimethylamino)methyl]phenyl}benzene (20). A modification of a literature procedure was used.[20] To a stirred solution of 4-bromo-3,5-bis[(dimethylamino)methyl]acetophenone (1.3 g, 8.7 mmol) in dry ethanol (20 mL) was added tetrachlorosilane (5.0 mL, 43.6 mmol) at 0 °C. The reaction mixture was heated to reflux and kept at that temperature for 16 h. The reaction mixture (a white suspension) was cooled to room temperature, and aqueous HCl (25 mL, 4 M) was added, resulting in a brown solution. This layer was washed with CH_2Cl_2 (2 × 50 mL), and an NaOH solution (4 M) was added until a pH of 13−14 was reached. Next, the aqueous layer was extracted with CH_2Cl_2 (3 × 50 mL) and the combined organic fractions were dried over Mg_2SO_4. All volatiles were evaporated in vacuo, affording a white sponge. The product was purified by recrystallization from hexane at −30 °C. Yield: 0.79 g (70%). ^{1}H NMR ($CDCl_3$, 200 MHz): δ 7.78 (s, 3H, Ar H), 7.67 (s, 6H, Ar H), 3.66 (s, 12H, CH_2), 2.35 (s, 26H, CH_3). ^{13}C NMR ($CDCl_3$, 75 MHz): δ 141.9, 140.0, 139.5, 128.7, 126.8, 125.9, 64.4, 46.0. MALDI-TOF-MS: *m*/*z* 884.7 ([M + H]$^+$, calcd 883.2). Anal. Calcd for $C_{42}H_{57}Br_3N_6$: C, 56.96; H, 6.49; N, 9.49. Found: C, 56.82; H, 6.56; N, 9.44.

Synthesis of 1,3,5-Tris{4-(bromopalladium)-3,5-bis[(dimethylamino)methyl]phenyl}benzene (21). Ligand **20** (0.65 g, 0.73 mmol) and Pd(dba)$_2$ (1.39 g, 2.40 mmol) were dissolved in benzene (100 mL) and stirred at room temperature for 20 h. All volatiles were evaporated in vacuo, THF (100 mL) was added, and stirring was continued for 1 h, affording a black precipitate. The mixture was filtered through Celite, and the filtrate was evaporated to dryness. The remaining solid was dissolved in CH_2Cl_2 (10 mL), and Et_2O (50 mL) was added, yielding a yellow solid. This procedure was repeated three times, resulting in a light yellow solid. Yield: 0.63 g (72%). Analytically pure brownish crystals were obtained by slow diffusion of Et_2O into a concentrated solution of the product in CH_2Cl_2. ^{1}H NMR ($CDCl_3$, 200 MHz): δ 7.53 (s, 3H, Ar H), 7.06 (s, 6H, Ar H), 4.06 (s, 12H, CH_2), 3.01, (s, 36H, CH_3). ^{13}C NMR ($CDCl_3$, 75 MHz): δ 157.4, 145.8, 142.9, 138.4, 124.6, 119.1, 74.8, 54.1. MALDI-TOF-MS: *m*/*z* 1128.6 ([M − Br]$^+$, calcd 1128.0). Anal. Calcd for $C_{42}H_{57}Br_3N_6Pd_3$: C, 41.87; H, 4.77; N, 6.97. Found: C, 42.03; H, 4.72; N, 6.88.

Synthesis of 1,3,5-Tris{4-bromoplatinum-3,5-bis[(dimethylamino)-methyl]phenyl}benzene (22): Ligand **20** (0.60 g, 0.69 mmol) and [Pt(tol)$_2$SEt$_2$]$_2$ were mixed in benzene (50 mL), and this mixture was refluxed for 3 h, resulting in a yellow precipitate. The reaction mixture was cooled to room temperature, and all volatiles were evaporated. Next, the yellow solid was extracted with CH_2Cl_2 (20 mL) and Et_2O was added, yielding a yellow precipitate. This yellow solid was collected, washed with Et_2O (3 × 20 mL) and dried in vacuo. Yield: 0.74 g (73%). ^{1}H NMR ($CDCl_3$, 200 MHz): δ 7.59 (s, 3H, Ar H), 7.11 (s, 6H, Ar H), 4.09 (s, $^3J_{Pt,H}$ = 22.0 Hz, 12H, CH_2), 3.16 (s, $^3J_{Pt,H}$ = 18.0 Hz, 36H, CH_3). ^{13}C NMR ($CDCl_3$, 50 MHz): δ 146.32, 144.13, 143.56, 137.24, 123.91, 118.79,

77.72, 55.93. Anal. Calcd for $C_{42}H_{57}Br_3N_6Pt_3$: C, 34.29; H, 3.91; N, 5.71. Found: C, 34.38; H, 3.82; N, 5.66.

Synthesis of 1,3,5-Tris{4-(aquapalladium)-3,5-bis[(dimethylamino)methyl]phenyl}benzene Tris(tetrafluoroborate) (23). To a solution of **21** in wet acetone (20 mL) was added $AgBF_4$ (0.20 g, 1.0 mmol) in water (1 mL). This mixture was stirred for 30 min at room temperature and then filtered over Celite. The filtrate was concentrated, and the product was extracted into acetone (20 mL). Upon slow addition of Et_2O (20 mL) a white precipitate was formed, which was collected and was dried in vacuo. Yield: 0.26 g (76%). ^{1}H NMR (acetone-d_6, 200 MHz): δ 7.72 (s, 3H, Ar H), 7.32 (s, 6H, Ar H), 4.23 (s, 12H, CH_2), 2.89 (s, 36H, CH_3). ^{13}C NMR (acetone-d_6, 75 MHz): δ 150.94, 146.28, 142.89, 138.79, 124.26, 119.46, 73.62, 51.78. Anal. Calcd for $C_{42}H_{63}B_3F_{12}N_6O_3Pd_3$: C, 39.42; H, 4.96; N, 6.57. Found: C, 39.64; H, 5.20; N, 6.42.

Typical Catalytic Experiment. Ethyl α-cyanoacetate (0.17 mL, 1.6 mmol), methyl vinyl ketone (0.40 mL, 4.8 mmol), diisopropylethylamine (28 μL, 0.16 mmol), and **1a** (3.2 mg, 8 μmol, 0.5 mol %) were dissolved in CH_2Cl_2 (5 mL), and the mixture was stirred at room temperature. The reaction mixture was sampled (100 μL) at regular intervals, and the samples were worked up by evaporating all solvent and methyl vinyl ketone with a gentle stream of nitrogen. The conversion in the worked up samples was determined by ^{1}H NMR spectroscopy. Conversions obtained were confirmed by GC-MS analysis of the reaction mixture. All reactions which were complete within 22 h were repeated and isolated yields obtained by bulb-to-bulb distillation. For all reactions yields were found to be between 85 and 100%.

Crystal Structure Determination of 21. Crystal data are as follows: $C_{42}H_{57}Br_3N_6Pd_3$ + solvent, fw = 1204.87,[25] yellow block, 0.30 × 0.30 × 0.24 mm^3, trigonal, $R\bar{3}c$ (No. 167), $a = b = 15.6134(2)$ Å, $c = 35.2061(5)$ Å, $V = 7432.64(17)$ Å^3, $Z = 6$, $\rho = 1.615$ g/cm^3. A total of 32 401 reflections were measured on a Nonius Kappa CCD diffractometer with a rotating anode ($\lambda = 0.710\ 73$ Å) at a temperature of 150(2) K. Of these, 1874 reflections were unique ($R_{int} = 0.062$).[25] The absorption correction was based on multiple measured reflections (program PLATON,[26] routine MULABS, $\mu = 3.53$ mm^{-1},[25] transmission factors 0.34−0.39). The structure was solved with Patterson methods (DIRDIF97)[27] and refined with SHELXL97[28] against F^2 values of all reflections. Non-hydrogen atoms were refined freely with anisotropic displacement parameters. Hydrogen atoms were refined as rigid groups. The crystal structure contains large isolated voids at the crystallographic origin and its five symmetry-related positions (193 Å^3/void, 1162 Å^3/unit cell) filled with disordered dichloromethane and diethyl ether molecules. Their contribution to the structure factors was secured by back-Fourier transformation (program PLATON,[26] CALC SQUEEZE, 473 e/unit cell). There were 85 refined parameters, with no restraints. R values ($I > 2\sigma(I)$): R1 = 0.0281, wR2 = 0.0670. R values (all reflections): R1 = 0.0288, wR2 = 0.0674. GOF = 1.125. The rest electron density was between −0.47 and 0.71 e/Å^3. Molecular illustration, structure checking, and calculations were performed with the PLATON package.[26]

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Supporting Information Available: Tables giving crystal data and structure refinement details, positional and thermal parameters, and bond distances and angles for **21**. This material is available free of charge via the Internet at http://pubs.acs.org.

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(25) Derived values do not contain the contribution of the disordered solvent.

(26) Spek, A. L. PLATON: A Multipurpose Crystallographic Tool; Utrecht University, The Netherlands, 2000.

(27) Beurskens, P. T.; Admiraal, G.; Beurskens, G.; Bosman, W. P.; Garcia-Granda, S.; Gould, R. O.; Smits, J. M. M.; Smykalla, C. The DIRDIF97 Program System, Technical Report of the Crystallography Laboratory; University of Nijmegen, Nijmegen, The Netherlands, 1997.

(28) Sheldrick, G. M. SHELXL-97: Program for Crystal Structure Refinement; University of Göttingen, Göttingen, Germany, 1997.