Supplementary Material (ESI) for Chemical Communications

Supplementary Information

Component exchange as a synthetically advantageous strategy for the preparation of bicyclic cage compounds

Mateo Alajarín,*[a] José Berná,*[a] Carmen López-Leonardo,[a] Jonathan W. Steed[b]

[a] Departamento de Química Orgánica. Facultad de Química. Universidad de Murcia. Campus de Espinardo. 30100 Murcia, Spain. Fax: +34 968 364149; Tel: +34 968 367497; E-mail: alajarin@um.es; ppberna@um.es

[b] Department of Chemistry, University of Durham, South Road, Durham DH1 3LE, UK

1. General Experimental Section

All melting points were determined on a Kofler hot-plate melting point apparatus and are uncorrected. Infrared (IR) spectra were recorded neat or as nujol emulsions on a Nicolet Impact 400 spectrophotometer. NMR spectra were recorded at 298 K on a Bruker AC 200 or a Varian Unity 300. Chemical shifts are expressed in ppm, relative to Me_4Si at δ = 0.00 ppm for ^1H, while the chemical shifts for ^{13}C are reported relative to the resonance of $CDCl_3$ δ = 77.00 ppm. ^{31}P chemical shifts were externally referenced to 85% aqueous phosphoric acid. Abbreviations of coupling patterns are as follows: s, singlet; d, doublet; t, triplet; q, quadruplet. Mass spectra were recorded on a Hewlett-Packard 5993C spectrometer (EI) or on a VG-Autospec spectrometer (FAB^+). Microanalyses were performed on a Carlo Erba EA-1108 instrument.

2. Materials

Compounds tris(*o*-azidobenzyl)amine,[1] tris(*m*-azidobenzyl)amine,[2] triphosphazide *orto* **1**,[3] triphosphazide *meta* **2a**,[4] triphosphazide *meta* **2b**,[5] tris(2-diphenylphosphinoethyl)phosphine selenide[6] (**4**), tris(2-diphenylphosphinoethyl)amine[7] (**6**), and tris(5-azido-2-bromobenzyl)amine[2] were prepared following previously reported procedures.

3. Experimental procedures and characterization of the tri-λ^5-phosphazenes 5, 7 and 8

Self-assembly of triphosphazides from ternary mixtures (Scheme 1):

Path A: A solution of *triphos* (125 mg, 0.2 mmol) in diethyl ether (10 mL) and other formed by dissolving an equimolar mixture of tris(2-azidobenzyl)amine (82 mg, 0.2 mmol) and tris(3-azidobenzyl)amine (82 mg, 0.2 mmol) in diethyl ether (10 mL) were simultaneously added to a round-bottom flask containing diethyl ether (15 mL) under nitrogen at room temperature over a period of 45 min with stirring. The resulting mixture was then stirred for 90 min. The precipitated pale yellow solid was filtered, washed with diethyl ether (3 x 10 mL), and dried under vacuum to give a microcrystalline yellow powder corresponding to an equimolar mixture of the triphosphazides **1** and **2a**.

Path B: Alternatively, the reaction was carried out in a similar manner, using deuterated chloroform as solvent to follow the reaction progress by ^{1}H NMR. After 90 min, volatiles were removed under reduced pressure and the resulting residue was triturated with diethyl ether (2 x 5 mL) to get a yellow solid which showed identical analytical and spectroscopic data to those reported for triphosphazide **2a** while tris(2-azidobenzyl)amine remained in the ethereal solution.

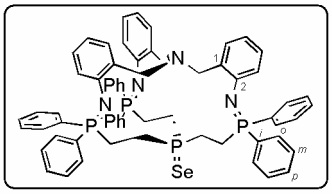
Synthesis of triphosphazide 2a by triazide exchange (Scheme 2): Equimolar amounts of tris(3-azidobenzyl)amine (21 mg, 0.05 mmol) and the triphosphazide **1** (52 mg, 0.05 mmol) were solubilized at room temperature in deuterated chloroform in a NMR tube to form a 0.1 M solution. The tube was sealed with Teflon caps to keep a stable

concentration and ^{1}H and ^{31}P NMR spectra were recorded until the equilibrium was reached. Then, the solvent was removed under reduced pressure and the resulting residue was triturated with diethyl ether (2 x 2 mL) to get a yellow solid which showed identical analytical and spectroscopic data to those reported for triphosphazide **2a** while tris(2-azidobenzyl)amine remained in the ethereal solution.

Synthesis of the tri-λ^5-phosphazenes 5, 7 and 8 (Scheme 3 and 4).

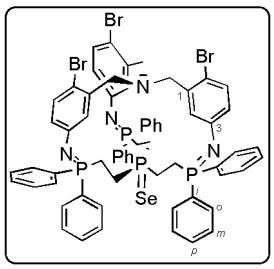
Path A (by a reassembly of the triphosphazides): A solution of the corresponding triphosphane (0.07 mmol) in deuterated chloroform (1 mL) was added dropwise over a period of 10 min to a stirred solution of the triphosphazide **1**, **2a** or **2b** (0.07 mmol) in deuterated chloroform (3 mL). The resulting mixture was stirred at room temperature for 36 h. Then, volatiles were removed under reduced pressure and the resulting residue was treated with diethyl ether (2 mL). The resulting solid was isolated by filtration and subjected to column chromatography using deactivated silica gel (5% Et_3N in hexanes) and a solvent gradient of $CHCl_3$ to $CHCl_3$/MeOH (95/5) to give the product as a white solid.

Path B (by a direct tripod-tripod coupling): A solution of a triazide (0.4 mmol) in diethyl ether (10 mL) and the appropriate triphosphane (0.4 mmol) in diethyl ether (10 mL) were simultaneously added dropwise to a round bottom flask containing the same solvent (20 mL) under nitrogen atmosphere at room temperature over a period of 1 h with stirring. The resulting mixture was stirred for 24 h. Then, the solvent was removed under reduced pressure to afford a pale brown solid that was treated with diethyl ether (5 mL). The resulting solid was isolated by filtration and purified by column chromatography as described above to give the corresponding tri-λ^5-phosphazene as a white solid.

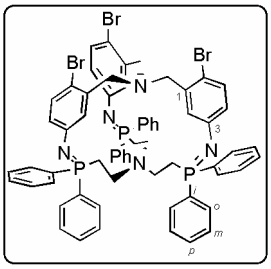


Tri-λ^5-phosphazene 5: Yield: 84% (A), 37% (B). M.p. 167 - 169 ºC; ^{1}H NMR (300 MHz, $CDCl_3$): δ = 2.40 (m, 6 H; CH_2PN), 3.00 (m, 6 H; CH_2PSe), 4.16 (s, 6 H; CH_2N),

6.27 (m, 3 H; H_{Ar}), 6.71 (dd, J(H,H) = 5.9, 3.5 Hz, 6 H; H_{Ar}), 7.23 - 7.65 (m, 33 H; H_{Ar}); ^{13}C NMR (75 MHz, $CDCl_3$): δ = 24.62 (br d, ^1J(C,P) = 94.5 Hz; CH_2PSe); 25.98 (dd, ^1J(C,P) = 40.0, ^2J(C,P) = 7.2 Hz; CH_2PN), 53.97 (CH_2N), 117.81 (C_6), 120.72 (d, ^3J(C,P) = 9.3 Hz; C_3), 126.07 (C_4), 128.95 (d, ^2J(C,P) = 11.0 Hz; *o*C-PhP), 130.20 (d, ^1J(C,P) = 80.0 Hz; *i*C-PhP), 130.38 (C_5), 131.87 (br s; *p*C-PhP), 131.93 (d, ^3J(C,P) = 9.3 Hz; *p*C-PhP), 134.25 (d, ^2J(C,P) = 22.0 Hz; C_1), 149.18 (C_2); ^{31}P NMR (121.4 MHz, $CDCl_3$): δ = 3.50 (d, ^3J(P,P) = 47.4 Hz, 3 P; PN), 37.94 (q, ^3J(P,P) = 47.4 Hz, 1 P; PSe); IR (Nujol): ν = 1466 (CP), 1112 (NP) cm^{-1}; MS (FAB$^+$): *m/z* (%) = 1077 (27) [M^+ + 1], 1076 (42) [M^+], 1012 (10), 786 (8); $C_{63}H_{60}N_4P_4Se$ (1076.03): calcd C 70.32; H 5.62; N 5.21; found C 70.11; H 5.55; N 5.18.



Tri-λ^5-phosphazene 7: Yield: 60% (A), 23% (B). M.p. 261 - 263 ºC; ^{1}H NMR (300 MHz, $CDCl_3$): δ = 2.70 - 2.85 (m, 12 H; CH_2CH_2P), 3.43 (br s, 6 H; CH_2N), 6.52 (dd, J(H,H) = 0.5, 1.9 Hz, 3 H; H_2), 7.13 (d, J(H,H) = 1.0, 8.6 Hz, 3 H; H_4), 7.24 (d, J(H,H) = 2.4 Hz, 3 H; H_{Ar}), 7.30 - 7.35 (m, 12 H; H_{arom}), 7.46 (m, 6 H; H_{arom}), 7.54 - 7.61 (m, 12 H; H_{arom}); ^{13}C NMR (75 MHz, $CDCl_3$): δ = 23.89 (dd, ^1J(C,P) = 73.0 Hz, ^2J(C,P) = 5.2 Hz; CH_2PSe), 23.91 (d, ^1J(C,P) = 58.0 Hz; CH_2PN), 58.29 (CH_2N), 111.77 (C_6), 123.66 (d, ^3J(C,P) = 23.1 Hz; C_2 or C_4), 123.67 (d, ^3J(C,P) = 6.7 Hz; C_2 or C_4), 128.91 (d, ^3J(C,P) = 11.6 Hz; *m*C-PhP), 129.81 (d, ^1J(C,P) = 92.8 Hz; *i*C-PhP), 131.49 (d, ^2J(C,P) = 9.3 Hz; *o*C-PhP), 132.10 (br s; *p*C-PhP), 132.56 (C_5), 138.51 (C_1), 150.13 (C_3); ^{31}P NMR (121.4 MHz, $CDCl_3$): δ = 4.92 (d, ^3J(P,P) = 36.9 Hz, 3 P; PN), 46.48 (q, ^3J(P,P) = 36.9 Hz, 1 P; PSe); IR (Nujol): ν = 1468 (CP), 1121 (NP) cm^{-1}; MS (FAB$^+$): *m/z* (%) = 1316 (19) [M^+ + 6], 1314 (83) [M^+ + 4], 1312 (100) [M^+ + 2], 1310 (7) [M^+]; $C_{63}H_{57}Br_3N_4P_4Se$ (1312.72): calcd C 57.64; H 4.38; N 4.27; found C 57.41; H 4.42; N 4.12.



Tri-λ^5-phosphazene 8: Yield: 76% (A), 40% (B). M.p. 276 - 278 ºC; ^{1}H NMR (300 MHz, $CDCl_3$): δ = 2.30 - 3.10 (m, 12 H; CH_2CH_2P), 3.31 (br s, 6 H; CH_2N), 6.50 (d, J(H,H) = 1.9 Hz, 3 H; H_2), 7.15 (d, J(H,H) = 8.4 Hz, 3 H; H_4), 7.21 - 7.67 (m, 33 H; H_{arom}); ^{13}C NMR (75 MHz, $CDCl_3$): δ = 28.32 (d, ^1J(C,P) = 46.3 Hz; NCH_2CH_2P), 42.78 (NCH_2CH_2P), 57.94 ($ArCH_2N$), 111.51 (C_6), 118.22 (d, ^3J(C,P) = 10.1 Hz; C_2), 123.98 (d, ^3J(C,P) = 23.6 Hz; C_4), 128.92 (d, ^3J(C,P) = 11.4 Hz; *m*C-PhP), 130.97 (d, ^1J(C,P) =101.3 Hz; *i*C-PhP), 131.16 (d, ^2J(C,P) = 9.2 Hz; *o*C-PhP), 132.33 (br s; *p*C-PhP), 132.64 (C_5), 138.93 (C_1), 151.16 (C_3); ^{31}P NMR (121.4 MHz, $CDCl_3$): δ = 7.34 (s); IR (Nujol): ν = 1465 (CP), 1119 (NP) cm^{-1}; MS (FAB$^+$): *m/z* (%) =1219 (11) [M^+ + 6], 1217 (91) [M^+ + 4], 1215 (100) [M^+ + 2], 1213 (28) [M^+]; $C_{63}H_{57}Br_3N_5P_3$ (1216.79): calcd C 62.19, H 4.72, N 5.76; found C 61.90, H 4.83, N 5.70.

4. General crystal data and structure refinement for the tri-λ^5-phosphazene 5:

a) b)

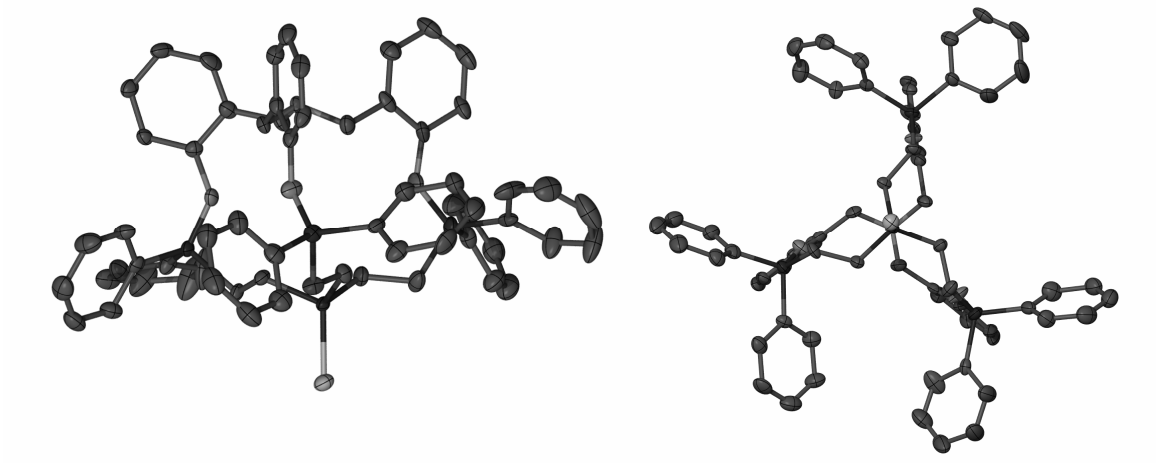


Figure S1: a) ORTEP drawing of the molecular structure of **5**, b) perspective view as projected along the threefold axis. In both, thermal ellipsoids are drawn at 50% probability level and the hydrogen atoms and solvent molecules are omitted for clarity.

Table S1. Crystal data and structure refinement for **5**.[§]

Empirical formula	C_{68} H_{71} Cl_3 N_4 O P_4 Se [**5**·$CHCl_3$·$(C_2H_5)_2O$]	
Formula weight	1269.48	
Temperature	110(2) K	
Wavelength	0.71073 Å	
Crystal system	Monoclinic	
Space group	P21/n	
Unit cell dimensions	a = 13.2007(4) Å	α= 90°.
	b = 23.8974(6) Å	β= 97.571(2)°.
	c = 20.0702(6) Å	γ = 90°.
Volume	6276.2(3) $Å^3$	
Z	4	
Density (calculated)	1.344 Mg/m^3	
Absorption coefficient	0.874 mm^{-1}	
F(000)	2640	
Crystal size	0.40 x 0.20 x 0.15 mm^3	
Theta range for data collection	2.05 to 25.00°.	
Index ranges	-15<=h<=15, -28<=k<=28, -20<=l<=23	
Reflections collected	30512	
Independent reflections	11027 [R(int) = 0.0858]	
Completeness to theta = 25.00°	99.6 %	
Absorption correction	Scalepack	
Max. and min. transmission	0.8800 and 0.7211	
Refinement method	Full-matrix least-squares on F^2	
Data / restraints / parameters	11027 / 24 / 805	
Goodness-of-fit on F^2	1.040	
Final R indices [I>2sigma(I)]	R1 = 0.0813, wR2 = 0.1819	
R indices (all data)	R1 = 0.1243, wR2 = 0.2021	
Largest diff. peak and hole	0.919 and -0.596 e.$Å^{-3}$	

[§] CCDC reference number 671014

5. Detection of intermediates during the synthesis of the macrobicyclic tri-λ^5-phosphazene 5 by triphosphane exchange.

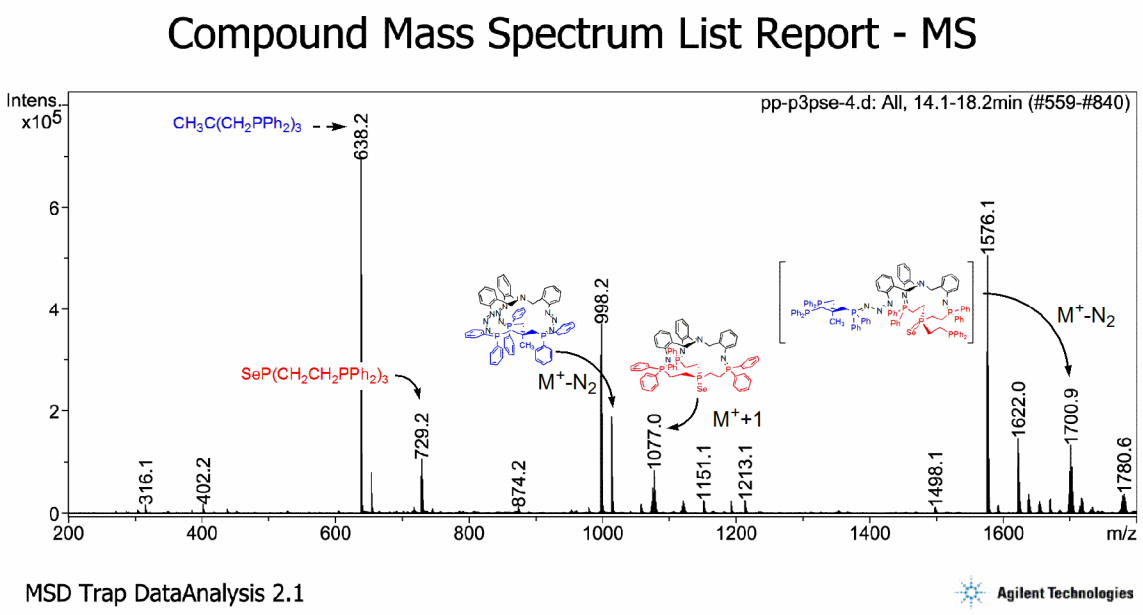


Figure S2: LC-MS analysis of the crude of the triphosphane exchange in **1** by tris(2-diphenylphosphinoethyl)phosphine selenide (**4**) to give the tri-λ^5-phosphazene **5**.

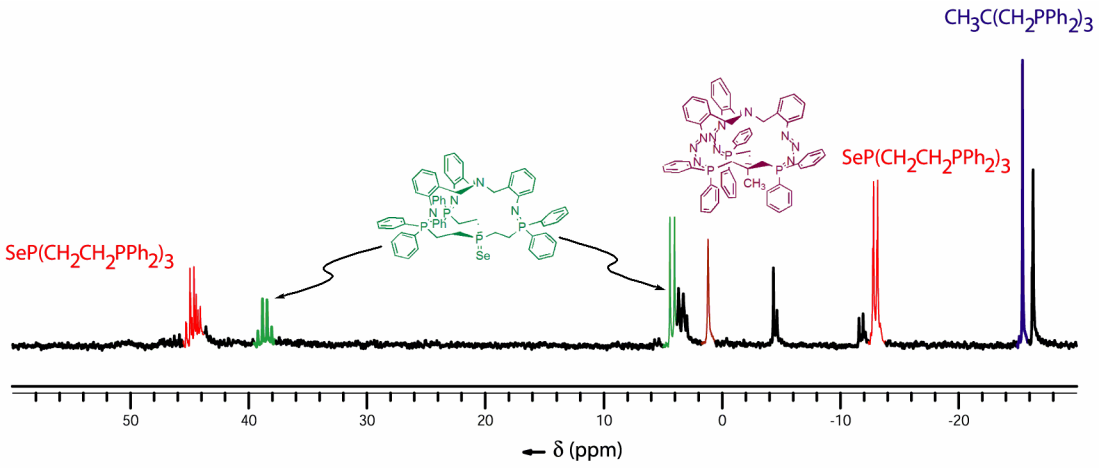


Figure S3: ^{31}P NMR spectrum (121 MHz, $CDCl_3$, 298K) of the crude of the triphosphane exchange in **1** by tris(2-diphenylphosphinoethyl)phosphine selenide (**4**) to give the tri-λ^5-phosphazene **5**. The signals in black are assigned to the intermediates with a tribenzylamine skeleton and two linked triphosphane moieties, one of *triphos* and other of tris(2-diphenylphosphinoethyl)phosphine selenide.

6. References

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