Star-shaped heavily fluorinated aromatic sulfurs: stabilization of palladium nanoparticles active as catalysts in cross-coupling reactions†

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Two star-shaped heavily fluorinated compounds have been prepared and used as stabilizers of palladium nanoparticles. These materials are useful and reutilizable catalysts in Mizoroki–Heck, Suzuki and Sonogashira cross-couplings.

Introduction

Fluoroorganic compounds have a unique set of physical and chemical properties.[1] The special physical properties are governed by the extremely low polarizability of fluorine, and the combination of high electronegativity with a moderate size. Another characteristic of fluoroorganic compounds is the excellent match between the fluorine and carbon 2s and 2p orbitals which explains the extreme chemical stability of the carbon–fluorine bond. The unique properties of highly fluorinated and perfluorinated solvents and reagents have opened up several solutions to the problem of recovering and recycling catalysts (fluorous biphase catalysis) and to a sustainable green chemistry (non-toxicity and extreme chemical inertness).[2]

Metallic nanoparticles, in general defined as having a diameter between 1 and 100 nm, have attracted a great deal of attention in the last ten years.[3] They are formed following a process of several steps which consist first in the generation of atoms, then nucleation to form a cluster and finally growing of the cluster up to a certain volume. Of course the cluster must be surrounded by a shell of an adequate protecting agent that prevents their agglomeration. Some of the well known protecting agents provide steric stabilization through a functional group with high affinity for metals including thiols, amines, phosphines and sulfides. Heavily fluorinated compounds do not seem ideal stabilizers for nanoparticles. It is well known that a consequence of the low polarizability of perfluorocarbons is very weak intermolecular dispersion interactions and an extremely low surface tension as there are very small attractive interactions among themselves and other materials. Despite these properties some of us have previously reported that some heavily fluorinated compounds can indeed stabilize transition-metal nanoparticles.[4] As an extension we wanted to design new constituents of protecting shields for nanoparticles possessing different features that could enhance the stabilizing effects: (i) heavily perfluorinated; (ii) sterically demanding; and (iii) possessing an endowed functional group with high affinity for metals.

In recent years, nanoparticles suspensions of transition metals have shown efficient activities in the field of catalysis.[5] One of the key goals in the use of metal nanoparticles in catalysis is the recyclability of the metal colloids. We present here the synthesis of new aromatic sulfurs from commercially accessible compounds such as cyanuric chloride and hexafluoro- or hexachlorobenzene. Two methods are proposed using stoichiometric amounts of thiols. Two heavily fluorinated star-shaped aromatic compounds, possessing functional groups with an affinity for palladium, have been prepared (Fig. 1, **4c** (63.9% F) and **7c** (65.8% F)) and used in the preparation of palladium(0) nanoparticles. These materials are useful and reutilizable catalysts in Mizoroki–Heck, Suzuki and Sonogashira cross-couplings.

Results and discussion

We have based the synthesis of 2,4,6-tri-substituted-1,3,5-triazines, **4**, on the functionalization of the less expensive cyanuric chloride, **1**. Several specific protocols have been developed for the nucleophilic substitution of the C–Cl bond by C–O, C–N and C–S.[6] We report here that chloride can be exchanged in compound **1** with a variety of sulfur nucleophiles by treating thiols **2a–c** in THF in the presence of Cs_2CO_3 as a base and substoichiometric amounts of Bu_4NCl to solubilize the thiolate anion (Scheme 1 and entries 1, 2, 3 of Table 1). This method was previously described[7] by our group to perform S_NAr reactions of weakly activated 4-fluorophenyl-

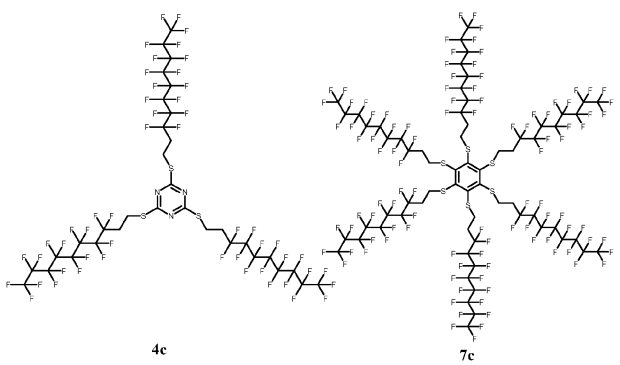

Fig. 1 Star-shaped heavily fluorinated compounds.

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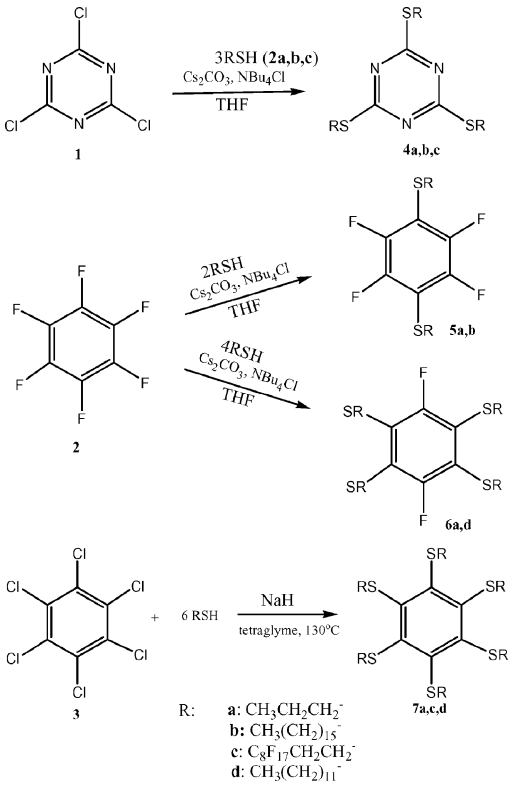


Scheme 1 Preparation of aromatic sulfurs **5**, **6** and **7**.

sulfonamides and worked with only one mol of nucleophile per chloride or fluoride atom, an important requirement when using valuable nucleophiles. Heavily fluorinated **4c** (63.9% of F) was obtained in 68% yield (entry 3 of Table 1).

Moreover, we explored the nucleophilic aromatic substitution of hexahalobenzenes **2** and **3**. First we selected hexafluorobenzene having in mind that among halogens fluoro is generally the best leaving group in S_NAr. Furthermore these substitutions are accelerated by electron-withdrawing effects, especially in positions *ortho* and *para* to the leaving group, and hindered by electron-donating groups. Using the same experimental protocol described for **1** (see experimental part, in this case refluxing THF was used), substitution of the six fluorine atoms of hexafluorobenzene by thiolates was not achieved. Furthermore there was no evidence of mono-, tri- or penta-substituted products, only di- (**5a, b**, Scheme 1 and entries 4 and 5 of Table 1) and tetra-substituted (**6a, d**, Scheme 1 and entries 6 and 7 of Table 1) compounds could be prepared depending on the stoichiometric amount of nucleophile. The monosubstituted product appeared to react with the nucleophile at least as readily as the hexafluorobenzene. The action of nucleophilic thiolate agents on monosubstituted derivatives (C_6F_5SR) led to the formation of *para*-isomers. The known ability of sulfur to stabilize a negative charge next to it, due to favourable overlap interactions with available d orbitals, rationalises the observed *para*-directing orientation of the –SR group giving *para*-$C_6F_4(SR)_2$ compounds.[8] Further substitutions are governed by significant activation of –SR at *para* and –F at *ortho* positions and led to $C_6F_2(SR)_4$ with the two remaining fluorines *para* to each other (Scheme 1).[9]

Table 1 Reactions of **1**, **2** and **3** with thiolates (Schemes 1 and 2)

Entry	Substrate	RSH	Method[a]	Time	Product	Yield(%)
1	**1**	**2a**	a	4 d	**4a**	68
2	**1**	**2b**	a	6 d	**4b**	85
3	**1**	**2c**	a	7 d	**4c**	68
4	**2**	**2a**	a	1 d	**5a**	81
5	**2**	**2b**	a	3 d	**5b**	94
6	**2**	**2a**	a	3 d	**6a**	88
7	**2**	**2d**	a	14 d	**6d**	92
8	**3**	**2a**	b	42 h	**7a**	93
9	**3**	**2d**	b	42 h	**7d**[10]	73
10	**3**	**2c**	b	42 h	**7c**	54

[a] Method a: RSH, Cs_2CO_3 (excess), NBu_4Cl (12 mol%), THF, r.t.; Method b: RSH, NaH, tetraglyme, 130 °C.

Then, conditions were changed to force reactivity. Reaction of hexafluorobenzene, **2**, with **2d** at 130 °C using NaH in refluxing tetraglyme[10] gave the tetrasubstituted compound **6d**. However, the reaction of hexachlorobenzene, **3**, with sodium thiolates of **2a, d, c** gave the hexasubstituted products in 93, 73, 54% yields, respectively (Scheme 1 and entries 8, 9 and 10 of Table 1). Heavily fluorinated **7c** (65.7% of F) was obtained in 54% yield.

As we have mentioned, we prepared **4c** and **7c** as candidates for nanoparticle stabilization. Thus, palladium nanoparticles were prepared by the reduction of soluble ionic $Na_2(Pd_2Cl_6)$ (prepared from palladium(II) chloride and sodium chloride, see experimental part) with methanol at 60 °C in the presence of compounds **4c** and **7c**. Addition of sodium acetate induced precipitation of the material. The results are summarized in Table 2. As expected when working with an excess of palladium salt (ratio 2), nanoparticles possessing a higher amount of metal (13.3%) were obtained. In all cases very small nanoparticles of fcc-Pd(0) were formed (1.7–5 nm, Table 2 and Fig. 2). The nanoparticle size is normally associated with its reactivity. The decomposition points of the materials were similar to the melting points of **4c** and **7c**. With respect to the phenomenon of stabilization we propose that nanoparticles are entrapped in the solid network of the heavily fluorinated compounds. Initial interactions are probably due to the presence of sulfur and nitrogen, good coordinating atoms for palladium. Then, the presence of long perfluorinated chains giving a special shape to the molecules induces the steric stabilization that prevents agglomeration of the nanoparticles.

These materials were tested as catalysts in cross-coupling reactions (Scheme 2). We have described fluorous biphasic systems that permitted recovery and reutilization of palladium nanoparticles as catalyst.[4a,g] Now we intend to take advantage of the low solubility of the highly fluorinated palladium nanoparticles in organic solvents and water to use them as heterogeneous catalysts.

For the Mizoroki–Heck[11] reaction we used tributylamine as base in refluxing acetonitrile and catalytic material corresponding to Pd_n(1). The weight of the catalyst introduced in the reaction corresponded to 4% molar palladium with respect to the limiting reagent. The material was reused after centrifugation and we carried out the reaction five consecutive times with the same batch of catalyst without loss of activity (Table 3).

Table 2 Palladium nanoparticles stabilized by fluorous compounds **4c** and **7c**

Material	Stabilizer	Initial molar ratio Pd : **4**[a]	ϕ (nm)[b]	No. of atoms per particle[c]	Electron diffraction	% Pd[d]	Decomposition point (°C)
$Pd_n(1)$	**4c**	2.03	2.7 ± 0.8	6.9×10^2	fcc Pd	11.87	113–115
$Pd_n(2)$	**4c**	2.04	2.2 ± 0.8	3.8×10^2	fcc Pd	13.30	112–114
$Pd_n(3)$	**4c**	1.06	1.7 ± 0.3	1.7×10^2	fcc Pd	7.30	113–116
$Pd_n(4)$	**7c**	0.98	5 ± 2	4.4×10^3	fcc Pd	3.68	142–144

[a] In the form of $PdCl_2$. [b] Determined by transmission electron microscopy analysis (HRTEM). [c] From $0.74V_{nanoparticle}/V_{atom}$; 0.74 is the occupation factor for a face-centred cube crystal structure. [d] Pd% determined by inductively coupled plasma (ICP).

For the reaction between 4-bromoacetophenone and phenyl boronic acid (Suzuki cross-coupling)[12] we used potassium carbonate as base in mixtures of DMF–H_2O at 110 °C and 0.5% molar of $Pd_n(2)$. We explored the reutilization of the catalyst after centrifugation. The same batch was used five times without any appreciable loss of activity (Table 3).

Nanoparticles $Pd_n(2)$ containing 13.3% of metal were tested also in the Sonogashira[13] coupling of 4-iodoanisole and phenylacetylene using copper as cocatalyst. We carried out some preliminary reactions using diisopropylamine as a base. We soon noticed that palladium nanoparticles were damaged through the action of the amine, probably due to the nitrogen atom donor ability. Best results were obtained using an inorganic base, potassium carbonate, in refluxing ethanol. For an optimal reutilization of the catalyst the reaction mixture was centrifuged and the residue consisting of $Pd_n(2)$ and K_2CO_3 was directly reused in the subsequent reaction. Normally recovered nanoparticles were washed with water to extract the inorganic base. However, in Sonogashira conditions addition of water was unsuccessful. To ensure that a sufficient quantity of base was present in the next reaction cycle, one equivalent of potassium carbonate was added. The reaction was carried out six consecutive times with the same batch of palladium nanoparticles (Table 3).

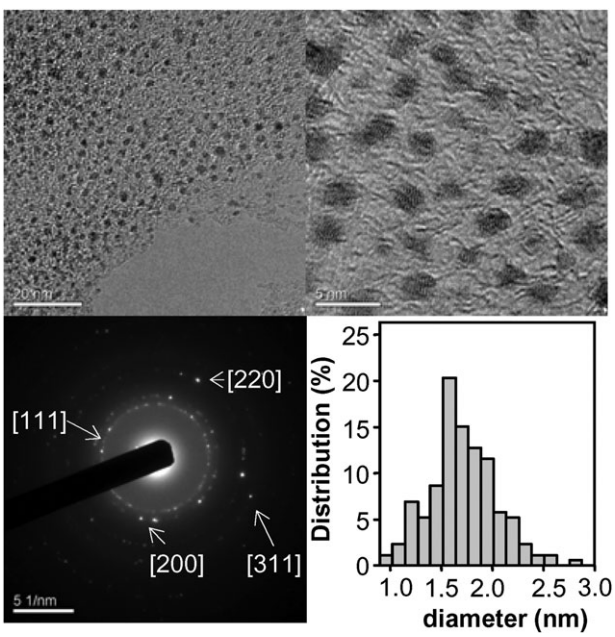


Fig. 2 HRTEM images, particle size distribution and electron diffraction of $Pd_n(3)$.

Conclusions

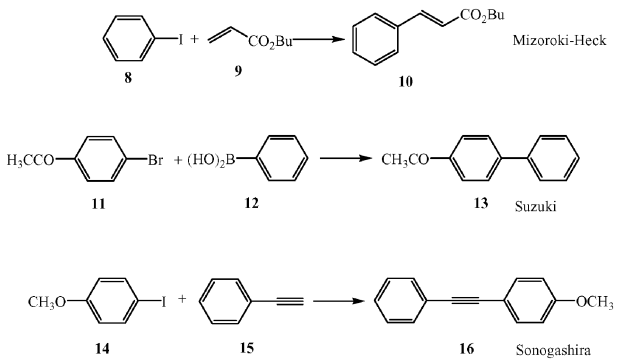
A series of new aromatic thioethers have been prepared from commercial sources. Two methodologies can be used that work with only one mol of nucleophile per chloride or fluoride atom, an important requirement when using valuable thiols. We have prepared two heavily fluorinated star-shaped compounds possessing functional groups with high affinity for metals that were designed to stabilize palladium nanoparticles. Small palladium nanoparticles could be prepared and these materials proved to be efficient as recoverable catalysts in cross-coupling reactions.

Experimental

Compounds **10**[4g], **13**[14] and **16**[15] have been previously reported.

Typical experiment using cyanuric chloride

A solution of cyanuric chloride, **1**, (1.01 g, 5.48 mmol) and tetrabutylammonium chloride (0.034 g, 0.12 mmol) in 7 mL of anhydrous THF was added under argon *via* cannula to a stirred suspension of caesium thiolate in 8 mL of anhydrous THF, made from Cs_2CO_3 (11.11 g, 34.10 mmol) and propanethiol (1.5 mL, 16.54 mmol). The mixture was stirred at room temperature during 4 days. Salts were filtered and the solvent evaporated. The residue was passed through a column of silica gel with a mixture of hexanes–AcOEt as eluent to afford 2,4,6-tris(propylthio)-1,3,5-triazine, **4a**, (1.13 g, 68%). IR (ATR): 2964, 2927, 2869, 1480, 1262, 1233, 631 cm^{-1}; ^{1}H-NMR ($CDCl_3$, 250 MHz): δ = 1.02 (t, J = 7.4 Hz, 9H), 1.73 (m, 6H), 3.05 (t, J = 7.2 Hz, 6H); ^{13}C-NMR ($CDCl_3$, 62.5 MHz): 13.7, 22.9, 32.5, 179.8. Anal. calcd for $C_{12}H_{21}N_3S_3$: C, 47.49; H, 6.97; N, 13.84; S, 31.69; found: C, 47.40; H, 6.92; N, 13.77; S, 31.45%.



Scheme 2 Tested cross-coupling reactions using palladium nanoparticles as catalyst.

Table 3 Experimental conditions for reactions shown in Scheme 2

Reaction	Base	Solvent	Catalyst	Pd (mol%)	T (°C)	Time[a] (h)	Yields of product (%) for five consecutive cycles
Mizoroki–Heck	Bu_3N	CH_3CN	Pd_n(1)	4.1	reflux	48/48/72/72/72	**10**[b] 89 (68% isolated)/95/98/93/100
Suzuki	K_2CO_3	DMF–H_2O 95/5	Pd_n(2)	0.5	110	4/4/4/4/4	**13**[c] 98 (91% isolated)/100/100/96/94
Sonogashira	K_2CO_3	EtOH	Pd_n(2)	1	80	2/2/2/2/2/2	**16**[c] 100 (81% isolated)/100/100/100/100/72

[a] Reaction times for consecutive runs. [b] Determined by ^{1}H-NMR. [c] Determined by GC using undecane as internal standard.

2,4,6-Tris(hexadecylthio)-1,3,5-triazine, 4b

Mp 74–75 °C; IR (ATR): 2958, 2917, 2845, 1491, 1458, 1263, 1249, 1232 cm^{-1}; ^{1}H-NMR ($CDCl_3$, 250 MHz): δ = 0.88 (t, J = 6.5 Hz, 9H), 1.25 (s, 72H), 1.41 (m, 6H), 1.69 (m, 6H), 3.07 (t, J = 7.4 Hz, 6H); ^{13}C-NMR ($CDCl_3$, 62.5 MHz): 14.5, 23.0, 29.2, 29.5, 29.7, 29.9, 30.0, 30.1, 30.6, 32.3, 179.9. Anal. calcd for $C_{51}H_{99}N_3S_3$: C, 72.02; H, 11.73; N, 4.94; S, 11.31; found: C, 72.03; H, 11.63; N, 5.04; S, 10.97%.

2,4,6-Tris(1*H*,1*H*,2*H*,2*H*-perfluorodecylthio)-1,3,5-triazine, 4c

The reaction mixture was stirred at room temperature during 7 days. Then, water and ethyl acetate were added and the solid was filtered, and washed with water and acetone. The solid was suspended in FC77 (perfluoro compounds, mainly C8) under stirring at 50 °C during 2 hours and then filtered and dried.

Mp 113–115 °C; IR (ATR): 1470, 1242, 1196, 1142 cm^{-1}; ^{1}H-NMR ($CDCl_3$ + FC113 (1,1,2-trichloro-1,2,2-trifluoroethane), 250 MHz): δ = 2.63 (m, 6H), 3.38 (t, J = 7.4 Hz, 6H); ^{13}C-NMR ($CDCl_3$, 62.5 MHz): 22.1, 32.5 (t, J = 22.4 Hz), 180.2; MALDI-TOF: m/z 1515.96 (M^+).

1,2,4,5-Tetrafluoro-3,6-bis(propylthio)benzene, 5a

Mp 38–40 °C; IR (ATR): 2948, 2929, 2869, 1458, 945 cm^{-1}; ^{1}H-NMR ($CDCl_3$, 250 MHz): δ = 1 (t, J = 7.3 Hz, 6H), 1.60 (m, J = 7.3 Hz, 4H), 2.91 (t, J = 7.2 Hz, 4H); ^{13}C-NMR ($CDCl_3$, 62.5 MHz): 13.3, 23.5, 36.9, 114.7 (m), 147.3 (J = 247.9 Hz). Anal. calcd for $C_{12}H_{14}F_4S_2$: C, 48.31; H, 4.73; found: C, 48.55; H, 4.64%.

1,2,4,5-Tetrafluoro-3,6-bis(hexadecylthio)benzene, 5b

Mp 76–79 °C; IR (ATR): 2913, 2847, 1463, 953 cm^{-1}; ^{1}H-NMR ($CDCl_3$, 250 MHz): δ = 0.87 (t, J = 6.5 Hz, 6H), 1.38 (m, 48H), 1.38 (m, 4H), 1.56 (m, 4H), 2.93 (t, J = 7.3 Hz, 4H); ^{13}C-NMR ($CDCl_3$, 62.5 MHz): 14.5, 23.1, 28.7, 29.4, 29.7, 29.8, 29.9, 30.0, 30.2, 32.3, 35.0, 114.8 (m), 147.2 (J = 247.9 Hz). Anal. calcd for $C_{33}H_{66}F_4S_2$: C, 68.83; H, 10.03; found: C, 68.89; H, 10.28%.

1,4-Difluoro-2,3,5,6-tetrakis(propylthio)benzene, 6a

IR (ATR): 2962, 2925, 2868, 1377 cm^{-1}; ^{1}H-NMR ($CDCl_3$, 250 MHz): δ = 0.98 (t, J = 7.3 Hz, 12H), 1.55 (m, J = 7.3 Hz, 8H), 2.91 (t, J = 7.3 Hz, 8H); ^{13}C-NMR ($CDCl_3$, 62.5 MHz): 13.6, 23.4, 37.7 (t, J = 2.9 Hz), 159.4 (dd, J = 241.3 and 3.8 Hz); ^{19}F-NMR (235.2 MHz, $CDCl_3$): δ = −98; MS: m/z 410 (M^+), 368, 326, 284, 242, 208, 177, 43. Anal. calcd for $C_{18}H_{28}F_2S_4$: C, 52.64; H, 6.87; found: C, 52.68; H, 7.01%.

1,4-Difluoro-2,3,5,6-tetrakis(dodecylthio)benzene, 6d

IR (ATR): 2958, 2914, 2846, 1466, 1377 cm^{-1}; ^{1}H-NMR ($CDCl_3$, 250 MHz): δ = 0.86 (t, J = 6.5 Hz, 12H), 1.23 (m, 64H), 1.36 (m, 8H), 1.53 (m, 8H), 2.93 (t, J = 7.2 Hz, 8H); ^{13}C-NMR ($CDCl_3$, 62.5 MHz): 14.4, 23.0, 29.0, 29.5, 29.7, 29.8, 29.9, 30.0, 30.1, 32.4, 35.7 (t, J = 3.1 Hz), 127.7 (m), 159.2 (dd, J = 242.2 and 3.8 Hz); Anal. calcd for $C_{54}H_{100}F_2S_4$: C, 70.83; H, 11.01; found: C, 70.71; H, 11.03%.

Typical experiment using hexachlorobenzene

A mixture of NaH 60% suspension in mineral oil (0.23 g, 5.75 mmol) and 1*H*,1*H*,2*H*,2*H*-perfluorodecylthiol (1.3 mL, 4.49 mmol) in tetraglyme (24 mL) in a Schlenk tube was stirred at r.t. for one hour. Then, hexachlorobenzene was added (0.70 mmol) and the mixture was stirred at 130 °C for 42 hours. The formed solid was filtered and washed with CH_2Cl_2. Then, the solid was suspended in FC77 under stirring at 50 °C during 2 hours and then filtered and dried to afford 1.094 g (54%) yield of hexakis(1*H*,1*H*,2*H*,2*H*-perfluorodecylthio)benzene **7c**. Mp 141–143 °C; IR (ATR): 1241, 1198, 1143, 1082 cm^{-1}; ^{1}H-NMR ($CDCl_3$ + FC113 (1,1,2-trichloro-1,2,2-trifluoroethane), 250 MHz): δ = 2.39 (m, 12H), 3.30 (t, J = 8.0 Hz, 12H); ^{13}C-NMR ($CDCl_3$, 62.5 MHz): 29.7, 32.5 (t, J = 23.1 Hz), 148.2; MALDI-TOF: m/z 2945.86 (M^+).

Hexakis(propylthio)benzene, 7a

IR (ATR): 2959, 2928, 2870, 1457, 1377, 1271, 632 cm^{-1}; ^{1}H-NMR ($CDCl_3$, 250 MHz): δ = 0.90 (t, J = 7.3 Hz, 18H), 1.44 (m, J = 7.3 Hz, 12H), 2.91 (t, J = 7.4 Hz, 12H); ^{13}C-NMR ($CDCl_3$, 62.5 MHz): 13.8, 23.0, 39.9, 145.9 (m), 147.2 (J = 247.9 Hz). Anal. calcd for $C_{24}H_{42}S_6$: C, 55,12; H, 8.09; found: C, 55.22; H, 8.30%.

Typical preparation of nanoparticles

A mixture of palladium chloride (0.035 g, 0.20 mmol), sodium chloride (0.012 g, 0.21 mmol) and 2 mL of methanol was stirred at room temperature for 24 h. The mixture was filtered through a glass wool plug. Additional methanol (28 mL) was added to the filtrate. The solution was heated at 60 °C under stirring and 2,4,6-tris(1*H*,1*H*,2*H*,2*H*-perfluorodecylthio)-1,3,5-triazine, **4c**, (0.149 g, 0.10 mmol) was added. Then, the mixture was heated under stirring during 24 h. Sodium acetate (0.094 g) was added and stirring was maintained at room temperature for 1 h. The formed black solid was filtered, washed with methanol, water and acetone; it was then dried to afford 0.283 g of a black solid Pd_n(2), which had a decomposition point of 112–114 °C. The IR, ^{1}H-NMR and ^{13}C-NMR of the solid were identical to those of **4c**. The size of the nanoparticles was 2.2 ± 0.8 nm, as determined by transmission electron microscopy. Pd analysis (ICP): 13.30%.

Mizoroki–Heck reaction. Typical experimental procedure

Butyl acrylate (0.059 mL, 0.41 mmol), iodobenzene (0.030 mL, 0.27 mmol), Pd_n(1) (0.010 g, 0.011 mmol), tributylamine (0.130 mL, 0.55 mol) and 4 mL of acetonitrile were stirred at 80 °C during 48 hours. Then the suspension was centrifuged to afford a black solid and a solution which was decanted and the solvent evaporated. Then CH_2Cl_2 was added and the organic solution was washed with 1 M hydrochloric acid. The organic layer was dried and the solvent evaporated. The residue was purified by chromatography through silica-gel using hexane–ethyl acetate 95/5 as eluent to give 0.0370 g (68% yield) of butyl cinnamate **10**.[4g] The black solid (Pd_n(2)) was washed with acetonitrile and reused in the next reaction.

Suzuki reaction. Typical experimental procedure

Phenyl boronic acid (0.323 g, 2.65 mmol), 4-bromoacetophenone (0.351 g, 1.76 mmol) and Pd_n(2) (0.008 g, 0.010 mmol) were suspended in 3.5 mL of DMF–H_2O 95/5. Then K_2CO_3 (0.495 g, 3.58 mmol) was added and the mixture was stirred at 110 °C during 4 hours. After addition of AcOEt the mixture was centrifuged. The solid residue was a mixture of Pd_n(2) and K_2CO_3 which was washed with water and acetone. The black solid Pd_n(2) was reused in the next cycles. Addition of water to the organic layer afforded the precipitation of **13**, which was filtrated to give 0.315 g (91%) of 4-acetylbiphenyl **13**.[14]

Sonogashira reaction. Typical experimental procedure

4-Iodoanisole (0.200 g, 0.85 mmol), phenylacetylene (0.10 mL, 0.91 mmol), Pd_n(2) (0.007 g, 0.009 mmol), K_2CO_3 (0.240 g, 1.74 mmol), CuI (0.003 g, 0.016 mmol), PPh_3 (0.004 g, 0.015 mmol) and 4 mL of ethanol were stirred at 80 °C during 2 hours. The mixture was then centrifuged and the residue, a mixture of Pd_n(2) and K_2CO_3, was reused in the next cycle (although some K_2CO_3 (0.12 g, 8.7 mmol) was added to the consecutive reactions). The solution was decanted and some diethyl ether was added. Then the organic layer was washed with water, dried and evaporated. The residue was purified by chromatography through silica-gel using hexanes–ethyl acetate 98/2 as eluent to give 0.127 g (81% yield) of 1-methoxy-4-(phenylethynyl)benzene **16**.[15]

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