DOI: 10.1002/ejic.200700532

On the Mechanism of Palladium-Catalyzed Cross-Coupling of Diazonium Salts with Aryltrifluoroborates: A Combined ESI-MS/NMR Study

Nicola Taccardi,[a] Rossella Paolillo,[a] Vito Gallo,[a] Piero Mastrorilli,*[a] Cosimo F. Nobile,[a] Minna Räisänen,[b] and Timo Repo[b]

Keywords: Homogeneous catalysis / Metallacycles / Mass spectrometry / Cross-coupling / Diazo compounds

A combined ESI-MS/NMR mechanistic study on the palladium-catalysed cross-coupling reaction between aryldiazonium salts and aryltrifluoroborates with bis(μ-acetato)bis(4,4′-difluoroazobenzene-C^2,N)dipalladium(II) (**4**) as the precatalyst is reported. The reaction follows a Pd^0/Pd^{II} cycle after reduction of **4** to a molecular Pd^0 species (**I**), which according to the combined ESI-MS and ^{19}F NMR studies, bears an arylated azobenzene ligand. Oxidative addition by the diazonium salt generates the arylpalladium(II) intermediate (**II**), which was also detected in solution. The catalytic cycle is completed with a transmetallation between **II** and the organoborate, which is followed by fast reductive elimination of the cross-coupling product to restore the molecular Pd^0 species **I**. A concurrent activation path was also observed which consists of the formation of (4,4′-difluoroazobenzene-C^2,N)dipalladium(II) tetrafluoroborate (**7**) by the reaction of **4** with the diazonium salt and subsequent reduction by the aryltrifluoroborate to give **I**.

Introduction

An innovative route to biaryls by palladium-catalysed cross-coupling between diazonium salts and aryltrifluoroborates has been proposed recently.[1] This protocol, which is an improved modification of the more popular Suzuki cross-coupling reaction,[2] does not require either temperatures higher than ambient or the addition of a base.

We have recently published a paper on the title reaction carried out in IL/methanol (IL = ionic liquid) mixtures where several (zero- and divalent) palladium complexes were used as precatalysts.[3] In this framework it was found that palladacycles of general formula $[(C^{\frown}N)Pd(\mu\text{-}OAc)]_2$ (see Scheme 1) were outstanding in terms of activity and selectivity of the reaction.

Our preliminary mechanistic investigations of this reaction demonstrated that the catalysis is molecular and is influenced by the ligand on palladium. Moreover, we found that an excess of diazonium salt (but not of aryltrifluoroborate) allowed the catalytic solutions to be recycled.[3]

In this paper we report a combined ESI-MS and ^{19}F NMR mechanistic study on the title reaction using $KPhBF_3$ and $p\text{-}XC_6H_4N_2BF_4$ (X = CH_3 or F) as substrates, [bis(μ-acetato)bis(4,4′-difluoroazobenzene-C^2,N)dipalladium(II)] (**4**) as a precatalyst and methanol as solvent (Scheme 2).

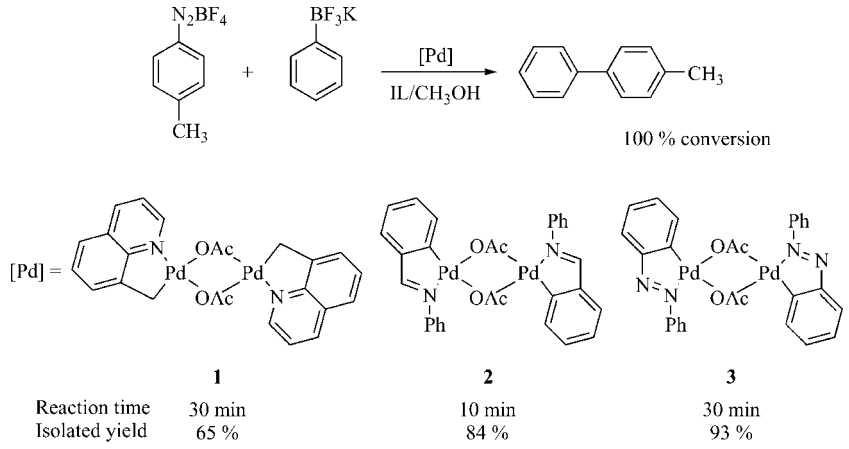
The rationale for the use of the fluorinated substrate and precatalyst resides in the possibility of monitoring the reaction progress by ^{19}F NMR spectroscopy, while methanol was used instead of IL/MeOH mixtures in order to simplify the experimental procedures.[4] ESI-MS, which is used here as a complementary analytical method, is a rapidly emerging technique for mechanistic investigations due to the possibility of easily revealing all species present in an actual catalyst solution.[5] The classical Suzuki cross-coupling[6] and other palladium-catalyzed reactions,[7] for example, have recently been studied by means of ESI-MS.[8]

In order to ascertain the effect of fluorine substitution of the azobenzene moiety in complex **3** on the catalysis, we preliminarily checked the catalytic activity of **4** in methanol using *p*-tolyldiazonium tetrafluoroborate ($p\text{-}CH_3C_6H_4N_2BF_4$) and $KPhBF_3$. Precatalyst **4** (1% mol) gave an 81% yield after 80 min while the non-fluorinated analogue **3** gave a 55% yield after 15 min[3] (the reactions were stopped when quantitative conversions were reached). The effect of the fluorine substitution on the ligand further confirms the molecular nature of the catalysis.

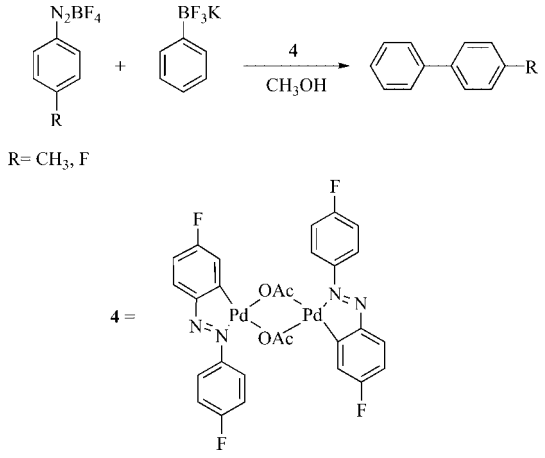
Results and Discussion

The commonly accepted catalytic cycle for a Pd^{II}-initiated Suzuki cross-coupling is depicted in Scheme 3.[2] It consists of a preliminary reduction of Pd^{II} to Pd^0 followed by the oxidative addition of the electrophile ArX (where X is typically a halide or triflate), subsequent transmetallation

[a] Dipartimento di Ingegneria delle Acque e di Chimica del Politecnico di Bari,
via Orabona 4, 70125 Bari, Italy
Fax: +39-080-596-3611
E-mail: p.mastrorilli@poliba.it
[b] Laboratory of Inorganic Chemistry, Department of Chemistry, University of Helsinki,
P.O. Box 55, 00014 Helsinki, Finland
Supporting information for this article is available on the WWW under http://www.eurjic.org or from the author.

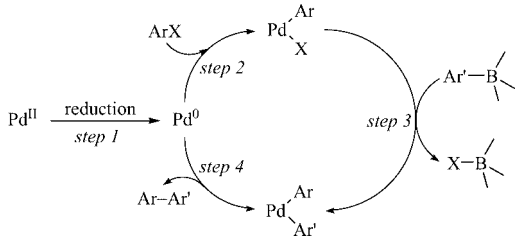


Scheme 1. Examples of highly active palladacycles for the cross-coupling reaction.[3] IL = 1-*n*-butyl-3-methylimidazolium tetrafluoroborate.



Scheme 2. Cross-coupling reaction with a fluorinated substrate and precatalyst **4**.

of the organoborate and reductive elimination leading to the cross-coupling product and regeneration of the Pd^0 species, which restarts the catalytic cycle.



Scheme 3. General catalytic cycle for the Suzuki cross-coupling leading to biaryls.

In order to verify whether such a cycle also holds when ArX is replaced by an aryldiazonium salt and the organoboron compound is changed to $KPhBF_3$, every single step shown in Scheme 3 was examined.

Reaction of the Precatalyst with $KPhBF_3$

The reaction mixture comprised of **4** and $KPhBF_3$ in methanol was monitored by ^{19}F NMR spectroscopy at room temperature (Figure 1). The lack of signals attributable to **4** is due to its poor solubility in methanol.

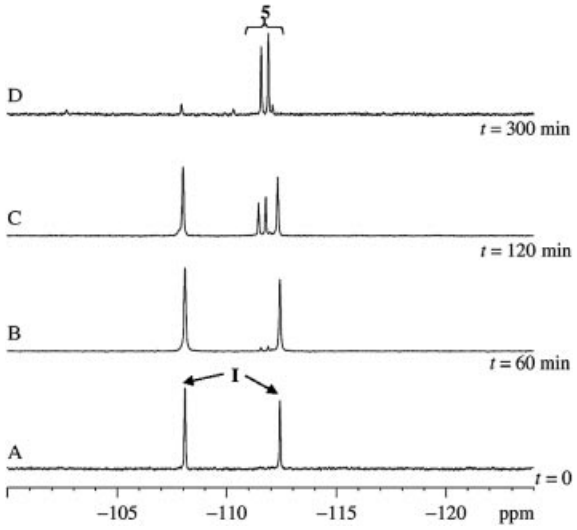


Figure 1. ^{19}F NMR spectroscopic monitoring of reaction mixtures of **4** and $KPhBF_3$ in methanol as a function of time (Pd:$KPhBF_3$ = 1:15 mol/mol).

It is apparent that a new species **I** with ^{19}F NMR resonances at δ = –108.1 and –112.4 ppm forms immediately upon mixing $KPhBF_3$ with azapalladacycle **4**. The signals assigned to **I** progressively decrease in intensity over 5 h, with concomitant appearance of two new signals at δ = –111.7 and –111.9 ppm and formation of palladium black. These latter signals belong to 4,4′-difluoro-2-phenylazobenzene (**5**), which was isolated and fully characterized. The formation of Pd black and **5** indicates two possible struc-

tures for **I**, one of which is a Pd^{II} complex in which the bridging acetate of **4** has been replaced by a σ-bonded phenyl group and the other of which consists of already formed ligand **5** bonded to Pd^0 (Scheme 4; in this and in the following structures the solvent molecules possibly bound to palladium are omitted).

High resolution ESI-MS (HRMS) analysis of the solution showed an intense peak at *m/z* 419 (negative ion mode). This peak represents the fluoride adduct of **I** (exact mass = 400.00 daltons), as confirmed by the simulation of its isotopic pattern (Figure 2). The presence of other anions at *m/z* 399 $[M - HF]^-$ and 293 $[M - Pd - HF]^-$ in the MS/MS spectrum provided the basis to discriminate between the two structures depicted in Scheme 4. The latter ion, which corresponds to the deprotonated form of **5**, clearly indicates that species **I** seen in the ^{19}F NMR spectrum is a Pd^0 complex of **5**.

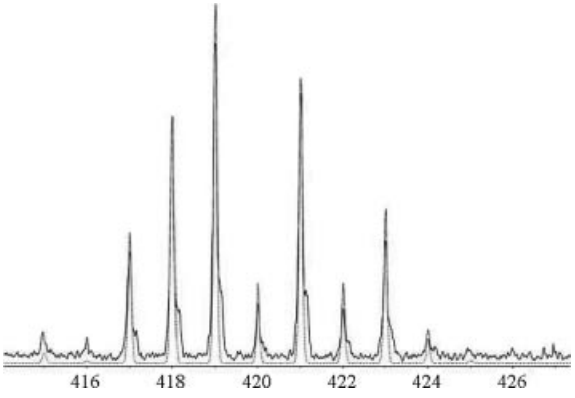
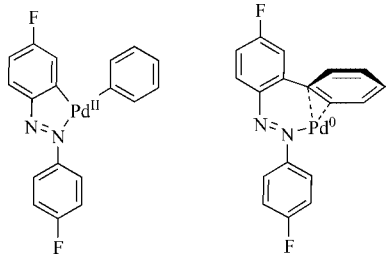
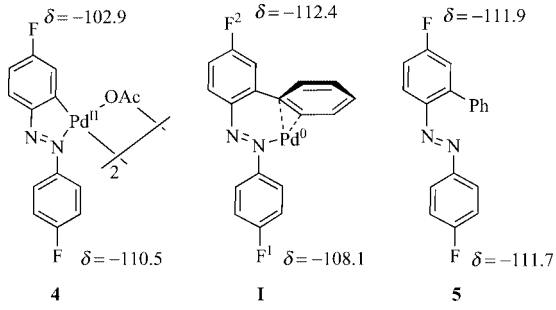


Figure 2. Experimental (solid line) and simulated (dotted line) HRMS(–) spectrum of **I** as its fluoride adduct. The error between simulated and observed isotopic patterns is –1.72 ppm.



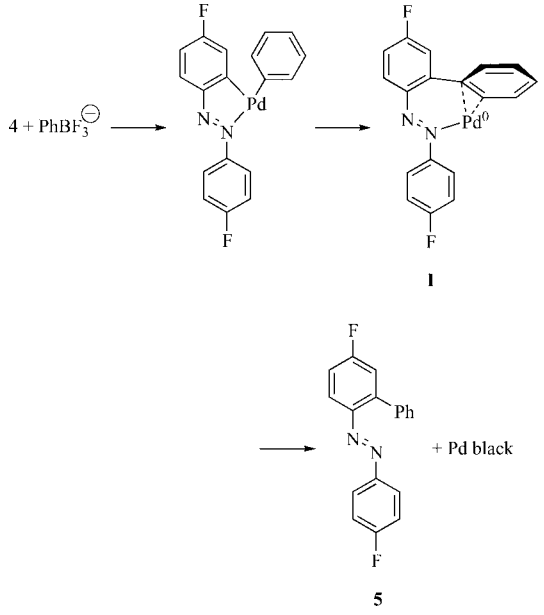
Scheme 4. Two possible structures for species **I**.

Although different structures with the same molecular formula (e.g. coordination of the other N atom, η^2 coordination of the N=N moiety or different coordination modes for the dangling phenyl) cannot be definitively ruled out,[9] the ^{19}F NMR resonances of **I** are in agreement with the structure depicted in Scheme 5. As suggested by a comparison of the ^{19}F NMR signals of **I** with those of **4**[10] and **5**, the signal at δ = –108.1 ppm in **I** can be attributed to F^1 while that at δ = –112.4 ppm, which is compatible with a fluorine on a 2-phenylated aryl ring in **5**, can be attributed to F^2.



Scheme 5. ^{19}F NMR features of **4**, **I** and **5**. All the chemical shifts are given for the species in methanol.

The formation of **I** and its subsequent decomposition, as shown in Figure 1, are depicted in Scheme 6. Such a process is not unexpected for a Pd^0 species such as **I** and has already been suggested for analogous palladacycles.[11]



Scheme 6. Reaction of **4** with phenyltrifluoroborate generates Pd^0 complex **I**, which slowly decomposes to **5**.

Reaction of I with Diazonium Salts

The addition of a slight excess of diazonium salt to the catalyst solution caused the disappearance of **I** and concomitant formation of coupling products (GLC analysis) and **5** (δ = –111.7 and –111.9 ppm). Depending on the applied diazonium salts (in this case *p*-$FC_6H_4N_2BF_4$ and *p*-$CH_3C_6H_4N_2BF_4$), two new species were also formed (see parts B in Figures 3 and 4).

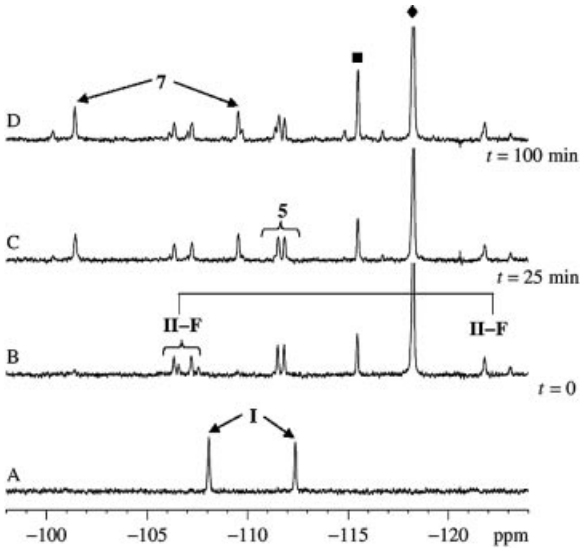


Figure 3. ^{19}F NMR monitoring of the reaction mixture of **4**/$KPhBF_3$ and *p*-$FC_6H_4N_2BF_4$ in methanol. A: **4**/$KPhBF_3$; B: immediately after addition of *p*-$FC_6H_4N_2BF_4$; C and D: after 25 and 100 min, respectively. ■ = 4,4′-difluorobiphenyl; ♦ = 4-fluorobiphenyl. Pd/diazonium/$KPhBF_3$ molar ratio of 1:18:15.

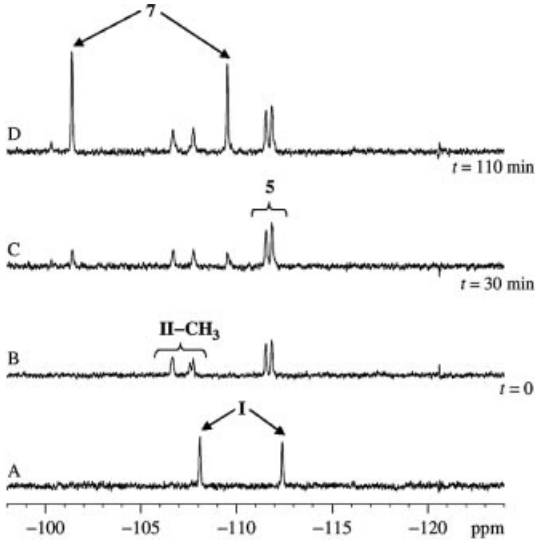
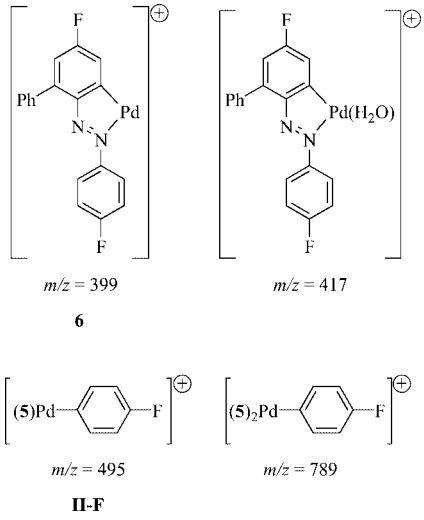


Figure 4. ^{19}F NMR monitoring of the reaction mixture of **4**/$KPhBF_3$ and *p*-$CH_3C_6H_4N_2BF_4$ in methanol. A: **4**/$KPhBF_3$; B: immediately after addition of *p*-$CH_3C_6H_4N_2BF_4$; C and D: after 30 and 110 min, respectively. Pd/diazonium/$KPhBF_3$ molar ratio of 1:18:15.

The new species formed in the case of *p*-fluorobenzenediazonium (**II-F**) shows three broad signals at δ = –106.4, –107.2 and –121.8 ppm that integrate in a 1:1:1 ratio (Figure 3), while that formed with *p*-tolyldiazonium (**II-CH$_3$**) shows only two broad signals at δ = –106.7 and –107.8 ppm that integrate in a 1:1 ratio (Figure 4).

HRMS(+) analysis of a solution containing **II-F** (that of Figure 3, B) revealed the presence of species with *m*/*z* values of 399, 417, 495 and 789. Analysis of the isotopic pattern of these peaks indicated the structures depicted in Scheme 7.



Scheme 7. Pd^{II} species detected by HRMS(+) in the reaction mixture of **4**/$KPhBF_3$ after the addition of *p*-$FC_6H_4N_2BF_4$.

As already mentioned, the ^{19}F NMR signals of intermediate **II-F** at δ = –106.4, –107.2 and –121.8 ppm integrate in a 1:1:1 ratio and can therefore be assigned to the three fluorine atoms of the structure with *m*/*z* 495 (see Supporting Information),[12] with the downfield ones being due to the fluorine atoms of coordinated **5** and the upfield one being due to the fluorine of the σ-bonded *p*-fluorophenyl group.[13]

A structure similar to **II-F**, but with a *p*-tolyl ligand in the place of *p*-fluorophenyl, can be attributed to **II-CH$_3$**. Complexes **II-F** and **II-CH$_3$** are the products of oxidative addition of *p*-fluorophenyldiazonium and *p*-tolyldiazonium salts, respectively, to **I**.

When the reaction between **I** and *p*-$FC_6H_4N_2BF_4$ was carried out in the presence of an excess of $KPhBF_3$ (Pd/$KPhBF_3$/diazonium molar ratio of 1:18:15) the same intermediates as in Figure 3 were detected (Figure 5). However, addition of the diazonium salt did not result in the immediate disappearance of **I**, as shown in part B of Figure 5, and

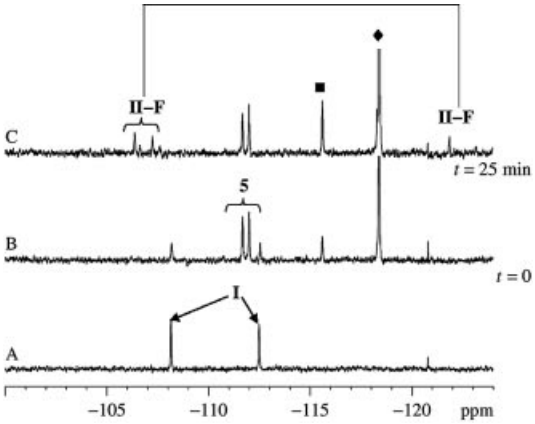


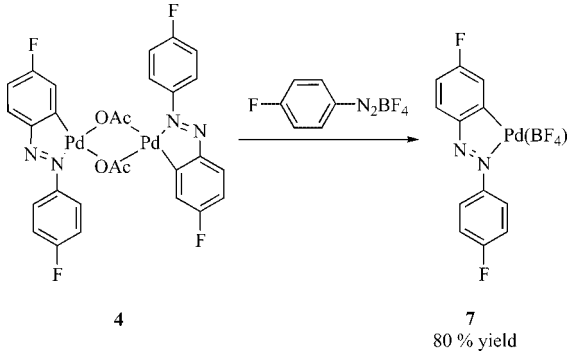
Figure 5. Reaction of **4** with excess $KPhBF_3$ and *p*-$FC_6H_4N_2BF_4$. A: **4**/$KPhBF_3$; B: immediately after addition of *p*-$FC_6H_4N_2BF_4$; C after 25 min. ■ = 4,4′-difluorobiphenyl; ♦ = 4-fluorobiphenyl. Pd/diazonium/$KPhBF_3$ molar ratio of 1:15:18.

the signals of **II-F** appeared only after consumption of **I** (Figure 5, C). Accordingly, HRMS analysis of the solution resulting from the addition of *p*-$FC_6H_4N_2BF_4$ (Figure 5, B) did not show the cations with *m*/*z* 399, 417, 495 and 789 whereas anions with *m*/*z* 419 ([**I** + F]$^-$), 399 ([**I** – H]$^-$), 487 ([**I** + BF_4]$^-$) and 499 ([**I** + BF_3OMe]$^-$) were detected in negative ion mode.

Concurrent Activation of the Precatalyst

^{19}F NMR analysis of the reaction solutions prepared from **4**, $KPhBF_3$ and diazonium salt in excess showed the formation of a new Pd complex (**7**; δ = –101.3 and –109.5 ppm) which after 1.5 h is the main Pd species in solution (see parts D in Figures 3 and 4).

Complex **7** was characterized as (4,4′-difluoroazobenzene-C^2,*N*)palladium(II) tetrafluoroborate, which arises from the reaction of *p*-fluorobenzenediazonium tetrafluoroborate with residual **4** (Scheme 8). Pure **7** was isolated in 80% yield from the reaction between **4** and *p*-$FC_6H_4N_2BF_4$ (1:1 Pd:diazonium salt molar ratio) in methanol at room temperature. The formation of **7** results from the abstraction of the bridging acetate of **4** by the diazonium salt[14] rather than simple metathesis of the acetate ligands with tetrafluoroborate, as demonstrated by the lack of reaction between **4** and $NaBF_4$ or [bmim]BF_4 (bmim = 1-*n*-butyl-3-methylimidazolium). Related (azobenzene-C^2,*N*)palladium(II) tetrafluoroborates have been previously synthesized by Heck starting from bis(μ-chloro)bis(azobenzene-C^2,*N*)-dipalladium(II) and $AgBF_4$.[15]



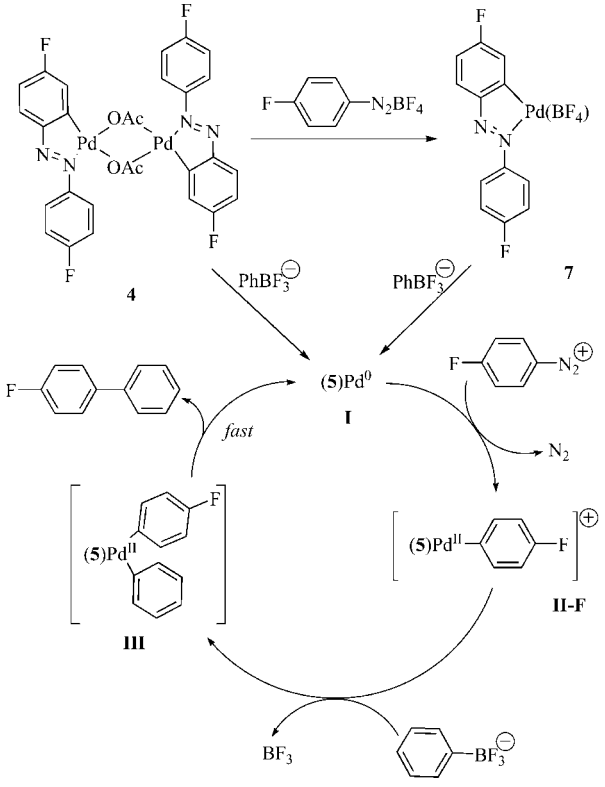
Scheme 8. Formation of complex **7**.

Complex **7** was found to be catalytically active. Thus, when **7** was used as precatalyst in the cross-coupling reaction between *p*-$CH_3C_6H_4N_2BF_4$ and $KPhBF_3$ in methanol an 88% yield of 4-methylbiphenyl was obtained in 15 min. A similar yield was obtained with the parental complex **4** only after 80 min. The higher activity of **7** compared with that of **4** can be explained by two considerations: i) complex **4** is poorly soluble in the reaction medium, while **7** is completely soluble, and ii) complex **7** is a coordinatively unsaturated species and therefore highly reactive towards prereduction reaction with $KPhBF_3$. In fact, the quantitative conversion of **7** into **I** and the subsequent slow decomposition of the latter into **5** and palladium black could be observed when following the reaction between **7** and $KPhBF_3$ by ^{19}F NMR spectroscopy. Thus, complex **7** can contribute to the formation of **I** and accumulates only when the aryltrifluoroborate has been consumed.

The fact that **7** survived the work-up procedures suggests that it could be responsible for the aforementioned recyclability of the catalytic solutions for reactions carried out in IL/MeOH mixtures in the presence of excess diazonium salt.[3]

Catalytic Cycle

On the basis of the experimental data described above, the catalytic cycle shown in Scheme 9 can be proposed for palladium-catalyzed cross-coupling of diazonium salts with aryltrifluoroborates.



Scheme 9. Proposed catalytic cycle for the palladium-catalyzed cross-coupling of diazonium salts with aryltrifluoroborates.

The catalyst precursor **4** reacts with the trifluorophenylborate to give the Pd^0 species **I**, which is responsible for the observed catalytic activity. This species undergoes oxidative addition of the aryldiazonium salt to give the cationic arylpalladium(II) complex **II-F**, which bears the azobenzene **5** as a ligand. The catalytic cycle is completed by a transmetallation reaction between **II-F** and the organoborate to give the neutral compound **III**, which is followed by reductive elimination of the cross-coupling product. Compound **I** can also be formed from the reaction between **7** (formed from **4** and the aryldiazonium salt) and $PhBF_3^-$.

No transmetallation intermediates were detected, which indicates that the reductive elimination step from **III** is very

fast.[16] The ^{19}F NMR spectroscopic data (Figure 4) allowed us to extend this mechanism to the reaction with a *p*-tolyldiazonium salt, where an intermediate analogous to **II-F** was detected.

Conclusions

We have demonstrated that the cross-coupling between aryltrifluoroborates and diazonium salts facilitated by the acetato(azobenzene-C^2,*N*)palladium(II) complex **4** follows a catalytic cycle involving Pd^0 and Pd^{II} species. The active species is a Pd^0 complex (**I**) bearing an arylated azobenzene as a ligand that can form by two different pathways, namely direct reaction of **4** with the arylborate or by arylation of (azobenzene-C^2,*N*)Pd(BF_4) (**7**), which is generated by action of the diazonium salt on **4**. The Pd^0 complex **I** undergoes addition of the diazonium salt to give the cationic arylpalladium(II) complex **II** which, upon transmetallation with organoborate and fast reductive elimination, restores the active species **I**.

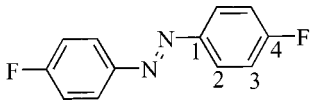
A combination of ^{19}F NMR and ESI-MS data has therefore allowed us to detect both intermediates **I** and **II** from the actual catalyst solutions.

Experimental Section

General: Unless otherwise specified, all manipulations were carried out in air. Potassium phenyltrifluoroborate,[1] *p*-tolyldiazonium tetrafluoroborate[17] and *p*-fluorobenzenediazonium tetrafluoroborate[17] were synthesized according to literature methods. All the other reagents were commercial and used as received. All the solvents were HPLC grade and were purified by standard techniques. Flash chromatography was performed on SiO_2 Kieselgel (230–400 mesh). The NMR spectra were recorded with a Bruker AX400 spectrometer (400 MHz for ^1H) at 295.0 K; chemical shifts are reported in ppm relative to $SiMe_4$ for ^1H and ^{13}C, and $CFCl_3$ for ^{19}F; ^1H and ^{13}C signals were attributed by means of $^{13}C\{^1H\}$APT, $^{13}C\{^1H\}$DEPT, ^1H COSY, ^1H-^{13}C HMQC and ^1H-^{13}C HMBC experiments. Deuterated solvents were purchased from Aldrich or Acros and used as received. Mass spectrometric analyses were performed using an ion-trap mass spectrometer equipped with an electrospray ion source (Bruker Esquire3000^{plus}). All analyses were carried out in both positive- and negative-ion modes. The sample solutions were introduced by continuous infusion with the aid of a syringe pump at a flow-rate of 180 μL min^{-1}. The instrument was operated in the positive-ion mode (ESI^+) with an end-plate offset of –500 V and a capillary offset of –4000 V. The nebuliser pressure was 0.8 bar (N_2) and the drying gas (N_2) flow 7 L h^{-1}. The capillary exit and skimmer 1 voltages were 90 and 30 V, respectively. The drying gas temperature was set at 200 °C. The mass spectrometric parameters in the negative ion mode (ESI^-) were as follows: end-plate offset: –500 V; capillary: –4000 V; capillary exit: –120 V; skimmer 1: –50 V; nebulizer pressure: 0.4 bar; drying gas flow: 5 L h^{-1}; drying gas temperature: 200 °C. All the samples for mechanistic studies were prepared and handled in air using HPLC-grade methanol. The software used for the simulations was Bruker Daltonics DataAnalysis (version 3.3).

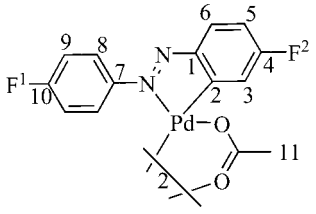
C, H, N elemental analyses were carried out with a Carlo Erba EA1108 CHNS-O elemental analyzer. Pd analyses were performed with a Perkin–Elmer SIMAA6000 atomic absorption spectrometer. The IR spectra were recorded with a Bruker Vector 22 FT-IR spectrometer. GLC analyses were performed on an HP5890 instrument equipped with a Supelco SPB-1 capillary column (30 m × 320 μm × 0.25 μm). GC-MS analyses were performed on an HP6890-HP5973MSD instrument equipped with an HP-5MS capillary column (30 m × 250 μm × 0.25 μm).

Synthesis of 4,4′-Difluoroazobenzene[18]



Sodium perborate (10.86 g, 0.109 mol) was added to a solution of 4-fluoroaniline (12.51 g, 0.113 mol) in 150 mL of glacial acetic acid. The system was heated at 50 °C under vigorous stirring and the reaction monitored by TLC. When the aniline has been completely consumed the system was cooled and the reaction mixture poured into a beaker containing 500 mL of cold water. The resulting suspension was neutralized with sodium carbonate and extracted with diethyl ether (3 × 150 mL). The organic phases were collected and washed with saturated sodium hydrogen carbonate (2 × 150 mL), water (2 × 250 mL) and brine (2 × 250 mL) then dried with anhydrous sodium sulfate, filtered and the solvents evaporated. The crude material was purified by column chromatography with petroleum ether (boiling range 40–70 °C) as eluent. Yield 2.46 g (20%) ppm. MS (70 eV, EI): *m*/*z* 218 (53) [M^+], 123 (28), 95 (100), 75 (34). $C_{12}H_8F_2N_2$ (218.20): calcd. C 66.05, H 3.70, N 12.84; found C 65.98, H 3.78, N 12.60. IR (KBr): $\tilde{\nu}$ = 430, 462, 540, 643, 668, 721, 755, 840, 951, 1008, 1093, 1141, 1201, 1232, 1288, 1302, 1415, 1499, 1593, 1653, 1896, 3061 cm^{-1}. ^1H NMR (400 MHz, $CDCl_3$): δ = 7.2 (m, 4 H, H^3), 7.9 (m, 4 H, H^2) ppm. ^{13}C NMR (101 MHz, $CDCl_3$): δ = 116.1 (d, $^2J_{C,F}$ = 23 Hz, C^3), 124.9 (d, $^3J_{C,F}$ = 9 Hz, C^2), 149.0 (d, $^4J_{C,F}$ = 2 Hz, C^1), 164.4 (d, $^1J_{C,F}$ = 252 Hz, C^4) ppm. ^{19}F NMR (376 MHz, CD_3OD): δ = –111.6 ppm (m).

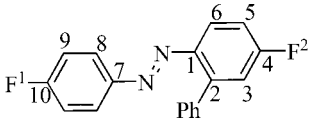
Synthesis of Bis(μ-acetato)bis(4,4′-difluoroazobenzene-C^2,*N*)dipalladium(II) (4)



Palladium acetate (0.450 g, 0.0020 mol) and 4,4′-difluoroazobenzene (0.436 g, 0.0020 mol) were dissolved in glacial acetic acid (50 mL) and the mixture was stirred at 50 °C. Once the 4,4′-difluoroazobenzene had been completely consumed (TLC monitoring) the system was cooled down to room temperature and methanol (200 mL) added to precipitate **4** as a black microcrystalline solid. This solid was filtered off, washed with diethyl ether (10 mL) and pentane (3 × 10 mL) and air-dried. Yield 0.629 g (82%). ESI-MS (CH_2Cl_2/CH_3CN): exact mass calcd. for $C_{28}H_{20}F_4N_4O_4Pd_2$: 763.95; found 364.0 [M/2 – OAc + CH_3CN]$^+$. $C_{28}H_{20}F_4N_4O_4Pd_2$ (765.32): calcd. C 43.94, H 2.63, N 7.32, Pd 27.81; found C 43.69, H 2.58, N 7.20, Pd 27.95. IR (KBr): $\tilde{\nu}$ = 436, 470, 534, 685, 779, 810, 844, 877, 1101, 1153, 1184, 1234, 1246, 1320, 1348, 1416, 1501, 1560, 1597, 3077 cm^{-1}. ^1H NMR (400 MHz, $CDCl_3$): δ = 2.1 (s, 6 H, H^{11}), 6.1 (m, 2 H, H^3), 6.8 (m, 2 H, H^5), 7.0 (m, 4 H, H^9), 7.4 (m, 4 H, H^8), 7.7 (m, 2 H, H^6) ppm. ^{13}C NMR (101 MHz, $CDCl_3$):

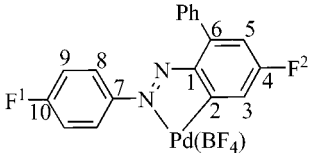
δ = 24.5 (s, C^{11}), 113.2 (d, $^2J_{C,F}$ = 25 Hz, C^5), 115.1 (d, $^2J_{C,F}$ = 23 Hz, C^9), 119.5 (d, $^2J_{C,F}$ = 21 Hz, C^3), 125.4 (d, $^3J_{C,F}$ = 9 Hz, C^8), 130.5 (d, $^3J_{C,F}$ = 10 Hz, C^6), 146.9 (d, $^4J_{C,F}$ = 3 Hz, C^7), 158.2 (d, $^3J_{C,F}$ = 7 Hz, C^2), 159.9 (d, $^4J_{C,F}$ = 3 Hz, C^1), 162.2 (d, $^1J_{C,F}$ = 264 Hz, C^4), 164.1 (d, $^1J_{C,F}$ = 253 Hz, C^{10}), 181.4 (s, COO) ppm. ^{19}F NMR (376 MHz, CD_3OD): δ = –110.5 (m, F^1), –102.9 (m, F^2) ppm.

Synthesis of 4,4′-Difluoro-2-phenylazobenzene (5)



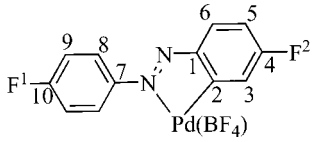
Complex **4** (0.380 g, 0.50 mmol), potassium phenyltrifluoroborate (0.250 g, 1.4 mmol) and potassium carbonate (0.225 g, 1.6 mmol) were suspended in methanol (10 mL). The system was refluxed for 1 h, then cooled and the methanol evaporated. The residue was extracted with diethyl ether (4 × 25 mL), then the organic fractions were collected and washed with water (2 × 50 mL) and brine (2 × 50 mL), dried with anhydrous sodium sulfate, filtered and the solvents evaporated. The crude product was purified by column chromatography with petroleum ether (boiling range 40–70 °C) as eluent. Yield 0.073 g (25%). MS (70 eV, EI): *m*/*z* 293 (99) [M^+ – 1], 184 (14), 170 (100), 151 (12), 123 (12), 95 (66), 75 (18). $C_{18}H_{12}F_2N_2$ (294.30): calcd. C 73.46, H 4.11, N 9.52; found C 73.69, H 4.28, N 9.30. IR (KBr): $\tilde{\nu}$ = 461, 542, 698, 737, 762, 781, 843, 880, 893, 1109, 1136, 1186, 1271, 1444, 1477, 1570, 1594 cm^{-1}. ^{1}H NMR (400 MHz, $CDCl_3$): δ = 6.9–7.0 (m, H^9, H^5), 7.1 (m, H^3), 7.2 (m, Ph), 7.5–7.6 (m, H^8, H^6) ppm. ^{13}C NMR (101 MHz, $CDCl_3$): δ = 115.2 (d, $^2J_{C,F}$ = 23 Hz, C^5), 116.0 (d, $^2J_{C,F}$ = 22 Hz, C^9), 117.2 (d, $^2J_{C,F}$ = 22 Hz, C^3), 118.0 (d, $^3J_{C,F}$ = 9 Hz, C^6), 125.1 (d, $^3J_{C,F}$ = 9 Hz, C^8), 127.7 (s, CH), 127.8 (s, CH), 130.7 (s, CH), 137.7 (d, $^4J_{C,F}$ = 2 Hz; 1 C), 143.6 (d, $^3J_{C,F}$ = 9 Hz, C^2), 145.8 (d, $^4J_{C,F}$ = 3 Hz, C^1), 149.2 (d, $^4J_{C,F}$ = 3 Hz, C^7), 164.0 (d, $^1J_{C,F}$ = 252 Hz, C^4), 164.2 (d, $^1J_{C,F}$ = 252 Hz, C^{10}) ppm. ^{19}F NMR (376 MHz, CD_3OD): δ = –112.0 (m, F^2), –111.7 (m, F^1) ppm.

Synthesis of (4,4′-Difluoro-6-phenylazobenzene-*C*^{2},*N*)palladium(II) Tetrafluoroborate (6)



$PdCl_2$ (36 mg, 0.2 mmol) and **5** (60 mg, 0.2 mmol) were placed in a centrifuge tube and dmso (1 mL) was added. The system was heated to 140 °C for 10 min, then cooled to room temperature. Methanol (3 mL) was added to the resulting deep red solution to precipitate an orange solid, which was centrifuged, washed with methanol (3 × 3 mL) and diethyl ether (3 × 3 mL) and vacuum dried. A 25-mg portion of this solid was placed in an NMR tube and a solution of $AgBF_4$ (12 mg, 0.06 mmol) in CD_3OD (0.5 mL) was added. The NMR tube was sonicated briefly and the resulting suspension allowed to settle before analysis. ^{1}H NMR (400 MHz, CD_3OD): δ = 6.8 (m, 1 H), 7.2 (m, 1 H), 7.3 (m, 2 H, H^9), 7.5 (m, 3 H, Ph), 7.6 (m, 2 H, Ph), 7.7 (m, 2 H, H^8) ppm. ^{13}C NMR (101 MHz, CD_3OD): δ = 116.0 (d, $^2J_{C,F}$ = 24 Hz, CH), 117.1 (d, $^2J_{C,F}$ = 24 Hz, C^9), 119.3 (d, $^2J_{C,F}$ = 23 Hz, CH), 126.5 (d, $^3J_{C,F}$ = 9 Hz, C^8), 129.3 (s, CH), 130.0 (s, CH), 131.2 (s, CH), 138.8 (C), 148.0 (d, $^3J_{C,F}$ = 10 Hz, 1 C), 148.9 (C), 157.9 (d, $^3J_{C,F}$ = 7 Hz, 1 C), 158.9 (C), 163.8 (d, $^1J_{C,F}$ = 265 Hz, 1 C), 165.7 (d, $^1J_{C,F}$ = 252 Hz, 1 C) ppm. ^{19}F NMR (376 MHz, CD_3OD): δ = –109.9 (m, F^1), –100.4 (m, F^2) ppm.

Synthesis of (4,4′-Difluoroazobenzene-*C*^{2},*N*)palladium(II) Tetrafluoroborate (7)



Complex **4** (0.380 g, 0.50 mmol) and *p*-fluorobenzenediazonium tetrafluoroborate (0.210 g, 1.0 mmol) were suspended in dry methanol (10 mL) at room temperature under nitrogen. The suspension was vigorously stirred and the gas (dinitrogen) evolved monitored by means of a gas burette. Once the diazonium salt had completely reacted (approx. 24 mL of gas) the methanol was evaporated. The residue was treated with dry dichloromethane (3 × 10 mL) and the resulting suspension was filtered under N_2 through a Celite® pad. The filtrate was concentrated to about one third and dry *n*-hexane (50 mL) added to precipitate **7** as an orange powder. The product was decanted, washed with small portions of *n*-hexane and dried under vacuum. Yield 0.330 g (80%). ESI-MS (CH_3CN): exact mass calcd. for $C_{12}H_7BF_6N_2Pd$: 322.96; found 323.0 [M]$^+$. $C_{12}H_7BF_6N_2Pd$: 409.96; found 323.0 [M – BF_4]$^+$. $C_{12}H_7BF_6N_2Pd$ (410.42): calcd. C 35.12, H 1.72, N 6.83, Pd 26.93; found C 35.02, H 1.69, N 6.49, Pd 26.81. IR (nujol): $\tilde{\nu}$ = 470, 593, 779, 845, 1064, 1154, 1193, 1257, 1499, 1568, 1583, 2050 cm^{-1}. ^{1}H NMR (400 MHz, [D_6]dmso): δ = 7.1 (m, 1 H, H^3), 7.3 (m, 1 H, H^5), 7.5 (m, 2 H, H^9), 7.9 (m, 2 H, H^8), 8.1 (m, 1 H, H^6) ppm. ^{13}C NMR (101 MHz, [D_6]dmso): δ = 114.3 (d, $^2J_{C,F}$ = 24 Hz, C^5), 116.1 (d, $^2J_{C,F}$ = 23 Hz, C^9), 119.2 (d, $^2J_{C,F}$ = 23 Hz, C^3), 126.0 (d, $^3J_{C,F}$ = 9 Hz, C^8), 132.3 (d, $^3J_{C,F}$ = 10 Hz, C^6), 147.1 (d, $^4J_{C,F}$ = 3 Hz, C^7), 156.3 (d, $^3J_{C,F}$ = 7 Hz, C^2), 160.5 (d, $^4J_{C,F}$ = 3 Hz, C^1), 161.8 (d, $^1J_{C,F}$ = 263 Hz, C^4), 163.6 (d, $^1J_{C,F}$ = 250 Hz, C^{10}) ppm. ^{19}F NMR (376 MHz, CD_3OD): δ = –154.6 (br. s, BF_4), –109.6 (br. s, F^1), –101.6 (br. s, F^2) ppm.

Catalysis with Precatalyst 4: $KPhBF_3$ (221 mg, 1.2 mmol) and *p*-$CH_3C_6H_4N_2BF_4$ (206 mg, 1.0 mmol) were added, with vigorous stirring, to a suspension of **4** (7.65 mg, 0.010 mmol) in methanol (4 mL) in a 10-mL Schlenk tube. At the end of the reaction (80 min) the mixture was diluted with water (100 mL) and the products were extracted with diethyl ether (3 × 25 mL); the organic phases were collected and dried with Na_2SO_4. The products were purified by flash chromatography and characterized by GC-MS. The yield was determined by GLC using naphthalene as an internal standard.

Reaction of 4 with Potassium Phenyltrifluoroborate: HPLC-grade methanol (0.5 mL) was added to a vial containing complex **4** (7 mg, 9 μmol) and potassium phenyltrifluoroborate (25 mg, 137 μmol) and the mixture shaken for half a minute. The resulting suspension was transferred into an NMR tube containing an internal insert of $CDCl_3$ for the deuterium lock. A 0.05-mL aliquot of the same suspension was diluted to 5 mL with HPLC-grade methanol and used in ESI-MS experiments.

Reaction of Complex 4 with Potassium Phenyltrifluoroborate and Diazonium Salts: HPLC-grade methanol (0.5 mL) was added to a vial containing complex **4** (7 mg, 9 μmol) and potassium phenyltrifluoroborate (25 mg, 137 μmol) and the mixture shaken for half a minute. A solution of diazonium salt (165 μmol) in HPLC-grade methanol (0.5 mL) was added to the resulting suspension and the

vial again shaken for half a minute. About 0.5 mL of the suspension was transferred into an NMR tube containing an internal insert of $CDCl_3$ for the deuterium lock. A 0.1-mL aliquot was diluted to 5 mL with HPLC-grade methanol and used in ESI-MS experiments. The reaction mixtures were analyzed by GLC and GC-MS to identify the coupling products.

Supporting Information (see also the footnote on the first page of this article): ^{19}F, ^{1}H and ^{13}C NMR spectra of **4**–**7**. HR mass spectra of a methanol solution of complex **4**, *p*-$FC_6H_4N_2BF_4$ and $KPhBF_3$; experimental and simulated HRMS(+) spectrum of **II-F**.

Acknowledgments

Financial support from the European Cooperation in the field of Scientific and Technical Research (COST, D30 action, fellowship to N. T.) is gratefully acknowledged. We thank Ms. E. Andriani for experimental assistance.

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Received: May 21, 2007
Published Online: August 9, 2007

