The addition of bromine and iodine to palladacyclopentadienyl complexes bearing bidentate heteroditopic P–N spectator ligands derived from differently substituted quinolinic frames. The unexpected evolution of the reaction†

Luciano Canovese,*a Fabiano Visentin,a Thomas Scattolin,a Claudio Santoa and Valerio Bertolasib

We have synthesized two palladacyclopentadienyl derivatives bearing bidentate ligands heteroditopic 8-(diphenylphosphino)quinoline or 8-(diphenylphosphino)-2-methylquinoline. We have reacted the palladacyclopentadienyl complexes with Br2 and I2 to gain clues on the formation mechanism of the corresponding σ-butadienyl derivatives. We were able to obtain the pure σ-butadienyl derivative only in the case of Br2 reacting with the palladacyclopentadienyl complex bearing the unsubstituted quinoline. However, an equilibrium mixture of the σ-butadienyl and a novel zwitterionic species was obtained when the same complex reacts with I2. Furthermore, we have obtained exclusively an unprecedented zwitterionic complex when I2 reacts with the palladacyclopentadienyl complex bearing the substituted quinoline and a different ratio of an equilibrium mixture of σ-butadienyl and the zwitterionic species when the latter derivative reacts with Br2. The solid state structures of one σ-butadienyl complex and of the two novel zwitterionic derivatives were determined and an interpretation of the observed reactivity based on kinetic data and a computational study has been suggested.

Introduction

A number of catalyzed reactions are based on the stability and chemical versatility of palladium complexes toward oxidative addition and reductive elimination. In particular, interconversion between Pd(0) and Pd(II) derivatives† has been widely studied since it often represents the keystone for several cross coupling processes. In contrast, the red–ox reactions involving the Pd(II)–Pd(IV)–Pd(II) conversions are comparatively less investigated and are often related to addition of halogens or organic halides in catalytic or stoichiometric processes yielding conjugated dienes as their final products. The conjugated dienes are important compounds contained in many natural and bioactive products. Therefore, their synthesis is of remarkable importance as testified by the development of catalytic protocols based on cobalt,4 ruthenium,5 nickel6 and palladium.6b,7 Particular emphasis has been placed on the reactivity of palladacyclopentadienyl derivatives bearing different spectator ligands.2,3,8 We have recently carried out a detailed study on the oxidative addition of I2 to palladacyclopentadienyl complexes bearing monodentate isocyanides as spectator ligands.2,3,8 We were able to measure the rates of intramolecular conversion of the intermediate trans-diido palladium(II) into the cis-diidoacetylene-tetramethyl pallada-1-iodobuta-1,3-diene-1,2,3,4-tetraacarboxylate, its subsequent isomerisation to the trans-isomer, and support the experimental results with a computational study.9

We also think that the conversion of the metallacyclopentadienyl complexes into the σ-butadienyl derivatives deserves a further study since the stereospecific formation of the final butadienyl fragment is mainly governed by the transition state and the intermediate structures involved in this first step. We have therefore synthesized two palladacyclopentadienyl complexes bearing the bidentate heteroditopic ligands 8-(diphenyl-
phosphino)quinoline (DPPQ) or 8-(diphenylphosphino)-2-methyl quinoline (DPPQ-Me) which, while avoiding complications arising from cis–trans isomerization of the spectator ligands, impart to the palladium derivative properties that could be exploited in insertion reactions, isomerization of a co-ordinated olefin and nucleophilic attack on the allyl fragment. We have finally studied from the experimental and theoretical point of view the oxidative addition of the cited complexes using bromine and iodine.

The ligands, the palladacyclopentadienyl and the identified σ-butadienyl complexes are reported in the following Scheme 1.

Results and discussion

Synthesis of cyclometallated complexes 1a and 1b

The addition in acetone of the ligands DPPQ or DPPQ-Me under an inert atmosphere (Ar) to the polymer [PdC₄(COO-Me)₄]ₙ which was synthesized using published procedures, yields complexes 1a and 1b which were easily isolated with good yield. These compounds are characterized by the downfield shift of the phosphorus (ca. 40 ppm) and of the quinoline H₂ (complex 1a) or CH₃ (complex 1b) protons, with respect to the free ligands in the ³¹P NMR and ¹H NMR spectra. There are also distinct signals related to four different COOCH₃ groups in the ¹H and ¹³C NMR spectra (see ESI Fig. S1†).

Reactivity of complex 1a with Br₂

As can be seen in Scheme 1, complex 1a reacts with Br₂ to give the expected σ-butadienyl derivative 2a. The formation of 2a is apparent as can be deduced from the ¹H, ¹³C and ³¹P NMR spectra in CDCl₃ of the reaction product after precipitation from the concentrated reaction mixture with diethyl ether (see ESI Fig. S2†). As a matter of fact, the persistence of four different COOCH₃ groups with marked downfield shifts of the quinoline H₂ (δ ≈ 10.5 ppm clearly indicating its cis position to bromide) compared to those of the precursor, and the phosphorus peak (δ = 34.3 ppm) show the course of the reaction.

Due to its stability in solution and in the solid state it was possible to confirm definitively the structure of 2a as inferred from NMR, by X-ray diffraction. In Fig. 1 we report the ORTEP representation of the solid state structure of complex 2a which will be discussed later.

Reactivity of complex 1b with Br₂

The reaction of complex 1b with bromine under similar experimental conditions gives immediately complex 2b which can be quantitatively separated from the reaction mixture when precipitation with diethyl ether is induced soon after the addition of the Br₂ and at low temperature (273 K). The NMR spectra of complex 2b are very similar to those of 2a. In particular the ³¹P singlet of the former is almost isochronous to that of the latter (δ = 34.2 ppm) (see ESI Fig. S3†).

Complex 2b, however, is not stable in solution and in about 30 h undergoes a remarkable change which is evident when the NMR spectra of the starting and the final derivative are compared. In fact, the phosphorus peak shifts upfield by about 20 ppm and the signals ascribable to the four OCH₃ groups resonate in different positions in the ¹H NMR spectrum (see ESI Fig. S4†).

According to the structure of 4b, the ¹³C NMR spectrum shows a doublet at ca. 42 ppm (JCP ≈ 60 Hz) and a singlet at ca. 31 ppm ascribable to the alkyl carbons bound to the palladium centre.
The reaction and the suggested mechanism yielding this unprecedented complex 4b are shown in eqn (1):

\[ E = \text{COOMe} \]

\[ \begin{align*}
2b & \xrightarrow{k_r} 4b \\
E & \text{COOMe}
\end{align*} \]

The formation of the zwitterionic complex 4b might be explained as the result of an intramolecular nucleophilic attack of the phosphorus originally coordinated to the metal on the sp² carbon of the butadienyl fragment. The overall process is a slow equilibrium reaction and the amount of complex 2b that remained unreacted was evaluated to be 15% of its initial concentration \( K_E \approx 5.4 \).\(^{17} \)

Thus, it was possible to calculate \( k_f \) and \( k_r \) independently by non-linear regression of the concentration vs. time data implemented in the SCIENTIST® computing environment (Fig. 3). The \( k_f \) and \( k_r \) values were estimated to be \((4.93 \pm 0.01) \times 10^{-5}\) and \((8.93 \pm 0.02) \times 10^{-6} \text{ s}^{-1}\), respectively.\(^{18} \) The equilibrium constant was calculated as \( K = k_f/k_r = 5.52 \pm 0.02 \) which is in good agreement with the value determined from the experimentally detected final concentrations of species 2b and 4b \( (K \approx 5.4) \) (see also footnote SI 1 in the ESI†).

It is noteworthy that it was not possible to obtain derivative 4a from complex 1a. As a matter of fact, when the reaction of complex 1a with Br₂ was carried out for a prolonged time at high temperature in CDCl₃ (323 K) a massive decomposition occurred.

**Reactivity of complex 1b with I₂**

The addition at RT of an equimolecular amount of I₂ to a solution of 1b in CH₂Cl₂ gives readily and quantitatively complex 5b as the only reaction product (eqn (2)).

\[ \text{I}_2 \rightarrow \]

Complex 5b displays NMR spectra very similar to those of complex 4b previously described; in particular, the single signal in the ³¹P NMR spectrum resonates at 8.9 ppm, whereas the ¹³C NMR spectrum shows the characteristic peaks of the Pd–C–PPh₂ (doublet at ca. 44 ppm, \( J_{CP} = 61.8 \text{ Hz} \)) and Pd–C–I (singlet at 32.9 ppm) (see ESI Fig. S5†). Again the structure of derivative 5b was definitively resolved by X-ray diffractometry as reported in the Crystal structure determination section (Fig. 4).

However, when the reaction is carried out at a low temperature (253 K) it is possible to observe the formation of complex 3b which was identified on the basis of the similarity of its ¹H and ³¹P NMR spectra with those of the parent complex 3a (\textit{vide infra}). As expected, complex 3b readily reverts to complex 5b at RT (see ESI Fig. S6†).

Complex 1a when reacting with I₂ predictably takes the middle course and an equilibrium mixture of the σ-butadienyl 3a and zwitterionic 5a complexes is detectable in solution. In Fig. 5 the ¹H and ³¹P NMR spectra of the equilibrium mixture of complexes 3a and 5a taken soon after the addition of I₂ to
1a are reported. Remarkably, the immediately established concentration ratio between isomers remains constant over time.

A summary of the oxidative additions of Br₂ and I₂ on complexes 1a and 1b is reported in the following Scheme 2 in which the complexes within dotted squares (4a, 3b) have not been isolated.

Reactivity of complex 2b with I⁻

In order to gain some more information about the driving force promoting the widening of the coordinative ring, we have reacted complex 2b ([2b]₀ ≈ 1 × 10⁻² mol dm⁻³) with two equivalents of (n-Bu)₄NI, in CD₂Cl₂ at 298 K. The ¹H and ³¹P NMR spectra of the reaction mixture in CD₂Cl₂ show that an equilibrium reaction between the starting complex 2b and a new species 2b⁺ is immediately established. Complex 2b⁺ was formed as a consequence of the substitution of the Br⁻ coordinated to palladium with iodide. The equilibrium mixture is slowly converted into a new equilibrium mixture of the zwitterions 4b and 4b⁺, as summarized in Scheme 3. The presence of complex 4b was proved by comparison with the ¹H and ³¹P NMR spectra of an authentic sample of 4b. The structure of 4b⁺ was instead assessed by the comparison with the ¹H and ³¹P NMR spectra of the complex obtained by reacting complex 4b with an excess (2 : 1) of (n-Bu)₄NI (6c). In the latter case, only the bromide coordinated to palladium should be substituted according to the well-established theory of nucleophilic substitution on square planar complexes¹⁹ (see Scheme 3 and ESI Fig. S7a–c†).

As already stated, complex 3b is not stable and immediately gives zwitterion 5b at RT. In contrast, since the parent complex 2b⁺ reacts slowly to yield zwitterion 4b⁺ it is reasonable to surmise that the halide bound to sp² carbon is also a determinant in modulating the reaction rate. In summary, the rate of the reaction yielding the zwitterionic complexes seems to be due to an interplay of three different factors, i.e. the distortion of the coordinating ring,¹⁰ the trans influence of the halide trans to quinoline phosphorus, and the charge density on the butadienyl sp² carbon (which is clearly influenced by the electronegativity of the bound halide). Therefore, the best combination favoring the widening of the coordinated ring is the presence of the methyl substituted quinoline (and the consequent induced distortion of the original coordinative ring), the iodide trans to quinoline phosphorus, and the...
iodide bound to the butadienyl sp² carbon. Conversely, the other end is represented by the unsubstituted quinoline and the bromides bound to the palladium and to butadienyl sp² carbon.

Computational study

Such experimental observations were not in contrast to a detailed computational study carried out by the Gaussian 09 program. To save computing time the carboxymethyl group COOMe was replaced by the less disordered CN moiety (in the following discussion the CN derivatives will maintain the same labels of the original complexes marked with an apex).

Taking into account the limitations due to the errors implicit in this sort of calculation (ΔΔG° ≈ ± 2 kcal mol⁻¹) and the replacement of COOMe with CN groups, it was calculated that:

(i) complex 4b' is more stable than complex 2b' by 2.3 kcal mol⁻¹.
(ii) complex 5b' is more stable than complex 3b' by 5.0 kcal mol⁻¹.
(iii) complex 4a' is less stable than complex 2a' by 0.9 kcal mol⁻¹.

Scheme 2  General overview of the reactivity of complexes 1a and 1b towards the addition of Br₂ and I₂ (within the dotted squares the not isolated products).

Scheme 3  Schematic representation of the equilibrium reactions triggered by the addition of (n-Bu)₄NI to complex 2b in CD₂Cl₂ at RT.
Crystal structure determination

An ORTEP view of neutral complex 2a is shown in Fig. 1. A selection of bond distances and angles is given in Table S2.† The geometry around the Pd centre is a slightly distorted square planar. The four positions around the central Pd are occupied by the carbon Cα of the 1,2,3,4-tetras(phenyl)buta-1,3-diene-4-Br-1-yl anionic ligand, a Br anion, the pyridine nitrogen and phosphorus of the 8-diphenylphosphanyl-2-methyl-quinoline (DPPQ-Me) ligand. The deviations from the basal plane are: −0.0004(4) for Br1, 0.016(3) for N1, −0.021(1) for P1 and 0.022(3) Å for C22. Pd1 is situated at 0.0662(3) Å above this average plane. The C22 = C23-C24 = C25 buta-1,3-diene moiety displays an anti-clinal conformation with a torsion angle of −117.0(4)°.

An ORTEP view of the neutral isostructural complexes 4b and 5b is shown in Fig. 2 and 4.

A selection of bond distances and angles is given in Table S2.† In both complexes, the geometry around the Pd centre is square planar distorted towards a tetrahedral arrangement. The four positions around the central Pd are occupied by halogen atoms, Br in 4b or I in 5b. The pyridine nitrogen of the 8-diphenylphosphanyl-2-methyl-quinoline (DPPQ-Me) ligand and the α,δ-carbons of the buta-1,3-diene-4-Br(or 1)-1-yl moiety of the ligand are as in the previous complex 2a. The deviations of the four atoms from the basal plane are: −0.0053(5) for Br1, 0.224(3) for N1, −0.273(3) for C23 and 0.285(3) Å for C26 with the Pd1 atom at 0.0975(3) Å above this average plane, in complex 4b. For complex 5b they are: −0.0019(3) for I1, 0.222(3) for N1, −0.333(3) for C23 and 0.289(3) Å for C26 with the Pd1 atom at 0.1228(3) Å above this average plane, in complex 5b. In both complexes the Pd1–C23–C24–C25–C26 palladacyclopentene rings are approximately planar with maximum deviations from the mean planes of −0.081(4) for C25 and 0.074(3) Å for C26 in complex 4b and −0.072(3) for C25 and 0.058(3) Å for C26 in complex 5b.

The different coordination modes of the buta-1,3-diene ligand in complexes 4b and 5b with respect to that observed in complex 2a give rise to variations both in carbon hybridizations and in C-C bond distances.

Conclusions

The oxidative addition of Br2 or I2 to palladacyclopentadienyl complexes bearing the bidentate DPPQ or DPPQ-Me as spectator ligands yields different derivatives depending on the nature of the ancillary ligands and halogens. Thus, complex 1a reacts with Br2 yielding the σ-butadienyl derivative 2a and complex 1b with I2 to give the unprecedented zwiterionic complex 3b, only. The cross reactivity yields in both cases an equilibrium mixture of the σ-butadienyl and zwiterionic complexes 2b and 4b (in the case of complex 1b reacting with Br2) and 3a and 5a (in the case of complex 1a reacting with I2). The experimental results and in particular the reactivity of the butadienyl derivatives were interpreted taking into account the different lability of the bisdentate ligands (DPPQ-Me which is more labile than DPPQ), the higher trans-influence of I− compared to Br−, and the charge density on the butadienyl sp3 carbon which is modulated by the electron-acceptor nature of the bound halide. In order to give adequate support to the experimental observations a detailed study of the solid state structure of complexes 2a, 4b and 5b together with the determination of the reaction rates characterizing the equilibrium reaction between 2b and 4b were also carried out.

Experimental

Solvents and reagents

All the following distillation processes were carried out under an inert atmosphere (argon). Acetone and CH2Cl2 were distilled over 4 Å molecular sieves and CaH2 respectively. All the other chemicals were commercially available grade products and were used as purchased.

Data analysis. Nonlinear analysis of the data related to equilibrium and kinetics measurements was performed by locally adapted routines written in the SCIENTIST® environment.

IR and NMR measurements

The IR, 1H, 13C and 31P NMR spectra were recorded on a Perkin-Elmer Spectrum One spectrophotometer and on a Bruker 300 Avance spectrometer, respectively.

Computational details

The geometrical optimization of the complexes was carried out without symmetry constraints, using the hyper-GGA functional M0622,23 in combination with polarized triple-ζ-quality basis
Crystal structure determinations

The crystal data of compounds 2a, 4b and 5b were collected at room temperature using a Nonius Kappa CCD diffractometer with graphite monochromated Mo-Kα radiation. The data sets were integrated with the Denzo-SMN package30 and corrected for Lorentz, polarization and absorption effects (SORTAV).31 The structures were solved by direct methods using the SIR9732 and PARST34 implemented in the WINGX35 system of programs. The crystal data are given in Table S3.†

Crystallographic data have been deposited at the Cambridge Crystallographic Data Centre and allocated the deposition numbers CCDC 1053523, 1053524, and 1053525.

Synthesis of the ligands and starting complex

The ligands DPPQ,12 DPPQ-Me13 and the polymeric complex [PdCl4(COOMe)4]15 were synthesized according to the published procedures.

Synthesis of complex 1a

In a two necked 100 ml flask 198.0 mg (0.51 mmol) of [PdCl4(COOMe)4] and 172.2 mg (0.55 mmol) of DPPQ were dissolved in 20 ml of anhydrous acetone under an inert atmosphere (Ar). The resulting solution was stirred for 1 h and concentrated under vacuum to a reduced volume (2–3 ml). Dropwise addition of diethyl ether (5–10 ml) causes the precipitation of the title complex as a yellow microcrystalline solid. The solid was filtered off on a gooch filter, washed several times with diethyl ether and n-pentane and dried under vacuum to obtain 81.7 mg (94% yield) of the complex.

1H-NMR (300 MHz, CDCl3, T = 298 K, ppm): 3.41 (s, 3H, OCH3), 3.63 (s, 3H, OCH3), 3.72 (s, 3H, OCH3), 3.74 (s, 3H, OCH3), 7.37–7.54 (m, 6H, Ph), 7.65–7.70 (m, 2H, H1, H4), 7.82–7.98 (m, 4H, H7, Ph), 8.05 (d, 1H, J = 8.0 Hz, H5), 8.43 (dt, 1H, J = 8.3, 1.5 Hz, H3), 10.47 (dd, 1H, J = 5.1, 1.5 Hz, H2).34

Synthesis of complex 2a

In a two necked 50 ml flask, 71.1 mg (0.10 mmol) of compound 1 dissolved in 10 ml of anhydrous CH2Cl2 17.8 mg (0.111 mmol) of Br2 dissolved in 5 ml of CH2Cl2 was added under an inert atmosphere (Ar). The reaction mixture immediately decolorized and after 5 min stirring the solution was evaporated under vacuum to 3–4 ml. The dropwise addition of diethyl ether induces the precipitation of the title complex as a yellow microcrystalline solid. The solid was filtered off on a gooch filter, washed several times with diethyl ether and n-pentane and dried under vacuum to obtain 81.7 mg (94% yield) of the complex.

1H-NMR (300 MHz, CDCl3, T = 298 K, ppm): 3.41 (s, 3H, OCH3), 3.63 (s, 3H, OCH3), 3.72 (s, 3H, OCH3), 3.74 (s, 3H, OCH3), 7.37–7.54 (m, 6H, Ph), 7.65–7.70 (m, 2H, H1, H4), 7.82–7.98 (m, 4H, H7, Ph), 8.05 (d, 1H, J = 8.0 Hz, H5), 8.43 (dt, 1H, J = 8.3, 1.5 Hz, H3), 10.47 (dd, 1H, J = 5.1, 1.5 Hz, H2).34

†Cryst structure data (CCDC 1053523, 1053524, 1053525) have been deposited with the Cambridge Crystallographic Data Centre (CCDC 1053523, 1053524, 1053525).

Anal. calcd for C33H28NO8Pd: C 56.30, H 4.01, N 1.99.
Found: C 56.41, H 4.18, N 1.87.

Synthesis of complex 1b

Complex 1b was obtained following the same procedure as for complex 1a.

A yellow-orange microcrystalline solid was obtained with a 74% yield.

1H-NMR (300 MHz, CDCl3, T = 298 K, ppm): 2.86 (s, 3H, OCH3), 2.89 (s, 3H, OCH3), 3.39 (s, 3H, quinoline–CH3), 3.68 (s, 3H, CH3), 3.64 (s, 3H, OCH3), 7.89 (d, 1H, H1, J = 9.0 Hz), 8.18 (d, 1H, H4, J = 9 Hz); 7.42 (m, 10H).

31P{1H}-NMR (CDCl3, T = 298 K, ppm): 30.16.

Anal. calcd for C33H28NO8Pd: C 56.88, H 4.21, N 1.95.
Found: C 56.94, H 4.07, N 1.87.
Synthesis of complex 2b

Complex 3a was obtained following similar conditions to complex 2a but the synthesis was carried out at a low temperature (273 K) and the complex was collected within 10 min.

A pale-yellow microcrystalline solid was obtained with a 61% yield.

$^1$H-NMR (300 MHz, CDCl$_3$, $T = 298$ K, ppm): δ: 3.32 (s, 3H, quinoline–CH$_3$), 3.45 (s, 3H, OCH$_3$), 3.60 (s, 3H, OCH$_3$), 3.87 (s, 3H, OCH$_3$), 3.88 (s, 3H, OCH$_3$), 7.34–7.62 (m, 9H, PPh$_2$, H$_3$), 7.76–8.04 (m, 5H, H$_5$, H$_6$, H$_7$, PPh$_2$), 8.14 (dd, 1H, $J = 8.5$, 1.6 Hz, H$_8$).

$^{31}$P($^1$H)-NMR (CDCl$_3$, $T = 298$ K, ppm) δ: 34.3.

IR (KBr pellets): $\nu_{C-O} = 1732$, 1716 and 1704 cm$^{-1}$.

Anal. calcld for C$_3$H$_{25}$Br$_2$NO$_8$Pd·CH$_2$Cl$_2$: C 39.78, H 3.05, N 1.33. Found: C 39.65, H 2.97, N 1.19.

Notes and references


17 Thanks to the reduced solubility of zwitterionic complex 4b in CH2Cl2 compared to that of complex 2b, it was possible to separate crystals for diffractometric determination from the equilibrium mixture. In contrast, any attempts at separating suitable crystals of complex 2b were unsuccessful since only some crystals of complex 4b were obtained after about a week at 263 K.

18 As can be seen in Fig. 3 the starting concentration ([t = 0] of complex 4b is not null (the estimated values ensuing from the regression analysis are [2b] = 8.8 × 10–3 ± 4 × 10–6, [4b] = 1.16 × 10–3 ± 4 × 10–6). Since the reaction was carried out starting from an authentic sample of 2b which was isolated pure some days before the NMR study, we think that the interconversion reaction is also likely to occur in the solid state.


