

Organometallic nucleophiles. A mechanistic study of halide displacement at saturated carbon by 2- and 4-pyridyl complexes of palladium(II) and platinum(II)

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Abstract

The reactions of the 2- and 4-pyridyl complexes $[MX(C_5H_4N-C^n)(dppe)]$ and $trans-[MX(C_5H_4N-C^n)(PPh_3)_2]$ ($M = Pd, Pt$; $X = Cl, Br$; $n = 2, 4$) involving halide displacement from the organic halides $X-CH_2R$ ($X = Cl, Br$; $R = CN, Ph, CH=CH_2$) by the pyridyl nitrogen have been studied kinetically by conductivity in acetone or acetonitrile at 25 °C. The kinetic data fit the second-order rate law $k_2[X-CH_2R][complex]$, in agreement with an S_N2 process at saturated carbon. The higher rates are displayed by the 2-pyridylpalladium derivatives with $X = Br$ in both the metal complex and the organic halide. The higher nucleophilic power of the 2-pyridyl complexes compared with their 4-pyridyl analogs is paralleled by a higher basicity, as reflected by a higher pK_a value. In any case, the metal-containing substituent enhances considerably the reactivity and basicity of the pyridine nitrogen. The rates are scarcely influenced by the coordination geometry around the metal.

1. Introduction

2-Metallated pyridines feature enhanced basic and nucleophilic abilities, as shown by their high pK_a values (in the range 8–10) relative to pyridine itself (4.47 in water–dioxane 1:1 v/v at 0.1 mol dm⁻³ ionic strength) [1–9], and by the ease of nucleophilic displacement of halide ions from $X-CH_2R$ ($X = Cl, Br$; $R = CH=CH_2, COMe, Ph, CN$) [7–9] and even of the chloride from chlorinated solvents [6,10]. In particular, the nucleophilic power of the 2-pyridyl ligand in the complexes $[M(dmtc)(C_5H_4N-C^2)L]$ ($M = Pd, Pt$; $dmtc = dimethyldithiocarbamate$; $L = tertiary phosphine$) is much higher than that of 4-dimethylaminopyridine [8,9], which is widely used as a ‘hypernucleophilic’ catalyst in a variety of organic reactions [11,12]. In a previous study [8,9] we have described the mechanism of halide substitution by the above-mentioned derivatives $[M(dmtc)(C_5H_4N-C^2)L]$ on the organic substrates $X-CH_2R$, which involves an essentially S_N2 process at the CH_2 carbon, as suggested by solvent and leaving group

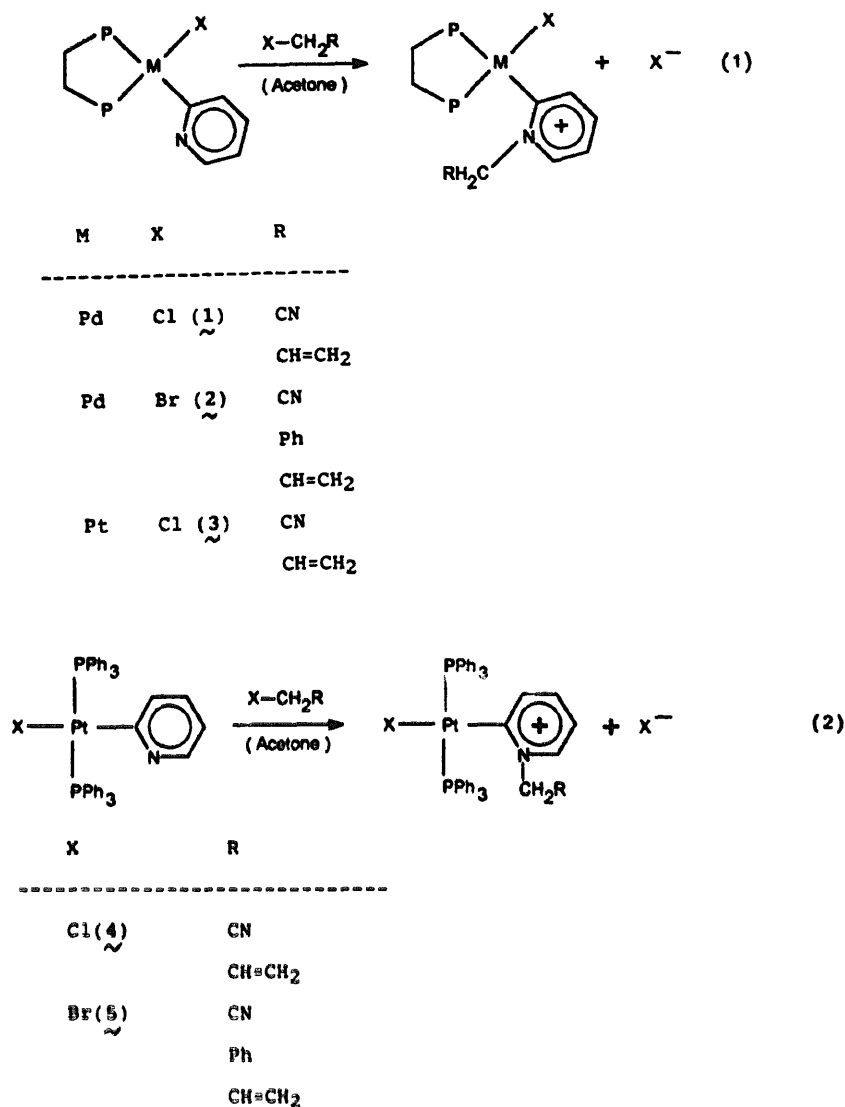
effects and by activation parameters. We have now extended these investigations to using 2- and 4-pyridyl complexes of the type $trans-[MX(C_5H_4N-C^n)(dppe)]$ ($M = Pd, Pt$; $X = Cl, Br$; $n = 2, 4$; $dppe = 1,2-bis(diphenylphosphino)ethane$) to gain further insight into the role played by the central metal, the coordination environment, and the position of the metal-containing unit on the pyridine ring.

2. Results and discussion

The 2-pyridyl complexes 1–5 and their 4-pyridyl counterparts 6–8 react with organic halides according to Eqs. (1) and (2) in Scheme 1 and Eqs. (3) and (4) in Scheme 2 respectively. The new starting complexes 2, 6 and 8 were prepared as described in the Experimental section, along with some final 2- and 4-pyridylum products resulting from the alkylation reaction with $EtI-CH_2CN$.

The analytical and selected spectral data for the new derivatives are also reported in the Experimental section.

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Scheme 1.

The kinetics of reactions (1)–(4) were monitored by conductometric techniques using a procedure described earlier [9]. All kinetic runs were carried out under pseudo-first-order conditions by use of an excess of the organic halide $X-CH_2R$ over the metal complex. The pseudo-first-order rate constants k_{obs} fit the second-order rate expression

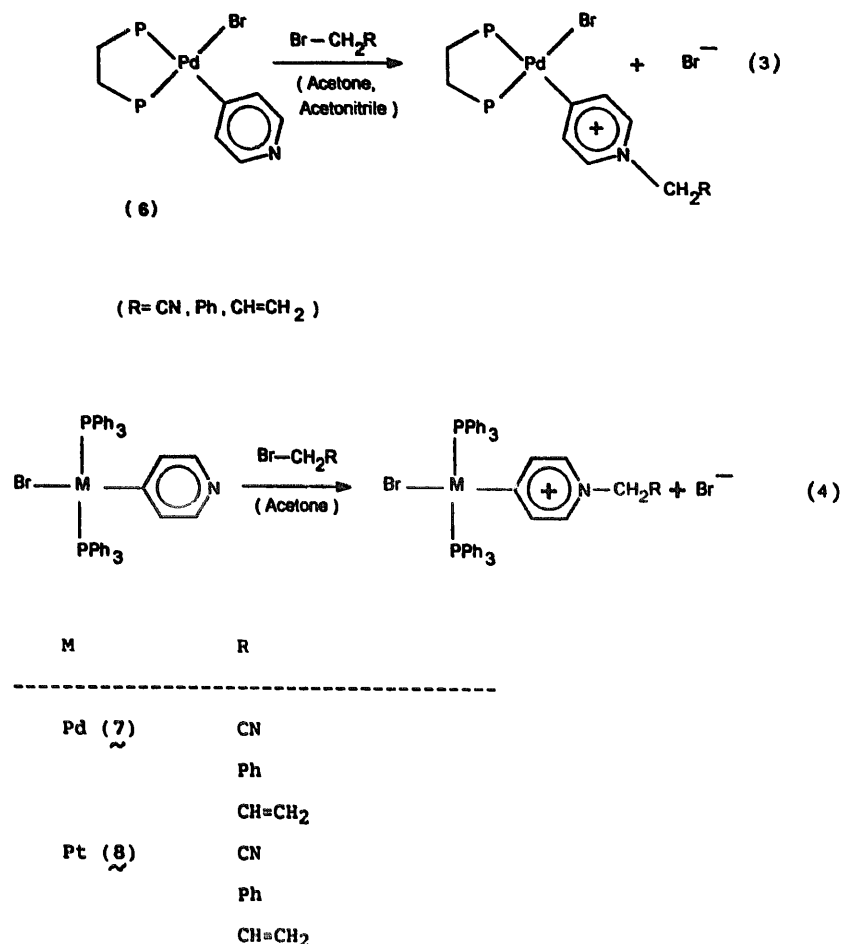
$$k_{obs} = k_2 [X-CH_2R] \quad (5)$$

without any statistically significant first-order contribution (Tables 1 and 2).

The same rate law was observed for the analogous substitution reactions involving the dimethyldithiocarbamate complexes of the type $[M(dmtc)(C_5H_4N-C^2)L]$ ($M = Pd, Pt$; $L =$ tertiary phosphine) [9]. It thus appears that the reactions of 2- and 4-metallated pyridines with $X-CH_2R$ are classical S_N2 processes at saturated car-

bon, such as those involving non-metallated pyridines as nucleophiles [13].

The kinetic data in Table 1 indicate that a marked increase in the rates (ca. two orders of magnitude) occurs when the halide is changed from $X = Cl$ to $X = Br$ in both the metal complex and the organic halide. This finding is to be mainly ascribed to a leaving group effect, in line with the long-established view that the primary factor which determines the rates of alkylation of pyridines and, in general, the quaternization of nitrogen bases is the $X-CH_2R$ bond breaking in the alkylating agent [14,15]. The change of halide ligand from Cl to Br in the 2-pyridyl complexes 1, 2 and 4, 5 can hardly be held responsible for so large an effect, since the corresponding pK_a values (see Table 1) are little affected by the nature of X. However, the choice of an identical halide X in both the complex and the



Scheme 2.

alkylating agent was dictated by the need to avoid undesired halide-exchange side reactions.

The 2-pyridyl complexes **2** and **5** react about one order of magnitude faster than their 4-pyridyl analogs **6**

and **8** respectively, other things being equal. The greater nucleophilic power of the 2-pyridyl ligand is attended by a higher basicity of the 2-pyridyl nitrogen, as shown by the pK_a values in Tables 1 and 2. A comparison

Table 1
Second-order rate constants for reactions (1) and (2) and pK_a values of the 2-pyridyl complexes 1–3 and 4, 5 at 25°C

Complex	M	X	pK_a^a	R	$10^3 k_2^b$ (mol ⁻¹ dm ³ s ⁻¹)
[MX(C ₅ H ₄ N-C ²)(dppf)]	Pd	Cl	8.23	CN	0.44 ± 0.01
				CH=CH ₂	0.17 ± 0.01
2	Pd	Br	9.68	CN	66.7 ± 0.8
				Ph	157 ± 2
				CH=CH ₂	48 ± 2
3	Pt	Cl	10.37	CN	1.8 ± 0.1
				CH=CH ₂	0.52 ± 0.01
trans-[PtX(C ₅ H ₄ N-C ²)(PPh ₃) ₂]		Cl	8.84	CN	1.5 ± 0.2
				CH=CH ₂	0.24 ± 0.02
5		Br	8.72	CN	116 ± 4
				Ph	155.3 ± 0.2
				CH=CH ₂	78.4 ± 0.8

^a Measured by potentiometric titration with HClO₄ in water/dioxane 1:3 v/v and ionic strength 0.1 mol dm⁻³ (LiClO₄).

^b In acetone.

Table 2
Second-order rate constants for reactions (3) and (4) and pK_a values of the 4-pyridyl complexes 6–8 at 25°C

Complex	M	pK_a^a	R	$10^3 k_2^b$ (mol ⁻¹ dm ³ s ⁻¹)
[PdBr(C ₅ H ₄ N-C ⁺)(dppe)] 6		6.69	CN	2.5 ± 0.2(1.78 ± 0.02) ^c
			Ph	9.0 ± 0.2(16 ± 2) ^c
			CH=CH ₂	3.2 ± 0.2(4.88 ± 0.05) ^c
<i>trans</i> -[MBr(C ₅ H ₄ N-C ⁺)(PPh ₃) ₂] 7	Pd	5.67	CN	2.0 ± 0.2
			Ph	11.3 ± 0.3
			CH=CH ₂	2.88 ± 0.03
8	Pt	6.50	CN	6.7 ± 0.1
			Ph	28 ± 1
			CH=CH ₂	6.8 ± 0.3

^a Measured by potentiometric titration with HClO₄ in water/dioxane 1:3 v/v and ionic strength 0.1 mol dm⁻³ (LiClO₄).

^b In acetone.

^c In acetonitrile.

with the pK_a value 4.47 of pyridine [8] and the k_2 value $(7.0 \pm 0.3) \times 10^{-5}$ mol⁻¹ dm³ s⁻¹ for the reaction of pyridine with Br-CH₂CH=CH₂ in acetone at 25°C clearly indicates that the metal-containing substituents in the pyridine ring of complexes 2, 5 and 6, 8 act as good electron releasing groups. The fact that substitution on position 2 entails higher nucleophilic and basic abilities than substitution on position 4 on the pyridine ring suggests that the electron release from the metal is essentially inductive in character. Accordingly, an X-ray structural study of the 2-pyridyl complex *trans*-[PtCl(C₅H₄N-C²)(PMe₂Ph)₂] has shown that there is hardly any π backbonding in the platinum–2-pyridyl bond, around which free rotation was observed in solution at ambient temperature [10]¹.

Replacement of palladium with platinum in the structurally related complexes 1, 3 and 7, 8 brings about a ca. three-fold increase in reactivity and also a one to two unity increase in the pK_a values, indicating a better electron donating ability of the platinum center.

The parallelism so far observed between nucleophilic ability and basic properties is not always extant, suggesting that the factors increasing the thermodynamic stability of the N-protonated derivatives are not always coincident with those which lower the activation energy of the S_N2 process. Thus, 4-dimethylaminopyridine (4-dmapy) exhibits a pK_a value of 8.51 and a second-order rate constant k_2 of 5.64×10^{-3} mol⁻¹ dm³ s⁻¹ for the reaction with Br-CH₂CH=CH₂ in acetonitrile at 25°C [9]. Replacement of the 4-NMe₂ group in 4-dmapy by

the metal-containing substituents in complexes 6–8 causes a marked decrease in the basicity of the pyridine nitrogen (pK_a in the range 5.67–6.69), whereas the reactivity towards Br-CH₂CH=CH₂ is little affected (k_2 in the range 2.88–6.8 × 10⁻³ mol⁻¹ dm³ s⁻¹ in acetone or acetonitrile at 25°C). In contrast, a change in the coordination geometry around the metal center from *trans*-PtCl(PPh₃)₂ of 4 to PtCl(dppe) of 3 and from *trans*-PdBr(PPh₃)₂ of 7 to PdBr(dppe) of 6 leads to pK_a increases of 1.53 and 1.02 respectively, without any relevant change in the nucleophilic power (cf. k_2 values for the reactions of 3 and 4 and those of 6 and 7 in Tables 1 and 2 respectively).

It is worth noting that the reactivity of the 2-pyridyl complexes 3 and 4 is also scarcely influenced by the higher steric requirements of the *trans*-PtCl(PPh₃)₂ unit of 4 relative to the PtCl(dppe) group of 3.

The substituent R of the organic halide X-CH₂R affects the reactivity in the order Ph > CN = CH=CH₂. The higher reaction rates observed for R = Ph (despite its higher steric demand) suggest that the phenyl group has a greater ability to lower the activation energy of the process through delocalization of the incipient positive charge in the transition state [13].

3. Experimental

3.1. Preparation of 2-pyridyl and pyridylium complexes

The complexes [MCl(C₅H₄N-C²)(dppe)] (M = Pd, Pt), *trans*-[PtX(C₅H₄N-C²)(PPh₃)₂] (X = Cl, Br) [4,6] and *trans*-[PdBr(C₅H₄N-C²)(PPh₃)₂] [2] were prepared by published methods. Some pyridylium derivatives of these compounds were also described as resulting from protonation or alkylation reactions at the pyridine nitrogen [4,6,7]. All chemicals and solvents were of reagent grade and used without further purification. The solvents were evaporated to small volume or to dryness at reduced pressure on a rotary evaporator.

¹ The higher reactivities of bromide versus chloride electrophiles and of 2- versus 4-pyridyl complexes might also ensue from some electrostatic interaction between the metal and the halide in an axial position, which could favor the orientation of the electrophilic carbon unit towards the pyridyl nitrogen atom, thereby assisting the N-C bond making process. Predictably, such an interaction would be more important for bromide than for chloride and could possibly take place only with the 2-pyridyl species.

3.2. Preparation of $[PdBr(C_5H_4N-C^n)(dppe)]$ ($n = 2, 4$)

(a) The ligand dppe (0.44 g, 1.1 mmol) was added to a stirred suspension of the binuclear complex $[PdBr(\mu-C_5H_4N-C^2,N)(PPh_3)_2]_2$ [16] (0.53 g, 0.5 mmol) in benzene (ca. 150 dm³). The resulting yellow solution was stirred for 2 h, concentrated to small volume and diluted with diethyl ether to precipitate the crude product. Reprecipitation from the same solvents gave the white complex $[PdBr(C_5H_4N-C^2)(dppe)]C_6H_6$ (0.57 g, 76.9% yield). The presence of a benzene molecule of crystallization was shown by elemental analysis and GC measurements in CH₂Cl₂ solution.

(b) The ligand dppe (0.44 g, 1.1 mmol) was added to a stirred suspension of *trans*- $[PdBr(C_5H_4N-C^4)(PPh_3)_2]$ (0.79 g, 1 mmol) in benzene (ca. 100 dm³). The reaction mixture was worked up as described above to yield the white complex $[PdBr(C_5H_4N-C^4)(dppe)]C_6H_6$ (0.65 g, 87.7% yield after reprecipitation from a benzene/diethyl ether mixture).

3.3. Preparation of *trans*- $[PtBr(C_5H_4N-C^4)(PPh_3)_2]$

Upon addition of an excess of NEt₃ (1.5 mol, 10.8 mmol) to a solution of 4-bromopyridine hydrochloride (1.17 g, 6 mmol) in CH₂Cl₂ (10 dm³) some precipitation of triethylammonium chloride occurred. After filtration the solution was diluted with toluene (100 dm³) and concentrated to a volume of ca. 50 dm³ to remove the more volatile CH₂Cl₂ and NEt₃ and to complete the precipitation of NHEt₃Cl. The resulting toluene solution of 4-bromopyridine was degassed, saturated with N₂ and added to a solution of $[Pt(PPh_3)_4]$ (2.49 g, 2 mmol) in

toluene (ca. 100 dm³) under N₂. The mixture was heated at 95 °C for 10 h and left overnight at room temperature. Concentration and dilution with Et₂O gave a yellow solid (1.80 g), which was extracted with benzene (ca. 80 dm³). After filtration of the insoluble residue, the solution was concentrated and diluted with Et₂O to precipitate a pale yellow compound (1.10 g) consisting of *trans*- $[PtBr(C_5H_4N-C^4)(PPh_3)_2]$ contaminated by trace amounts of *cis*- $[PtBr_2(PPh_3)_2]$ [$\delta(^{31}P)$ 13.7 ppm, $^1J(Pt-P)$ 3619 Hz in CDCl₃] and other unidentified products. The pure off-white complex was obtained by reprecipitation from a CH₂Cl₂/MeOH solvent mixture (0.81 g, 46.2%).

3.4. Reactions of the 2- and 4-pyridyl complexes with Br-CH₂CN

The reaction of $[PdBr(C_5H_4N-C^2)(dppe)]$, *trans*- $[PtBr(C_5H_4N-C^2)(PPh_3)_2]$, and *trans*- $[PtBr(C_5H_4N-C^4)(PPh_3)_2]$ with an excess of bromoacetonitrile yielded the cationic complexes $[PdBr\{(1-CH_2CN)C_5H_4N-C^2\}(dppe)]^+$ (94.5%), *trans*- $[PtBr\{(1-CH_2CN)C_5H_4N-C^2\}(PPh_3)_2]^+$ (89.8%), and *trans*- $[PtBr\{(1-CH_2CN)C_5H_4N-C^4\}(PPh_3)_2]^+$ (84.6%) respectively, isolated as perchlorate salts as previously described for the preparation of related compounds [7,9].

3.5. Analytical, spectral, and conductivity data

The new 2- and 4-pyridyl complexes and some of the (1-cyanomethyl)-2- and -4-pyridylum derivatives were characterized by elemental analysis, conductivity measurements, IR spectra in the solid, and by ¹H and ³¹P{¹H} NMR spectra. The analytical, conductivity, and ³¹P NMR data are listed in Table 3.

Table 3
Elemental analysis, conductivity and ³¹P NMR data

Compound	Analysis ^a				Molar conductivity ^b	³¹ P Resonances ^c
	C	H	N	Br		
$[PdBr(C_5H_4N-C^2)(dppe)]C_6H_6$ 2	59.5 (59.98)	4.5 (4.63)	1.9 (1.89)	10.7 (10.79)		48.6 d; 31.0 d ^d ² J(P-P) 32.1
$[PdBr(C_5H_4N-C^4)(dppe)]C_6H_6$ 6	59.6 (59.98)	4.6 (4.63)	1.8 (1.89)	10.4 (10.79)		52.3 d; 34.4 d ^d ² J(P-P) 23.2
<i>trans</i> - $[PtBr(C_5H_4N-C^4)(PPh_3)_2]$ 8	56.5 (56.11)	4.0 (3.90)	1.5 (1.60)	9.3 (9.11)		22.9 s ^d ; ¹ J(Pt-P) 3022 23.0 s ^e ; ¹ J(Pt-P) 3038
$[PdBr\{(1-CH_2CN)C_5H_4N-C^2\}(dppe)]ClO_4$	49.2 (49.40)	3.7 (3.77)	3.4 (3.49)		146.0	56.8 d; 48.4 d ^e ² J(P-P) 16.6
<i>trans</i> - $[PtBr\{(1-CH_2CN)C_5H_4N-C^2\}(PPh_3)_2]ClO_4$	50.8 (50.77)	3.5 (3.57)	2.7 (2.75)		145.0	17.5 s ^e ¹ J(Pt-P) 2544
<i>trans</i> - $[PtBr\{(1-CH_2CN)C_5H_4N-C^4\}(PPh_3)_2]ClO_4$	50.4 (50.77)	3.6 (3.57)	2.7 (2.75)		122.6	19.5 s ^e ¹ J(Pt-P) 2760

^a Calculated values in parentheses.

^b Values in Scm² mol⁻¹ for 10⁻³ mol dm⁻³ acetone solution at 25 °C.

^c Spectra recorded at 30 °C; $\delta(^{31}P)$ values in ppm from external 85% H₃PO₄, downfield shifts being taken as positive; coupling constants in Hz; s = singlet, d = doublet.

^d In CDCl₃.

^e In CD₂Cl₂.

The cationic 2- and 4-pyridylium complexes behave as univalent electrolytes in acetone solution [17]. The presence of ClO_4^- as counteranion is confirmed by their IR spectra, which show the typical $\nu(\text{Cl}-\text{O})$ and $\delta(\text{Cl}-\text{O})$ bands at ca. 1100 and 625 cm^{-1} respectively. Furthermore, the pyridine ring vibration at 1557–1567 cm^{-1} of the 2- and 4-pyridyl complexes shifts to higher frequency (1607–1613 cm^{-1}) in the corresponding 1-cyanomethyl derivatives.

In the ^1H NMR spectra of the latter compounds in CD_2Cl_2 , the $(1-\text{CH}_2\text{CN})\text{C}_5\text{H}_4\text{N}$ group is characterized by a $\delta(\text{CH}_2\text{CN})$ resonance occurring as a singlet at 5.84 ppm and 5.17 ppm for *trans*-[PtBr((1- $\text{CH}_2\text{CN})\text{C}_5\text{H}_4\text{N}-\text{C}^2$)(PPh_3) $_2$] $^+$ and *trans*-[PtBr((1- $\text{CH}_2\text{CN})\text{C}_5\text{H}_4\text{N}-\text{C}^4$)(PPh_3) $_2$] $^+$ respectively, and as an AB system centered at 5.50 ppm for the asymmetric [PdBr((1- $\text{CH}_2\text{CN})\text{C}_5\text{H}_4\text{N}-\text{C}^2$)(dppe)] $^+$ cation.

The IR spectra were recorded with Perkin-Elmer 1430 and 983 instruments using Nujol mulls and CsI windows in the range 4000–200 cm^{-1} . The conductivity measurements were carried out with a digital CDM 83 conductivity meter. The NMR spectra were recorded with Varian FT80A and Bruker AC200 spectrometers.

3.6. Kinetic and pK_a measurements

Kinetic runs under pseudo-first-order conditions were carried out with a more than ten-fold excess of $\text{X}-\text{CH}_2\text{R}$ over the metal complex whose concentration was around $10^{-3} \text{ mol dm}^{-3}$ by monitoring changes with time in the specific conductance χ_t of acetone or acetonitrile solutions of the reactants. χ_t vs. time data were fitted by non-linear regression to the Onsager-corrected rate law

$$\chi_t = \chi_0 + 1000\beta(\Lambda_\infty - s\sqrt{\beta})$$

where $\beta = a(1 - \exp(-k_{\text{obs}}t))$ (with a the metal substrate concentration), and χ_0 , Λ_∞ , s , and k_{obs} are the parameters to be optimized [18].

The pK_a values of the complexes were evaluated by potentiometric titration with HClO_4 in water/dioxane (1:3 v/v) at 0.1 mol dm^{-3} ionic strength (LiClO_4) at 25°C, according to literature procedures [19].

All statistical and graphical data analyses were car-

ried out with in-house non-linear regression computer programs written in TURBOBASIC™ (Borland Int.) and implemented on a personal computing system.

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