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PAPER

Reactions of platinum(IV)-bound nitriles with isomeric nitroanilines: addition *vs.* substitution†

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The platinum(IV) complex *trans*-[$PtCl_4(EtCN)_2$] reacts smoothly and under mild conditions with isomeric *o*-, *m*- and *p*-nitroanilines (NAs) yielding two different types of products depending on the NA isomer, *viz.* the nitroaniline complexes *cis*/*trans*-[$PtCl_4(NA)_2$] (*cis*/*trans*-**1**–**3**) and the amidine species *trans*-[$PtCl_4${NH=C(Et)$NHC_6H_4NO_2$-*m*}(EtCN)] (**4**), *trans*-[$PtCl_4${NH=C(Et)$NHC_6H_4NO_2$-*m*}$_2$] (**5**) and *trans*-[$PtCl_4${NH=C(Et)$NHC_6H_4NO_2$-*p*}(EtCN)] (**6**). Complexes **4** and **5** undergo cyclometalation, furnishing *mer*-[$PtCl_3${*N*H=C(Et)$NHC_6H_3NO_2$-*m*}(EtCN)] (**7**) and *mer*-[$PtCl_3${*N*H=C(Et)$NHC_6H_4NO_2$-*m*}-{*N*H=C(Et)$NHC_6H_3NO_2$-*m*}] (**8**), respectively. Moreover, **8** both in the solid state and in solution undergoes the second step of the cyclometalation, generating [$PtCl_2${*N*H=C(Et)$NHC_6H_3NO_2$-*m*}$_2$] (**9**). In **4**, the nitrile ligand is highly reactive toward nucleophilic addition and it undergoes facile hydration accompanied by the elimination of the nitrile, thus producing *cis*-[$PtCl_4$(*N*$H_2C_6H_4NO_2$-*m*){*N*H=C(OH)-Et}] (**10**), or methanol addition providing *trans*-[$PtCl_4${*N*H=C(Et)$NHC_6H_4NO_2$-*m*}{*N*H=C(Et)OMe}] (**11**). All compounds, besides **9**, were characterized by C, H, and N elemental analyses, high-resolution ESI-MS, IR, ^1H and $^{13}C\{^1H\}$ NMR spectroscopic techniques. Complex **9**, which was not isolated as a pure compound, was identified in the reaction mixture by ESI-MS and ^1H and $^{13}C\{^1H\}$ NMR spectroscopies. Complexes *trans*-**1**, *trans*-**2**, **4**, **5**, **6**, **8**, **10**, and **11** were additionally studied by X-ray diffraction.

Introduction

In general, interest in the conversion of nitriles at metal centers stems from the possibilities (*i*) to use nitriles as versatile synthons for the preparation of new compounds, often unreachable in pure organic synthesis, *via* C–O, C–N, C–C, C–P, and C–S bond making;[1,2] (*ii*) to provide environmentally friendly metal-catalyzed hydrolytic transformations of RCN species to amides, *e.g.*, of industrial and pharmacological significance;[1a,b,2a,3] (*iii*) to synthesize, *via* nucleophilic addition, diverse imino complexes, *e.g.*, exhibiting unusual structure–antitumor properties relationships.[2d,4]

The analysis of experimental material collected to date (for our reviews see ref. 1*a*,*d*; reviews from other groups on the subject see ref. 2*c*,*d*) shows that the largest fraction of research is devoted to the creation of a C–N bond by the addition sp^3- and sp^2-(H)N-nucleophiles, as well as by coupling of some nitrogen heterocycles[5] with ligated RCN species. Recent examples include nucleophilic addition of di- and triamines to (nitrile)Pt^{IV} species,[6] coupling of primary amines,[4b,7] ferrocenyl-functionalized amine,[8] and nucleobases[9] with Pt^{II}-bound nitriles.

Reactions of metal-activated nitriles and such *strong* sp^3-(*H*)-*N*-nucleophiles as ammonia, unfunctionalized primary and secondary amines[4b–d,7,10] and some functionalized (with OH,[11] NH_2,[5d,6,12] or CO_2R[13] moieties) amines are well documented and this coupling comprises one of the primary routes for the direct generation of ligated and metal-free amidines HN=C(R)-NR′R″.[1a,2c,d,4c,13,14] These species serve as useful building blocks for syntheses of many biologically important materials[2c,d,4a–c,10a] and, in particular, some (amidine)Pt^{IV} complexes exhibit cytostatic activity, *e.g.*, providing significant sensitization for the antitumor actions of the known drugs cyclophosphamide and doxorubicine.[2d,6]

In contrast to the coupling of the *strong* sp^3-(*H*)*N*-nucleophiles, the reactions of *weak* sp^3-(*H*)*N*-nucleophiles have not been studied. Being interested in the amplification of an ongoing project on reactions of metal-activated nitriles (for recent works see ref. 15) and, in particular, on the metal-mediated additions of various *HN*-nucleophiles to the C≡N moiety,[6] we focused our attention on the reaction of (nitrile)Pt^{IV} species with

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†Electronic supplementary information (ESI) available: Tables with crystal data; molecular structures of *trans*-[$PtCl_4(EtCN)_2$], *trans*-**1**, *trans*-**2**, **6**, **10**, and **11**; experimental details and characterization of *cis*/*trans*-**1**–**3**. CCDC 881311–881319. For ESI and crystallographic data in CIF or other electronic format see DOI: 10.1039/c2dt30986f

the isomeric nitroanilines as weak *HN*-nucleophiles having predominantly sp^3-character of the NH_2 group.[16] The nitroanilines (NA) were employed for this study as easily accessible and commercially available representatives of weak *N*-nucleophiles, where the electron-withdrawing group NO_2 decreases the nucleophilic properties of NAs to such a degree that nitroanilines react only with highly activated RCN species at platinum(IV) centers. Furthermore, the unsubstituted nitroaniline, $C_6H_5NH_2$, reduced Pt^{IV} complexes and could not be applied for the nucleophilic addition study.

Our goal was at least 3-fold (*i*) to verify how the isomerism of nitroanilines affects the interplay between these species and the (nitrile)Pt^{IV} moiety; (*ii*) to get an easy entry to platinum(IV) *N*-aryl amidine complexes; (*iii*) to study the reactivity of the iminoacylated *N*-arylamidine functionality.

Experimental

Materials and methods

NAs and solvents used in syntheses were obtained from commercial sources (Aldrich) and used as received. The solvents employed for preparation of **7–9** were purified by distillation and kept over zeolites. Synthesis of *trans*-$[PtCl_4(EtCN)_2]$ was produced by the known methodology[17] by chlorination of the platinum(II) complex *trans*-$[PtCl_2(EtCN)_2]$.[18] Yields are based on platinum; if it is not specified, isolated yields are given. The spectroscopy yields were determined *via* signal integration in the ^1H NMR spectra. For TLC, Merck 60 F_{254} SiO_2 plates were used. Elemental analyses for carbon, hydrogen, and nitrogen were carried out with a 185V Carbon Hydrogen Nitrogen Analyzer Hewlett Packard apparatus and an Elenentar Vario Micro instrument. Electrospray ionization mass-spectra were obtained on a Bruker micrOTOF spectrometer equipped with electrospray ionization (ESI) source and MeOH was used as the solvent (in all cases unless specifically indicated). The instrument was operated both in positive and negative ion modes using a *m*/*z* range of 50–3000. The capillary voltage of the ion source was set at −4500 V (ESI^+-MS) or 3500 V (ESI^--MS) and the capillary exit at ±(70–150) V. In the isotopic pattern, the most intensive peak is reported. Infrared spectra were recorded on Shimadzu FTIR-8400S and Bruker Vertex 70 spectrometers (4000–400 cm^{-1}) in KBr pellets. The ^1H and $^{13}C\{^1H\}$ NMR spectra were measured on Bruker-DPX300 and Bruker 400 Ultra Shield instruments at ambient temperature.

X-ray determination

The crystals of *trans*-$[PtCl_4(EtCN)_2]$, *trans*-**1**, *trans*-**2**, **4**, **5**, **6**, **8**, **10**, and **11** were obtained by a slow evaporation of solvents at 4–5 °C. All crystals were immersed in cryo-oil, mounted in a Nylon loop, and measured at a temperature of 100 K. The X-ray diffraction data were collected on a Nonius KappaCCD, Bruker Axs Smart Apex II, Bruker Axs KappaApexII diffractometers using Mo Kα radiation (λ = 0.710 73 Å). The *Apex2*,[19] *EvalCCD*[20] and *Denzo*/*Scalepack*[21] program packages were used for cell refinements and data reductions. The structures were solved by direct methods using *Shelxs 97*,[22] *SUPERFLIP*,[23] *SIR97*[24] or *SIR2008*[25] program with the *Olex 2*[26] graphical user interface. A semi-empirical or numerical absorption correction (*SADABS*[27] or *Xprep in Shelxtl v.6.14-1*[28]) was applied to all data. Structural refinements were carried out using *SHELXL-97*.[22] In the structure of **8**, the H_2O molecules and CH_3 group (C12 and C12B) were disordered over two sites with occupancy ratio 0.58/0.42 and 0.79/0.21 respectively. The C–C distances C11–C12 and C11–C12B were set to be similar. The anisotropic displacement parameters of the disordered oxygens were restrained so that their U_{ij} components approximate to isotropic behavior. The anisotropic displacement parameters of the disordered carbons were set to be similar. The H_2O and NH hydrogen atoms were located from the difference Fourier map but constrained to ride on their parent atom, with $U_{iso} = 1.5U_{eq}$ (parent atom). Other hydrogen atoms were positioned geometrically and were also constrained to ride on their parent atoms, with C–H = 0.95–0.98 Å, and $U_{iso} = 1.2–1.5U_{eq}$ (parent atom). The crystallographic details are summarized in Tables S1 and S2 (ESI†) and selected bond lengths and angles for *trans*-$[PtCl_4(EtCN)_2]$, *trans*-**1**, *trans*-**2**, **4**, **5**, **6**, **8**, **10**, and **11** are listed in the captions to Fig. 1–3 and Fig. S1–S6 (ESI†).

Synthetic work

The experimental details and characterization of nitroaniline complexes *cis*/*trans*-**1–3** are given in the ESI.†

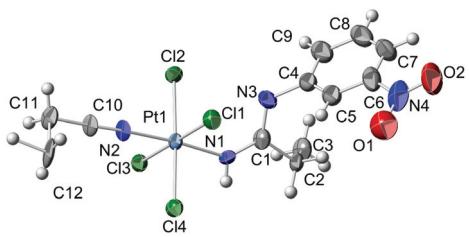


Fig. 1 Molecular structure of **4** with the atomic numbering scheme. Thermal ellipsoids are given at the 50% probability level. Selected bond lengths (Å) and angles (°): Pt(1)–N(1) 2.001(8), Pt(1)–N(2) 1.989(8), Pt(1)–Cl(1) 2.320(3), Pt(1)–Cl(2) 2.326(3), Pt(1)–Cl(3) 2.317(3), Pt(1)–Cl(4) 2.316(3), N(1)–C(1) 1.288(14), N(2)–C(10) 1.160(12), N(3)–C(1) 1.330(15), N(2)–Pt(1)–N(1) 175.4(4), Cl(3)–Pt(1)–Cl(1) 179.56(10), Cl(4)–Pt(1)–Cl(2) 177.75(9).

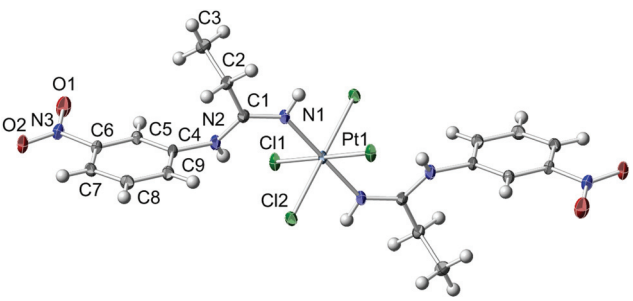


Fig. 2 Molecular structure of **5** with the atomic numbering scheme. Thermal ellipsoids are given at the 50% probability level. Selected bond lengths (Å) and angles (°): Pt(1)–N(1) 2.0278(16), Pt(1)–Cl(1) 2.3197(4), Pt(1)–Cl(2) 2.3176(4), N(1)–C(1) 1.301(2), N(2)–C(1)1.342(2), N(1)–Pt(1)–Cl(1) 93.88(5), Cl(2)–Pt(1)–Cl(1) 89.004(17).

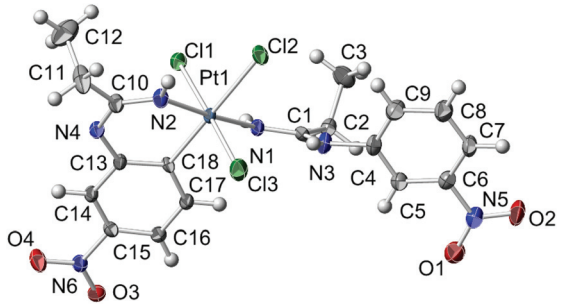


Fig. 3 Molecular structure of **8** with the atomic numbering scheme. Thermal ellipsoids are given at the 50% probability level. Selected bond lengths (Å) and angles (°): Pt(1)–N(1) 2.043(4), Pt(1)–N(2) 2.003(4), Pt(1)–C(18) 2.014(5), Pt(1)–Cl(1) 2.3015(12), Pt(1)–Cl(2) 2.4545(12), Pt(1)–Cl(3) 2.3113(13), N(1)–C(1) 1.299(6), N(2)–C(10) 1.299(6), N(3)–C(1) 1.323(7), N(4)–C(10) 1.349(6), N(2)–Pt(1)–C(18) 90.57(18), N(2)–Pt(1)–N(1) 173.98(18), Cl(1)–Pt(1)–Cl(2) 90.06(4), Cl(1)–Pt(1)–Cl(3) 177.89(5).

Reaction of *trans*-[$PtCl_4(EtCN)_2$] with isomeric NAs

(i) In a molar ratio of 1 : 1. The NA (30.9 mg, 0.224 mmol) was dissolved in CH_2Cl_2 (2 mL), whereupon the solid *trans*-[$PtCl_4(EtCN)_2$] (100.0 mg, 0.224 mmol) was added to the solution. The resulting suspension was stirred at 20–25 °C for 3 d for *o*- or 1 d for *m*- and *p*-NAs. The yellow solid residue of *cis*/*trans*-[$PtCl_4(NA)_2$] (*o*-NA, *cis*/*trans*-**1**; *m*-NA, *cis*/*trans*-**2**; *p*-NA, *cis*/*trans*-**3**) was precipitated, separated by filtration and dried in air at room temperature (RT). Yields were 64.4 mg, 47% (*cis*/*trans*-**1**), 4.1 mg, 3%, (*cis*/*trans*-**2**), and 60.2 mg, 44%, (*cis*/*trans*-**3**), correspondingly. The filtrates from the reactions with *m*-NA and *p*-NA were evaporated at RT to dryness, furnishing the yellow solid residue of *mono*-amidine complexes **4** (*m*-NA, NMR yield 90%) or **6** (*p*-NA, NMR yield 8%), respectively. The crude material was purified by chromatography on SiO_2 ($CHCl_3$–Me_2CO, 10 : 1, v/v) to give, in the first fraction, pure complexes **4** (81.0 mg, 62%) or **6** (6.6 mg, 5%). The formation of amidine complexes in the reaction involving *o*-NA was not observed.

(ii) In a molar ratio of 1 : 2. The NA (30.9 mg, 0.224 mmol) was dissolved in CH_2Cl_2 (2 mL), whereupon the solid *trans*-[$PtCl_4(EtCN)_2$] (50.0 mg, 0.112 mmol) was added to the solution. The resulting suspension was stirred at 20–25 °C for 5 d for *o*- and 1 d for *m*- and *p*-NAs. The yellow precipitate of *cis*/*trans*-**1–3** was filtered off, washed with $CHCl_3$ (two 1 mL portions) and dried in air at RT. Yields are 65.2 mg, 95% (*cis*/*trans*-**1**), 4.5 mg, 6.5%, (*cis*/*trans*-**2**), and 63.0 mg, 92% (*cis*/*trans*-**3**). The formation of **5** was observed only in the case of the reaction with *m*-NA. The filtrate from the reaction with *m*-NA was evaporated at RT to dryness and the resulting yellow solid residue was separated by chromatography on SiO_2 ($CHCl_3$–Me_2CO, 10 : 1, v/v) to give, in the first fraction, bis-amidine complex **5** (58.5 mg, 72%).

Reaction of *trans*-[$PtCl_4${NH=C(Et)$NHC_6H_4NO_2$-*m*}(EtCN)] (4) and *m*-NA

Complex **4** (50.0 mg, 0.085 mmol) was dissolved in CH_2Cl_2 (2 mL), whereupon the solid *m*-NA (11.7 mg, 0.085 mmol) was added to the solution. The resulting suspension was stirred for 2 d at 20–25 °C. The obtained orange solution was evaporated to dryness at RT. The resulting orange precipitate was *trans*-[$PtCl_4${NH=C(Et)$NHC_6H_4NO_2$-*m*}$_2$] (**5**) (58.4 mg, 95%).

***trans*-[$PtCl_4${*N*H=C(Et)$NHC_6H_4NO_2$-*m*}(EtCN)] (4).** Found: C, 24.55; H, 2.69; N, 9.53 (Calcd for $C_{12}H_{16}N_4Cl_4O_2Pt$: C, 24.63; H, 2.76; N, 9.57). ESI$^-$-MS, *m*/*z*: 582.9653; calcd for [M − H]$^-$ 582.9548. TLC: R_f = 0.70 (Me_2CO–$CHCl_3$ = 1 : 20, v/v). IR spectrum in KBr (selected bands, cm^{-1}): 3350 m and 3295 m ν(N–H), 3060 w and 2920 w ν(C–H), 2331 m ν(C≡N), 1641 s ν(C=N), 1610 m ν(C=C_{Ar}), 1540 s and 1534 s ν(C=C_{Ar} and/or $_{asymm}$N=O), 1350 s ν_{symm}(N=O), 744 w δ(C–H_{Ar}). ^{1}H NMR spectrum ($CDCl_3$, δ): 9.65 (s, 1H, NH_{amine}), 8.29 (d, 4.0 Hz, 1H), 8.14 (s, 1H), 7.71 (t, 1H), 7.61 (d, 4.0 Hz, 1H) (Ar), 5.90 (s, J_{Pt-H} = 14,5 Hz, 1H from NH_{imine}), 3.10 (q, 3.6 Hz, 2H, CH_2 from NH=CEt), 2.55 (q, 3.6 Hz, 2H, CH_2 from N≡CEt), 1.54 (t, 3.6 Hz, 3H, CH_3 from NH=CEt), 1.27 (t, 3.6 Hz, 3H, CH_3 from N≡CEt). ^{13}C{^{1}H} spectrum ($CDCl_3$, δ): 170.8 (C=N), 149.4 and 136.9 (C_{ipso}), 132.7, 131.3, 123.7, 121.9 (C_{Ar}), 120.0 (C≡N), 27.4 (NH=C*C*H_2CH_3), 13.2 (C≡N*C*H_2CH_3), 10.7 (NH=CCH_2*C*H_3), 10.0 (C≡NCH_2*C*H_3).

***trans*-[$PtCl_4${*N*H=C(Et)$NHC_6H_4NO_2$-*m*}$_2$] (5).** Found: C, 30.06; H, 2.99; N, 11.70 (Calcd for $C_{18}H_{22}N_6Cl_4O_4Pt$: C, 29.89; H, 3.07; N, 11.62). ESI$^-$-MS, *m*/*z*: 720.9893; calcd for [M − H]$^-$ 720.9975. TLC: R_f = 0.70 (Me_2CO–$CHCl_3$ = 1 : 25, v/v). IR spectrum in KBr (selected bands, cm^{-1}): 3380 m and 3300 m ν(N–H), 3092 w ν(C–H), 1632 s ν(C=N), 1613 m ν(C=C_{Ar}), 1583 m ν(C=C), 1526 s ν_{asymm}(N=O), 1347 s ν_{symm}(N=O), 741 w δ(C–H_{Ar}). ^{1}H NMR spectrum ($(CD_3)_2CO$), δ): 9.49 (s, 2H, NH_{amine}), 8.27 (d, 4.7 Hz, 2H), 8.21 (s, 2H), 7.84 (m, 4H) (Ar), 6.92 (s, br, 2H, NH_{imine}), 2.87 (q, 7.4 Hz, 4H), 1.19 (t, 7.4 Hz, 6H)(Et). ^{13}C{^{1}H} NMR spectrum ($(CD_3)_2CO$), δ): 172.2 (C=N), 149.9 and 138.6 (C_{ipso}), 132.9, 132.0, 123.0, 121.4 (C_{Ar}), 27.1, 11.7 (Et).

***trans*-[$PtCl_4${*N*H=C(Et)$NHC_6H_4NO_2$-*p*}(EtCN)] (6).** Found: C, 24.70; H, 2.87; N, 9.70 (Calcd for $C_{12}H_{16}N_4Cl_4O_2Pt$: C, 24.63; H, 2.76; N, 9.57). ESI$^-$-MS, *m*/*z*: 582.9597; calcd for [M − H]$^-$ 582.9548. TLC: R_f = 0.68 (eluent Me_2CO–$CHCl_3$ = 1 : 25, v/v). IR spectrum in KBr (selected bands, cm^{-1}): 3425 m and 3323 w ν(N–H), 2948 w ν(C–H), 2341 m ν(C≡N), 1659 s ν(C=N), 1603 s ν(C=C_{Ar}), 1530 s ν_{asymm}(N=O), 1348 m ν_{symm}(N=O), 674 w δ(C–H_{Ar}). ^{1}H NMR spectrum ($CDCl_3$, δ): 9.73 (s, br, 1H, NH_{amine}), 8.27 (d, 8.4 Hz, 2H), 7.75 (d, 8.4 Hz, 2H)(Ar), 5.95 (s, br, 1H from NH_{imine}), 2.84 (q, 7.5 Hz, 2H, CH_2 from NH=C*Et*), 2.71 (q, 7.0 Hz, 2H, CH_2 from N≡C*Et*), 1.39 (t, 7.6 Hz, 3H, CH_3 from NH=C*Et*), 1.16 (t, 7.2 Hz, 3H, CH_3 from N≡C*Et*). ^{13}C{^{1}H} spectrum ($CDCl_3$, δ): 171.7 (C=N), 148.6, 137.2 (C_{ipso}), 126.9, 124.6 (C_{Ar}), 119.1 (C≡N); 26.8 (NH=C*C*H_2CH_3); 12.9 (N≡C*C*H_2CH_3); 10.3 (NH=CCH_2*C*H_3); 9.8 (N≡CCH_2*C*H_3).

Cyclometalation of the amidine in 4

(i) In solution. Complex **4** (50.0 mg, 0.085 mmol) was dissolved in the freshly distilled CH_2Cl_2 (2 mL), dinitrogen was passed through the solution (30 min), and the reaction mixture was left to stand for 10 d at 30 °C in a closed flask. The yellow

precipitate of *mer*-[$PtCl_3${*N*H═C(Et)$NHC_6H_3NO_2$-*m*}(EtCN)] (**7**) (26.3 mg, 56%) was separated by filtration, washed with CH_2Cl_2 (1 mL) and dried in air at 20–25 °C. *(ii) In the solid state.* Complex **4** (50.0 mg, 0.085 mmol) was heated in the solid sate under dinitrogen for 7 d at 50 °C. The resulting orange-brown powder was dissolved in acetone (1 mL) and **7** (18.0 mg, 38%) was separated by column chromatography (Me_2CO–$CHCl_3$ = 1 : 20, v/v, second fraction).

***mer*-[$PtCl_3${*N*H═C(Et)$NHC_6H_3NO_2$-*m*}(EtCN)] (7).** Found: C, 26.12; H, 2.67; N, 10.14 (Calcd for $C_{12}H_{15}N_4Cl_3O_2Pt$: C, 26.27; H, 2.76; N, 10.21). ESI$^-$-MS, *m*/*z*: 546.9807; calcd for $[M - H]^-$ 546.9782. TLC: R_f = 0.41 (Me_2CO–$CHCl_3$ = 1 : 20, v/v). IR spectrum in KBr (selected bands, cm^{-1}): 3251 m ν(N–H), 3005 w and 2979 w ν(C–H), 2326 m ν(C≡N), 1658 s ν(C═N), 1573 m ν(C═C_{Ar}), 1527 s ν(C═C_{Ar} and/or $_{asymm}$N═O), 1384 s ν_{symm}(N═O), 731 w δ(C–H from Ar). ^{1}H NMR spectrum (CD_3OD, δ): 9.78 (s, 1H, NH_{amine}), 8.28 (d, 8.0 Hz 1H), 8.09 (d, 8.0 Hz 1H), 7.76 (s, 1H)(Ar), 4.42 (s, 1H, NH_{imine}), 2.58 (q, 7.2 Hz, 2H, CH_2 from Et), 2.41 (q, 7.4 Hz, 2H, CH_2 from Et), 1.31 (m, 6H, $2CH_3$ from 2Et). ^{13}C{^{1}H} NMR spectrum (CD_3OD, δ): 168.2 (C═N), 150.9, 141.14 (C_{ipso}); 129.5, 126.8, 122.4, 120.9 (C_{Ar}); 117.3 (C≡N); 38.2 (CH_2 from Et), 21.9 (CH_2 from Et), 11.8 (CH_3 from Et), 10.3 (CH_3 from Et).

Cyclometalation of the amidine in 5

Complex **5** (50.0 mg, 0.069 mmol) was dissolved in dry distilled MeOH (3 mL) and stirred for 1 d at 50 °C. The resulting solution was evaporated and the obtained yellow residue of *mer*-[$PtCl_3${*N*H═C(Et)$NHC_6H_4NO_2$-*m*}{*N*H═C(Et)$NHC_6H_3NO_2$-*m*}] (**8**) (31.7 mg, 67%) was washed with $CHCl_3$ (three 1 mL portions), Et_2O (1 mL) and dried under vacuum at RT.

***mer*-[$PtCl_3${*N*H═C(Et)$NHC_6H_4NO_2$-*m*}{*N*H═C(Et)$NHC_6H_3NO_2$-*m*}] (8).** Found: C, 31.37; H, 2.98; N, 12.09 (Calcd for $C_{18}H_{21}N_6Cl_3O_4Pt$: C, 31.48; H, 3.08; N, 12.24). ESI$^-$-MS, *m*/*z*: 685.0249; calcd for $[M - H]^-$ 685.0211. TLC: R_f = 0.51 (Me_2CO–$CHCl_3$ = 1 : 20, v/v). IR spectrum in KBr (selected bands, cm^{-1}): 3435 m ν(N–H), 2925 w ν(C–H), 1635 s ν(C═N), 1559 w ν(C═C), 1529 s ν(C═C_{Ar} and/or $_{asymm}$N═O), 1384 s ν_{symm}(N═O), 739 w δ(C–H from Ar). ^{1}H NMR spectrum ($(CD_3)_2CO$, δ): 9.92 (s, 1H, NH_{amine}), 8.50 (s, 1H, NH_{amine}), 8.40 (d, 7.8 Hz, 1H), 8.15 (d, 8.7 Hz, 1H), 8.03 (m, 2H), 7.90 (m, 2H), 7.65 (d, 8.7 Hz, 1H)(Ar), 6.13 (s, 1H, NH_{imine} from amidine), 4.14 (s, 1H, NH_{imine} from metallacycle), 2.93 (q, 7.4 Hz, 2H, CH_2 from Et), 2.84 (q, 7.5 Hz, 2H, CH_2 from Et), 1.32 (m, 6H, $2CH_2$ from 2Et). ^{13}C{^{1}H} NMR spectrum ($(CD_3)_2CO$, δ): 174.6, 160.1 (C═N), 149.6, 148.8, 147.6, 138.5 (C_{ipso}); 132.2, 130.9, 125.1, 122.7, 121.1, 120.6, 116.7, 111.7 (C_{Ar}); 49.7 (CH_2 from Et), 34.2 (CH_2 from Et), 12.3 (CH_3 from Et), 12.0 (CH_3 from Et).

Cyclometalation of the amidine in 8

(i) In solution. **8** (70.0 mg, 0.102 mmol) was dissolved in dry acetone (2 mL) and left to stand for 12 d at 50 °C. The resulting orange-brown solution was evaporated in air at 4–5 °C. The formed powder contains some degradation products along with [$PtCl_2${*N*H═C(Et)$NHC_6H_3NO_2$-*m*}$_2$] (**9**) (NMR yield 25%). *(ii) In the solid phase.* The powder of *mer*-[$PtCl_3${*N*H═C(Et)-$NHC_6H_4NO_2$-*m*}{*N*H═C(Et)$NHC_6H_3NO_2$-*m*}] (**2**) (70.0 mg, 0.102 mmol) was heated under dinitrogen for 3 d at 100 °C. The resulting solid contains **9** (NMR yield 20%) along with some degradation products, which were not separated.

[$PtCl_2${*N*H═C(Et)$NHC_6H_3NO_2$-*m*}$_2$] (9). ESI$^-$-MS, *m*/*z*: 649.0529; calcd for $[M - H]^-$ 649.0444. ^{1}H NMR spectrum ($(CD_3)_2CO$, δ): 9.83 (s, 2H, NH_{amine}), 8.47 (d, 8.1 Hz, 2H), 8.11 (d, 8.1 Hz, 2H), 7.73 (s, 2H)(Ar), 4.22 (s, 2H NH_{imine}), 2.78 (q, 7.4 Hz, 4H), 1.21 (t, 7.4 Hz, 6H)(Et). ^{13}C{^{1}H} NMR spectrum ($(CD_3)_2CO$, δ): 165.7 (C═N), 147.4, 144.8 (C_{ipso}), 125.4, 120.7, 113.1, 109.4 (C_{Ar}), 45.3, 12.5 (Et).

Hydration of the EtCN in 4

Complex **4** (50.0 mg, 0.085 mmol) was dissolved in undried $CHCl_3$ (2 mL) and left to stand for 8 h at 50 °C. The resulting solution was evaporated under vacuum at RT and the obtained residue was washed with Et_2O (two 1 mL portions). Yield of **10** was 31.8 mg, 68%.

***cis*-[$PtCl_4$(*N*$H_2C_6H_4NO_2$-*m*){*N*H═C(OH)Et}] (10).** Found: C, 19.68; H, 2.31; N, 7.60 (Calcd for $C_9H_{13}N_3Cl_4O_3Pt$: C, 19.72; H, 2.39; N, 7.67). ESI$^-$-MS, *m*/*z*: 545.9354; calcd for $[M - H]^-$ 546.9310. TLC: R_f = 0.38 (eluent Me_2CO–$CHCl_3$ = 1 : 20, v/v). IR spectrum in KBr (selected bands, cm^{-1}): 3308 w and 3289 m ν(N–H), 3010 w, 2954 w, and 2918 w ν(C–H), 1648 m and 1615 m ν(C═N), 1639 s ν(C–O), 1552 s ν(C═C), 1537 s ν(C═C_{Ar} and/or $_{asymm}$N═O), 1348 s ν_{symm}(N═O), 742 w δ(C–H from Ar). ^{1}H NMR spectrum ($CDCl_3$, δ): 9.85 (s, br, 1H, OH), 8.64 (s, br, 2H, NH_{2amine}), 8.25 (d, 6.9 Hz, 1H), 7.88 (d, 6.9 Hz, 1H), 7.98 (s, 1H), 7.81 (t, 1H, 6.8 Hz)(Ar), 5.78 (s, 1H from NH_{imine}), 2.14 (q, 7.2 Hz, 2H, CH_2 from Et), 1.21 (t, 7.3 Hz, 3H, CH_3 from Et). ^{13}C{^{1}H} NMR spectrum ($CDCl_3$, δ): 164.8 (C═N), 148.3 and 147.7 (C_{ipso}); 130.8, 124.7, 120.2, 118.1 (C_{Ar}); 22.7 (CH_2 from Et), 8.8 (CH_3 from Et).

Addition of methanol to the EtCN ligand in 4

Complex **4** (25.0 mg, 0.043 mmol) was dissolved in MeOH (2 mL) and stirred at 20–25 °C for 1 d, whereupon the resulting solution was evaporated at RT giving the yellow *trans*-[$PtCl_4${*N*H═C(Et)$NHC_6H_4NO_2$-*m*}{*N*H═C(Et)OMe}] (**11**) (24.7 mg, 94%).

***trans*-[$PtCl_4${*N*H═C(Et)$NHC_6H_4NO_2$-*m*}{*N*H═C(Et)OMe}] (11).** Found: C, 25.15; H, 3.14; N, 9.23 (Calcd for $C_{13}H_{20}N_4Cl_4O_3Pt$: C, 25.30; H, 3.27; N, 9.08); ESI$^+$-MS, *m*/*z*: 638.9714; calcd for $[M + Na]^+$ 638.9786. TLC: R_f = 0.70 (eluent Me_2CO–$CHCl_3$ = 1 : 40). IR spectrum in KBr (selected bands, cm^{-1}): 3337 m ν(N–H), 3038 w, 2924 m, and 2854 w ν(C–H), 1654 m and 1631 m ν(C═N), 1604 s ν(C═C_{Ar}), 1528 s and 1504 s ν(C═C_{Ar} and/or $_{asymm}$N═O), 1311 m ν_{symm}(N═O), 771 w δ(C–H_{Ar}). ^{1}H NMR spectrum ($(CD_3)_2CO$, δ): 9.58 (s, br, 1H, NH_{amine}), 8.37 (t, 9.5 Hz, 1H), 8.23 (d, 9.5 Hz, 1H), 7.86 (m, 2H)(Ar), 7.05 (s, br, 1H, NH_{imine}), 6.94

(s, br, 1H, NH_{imine}), 4.13 (s, 3H, CH_3 from OMe), 3.10 (q, 7.1 Hz, 2H, CH_2 from Et), 2.85 (q, 8.4 Hz, 2H, CH_2 from Et), 1.22 (t, 8.2 Hz, 3H, CH_3 from Et), 1.18 (t, 7.5 Hz, 3H, CH_3 from Et). $^{13}C\{^1H\}$ NMR spectrum ($(CD_3)_2CO$, δ): 177.8 (C═N), 172.4 (C═N), 149.1 and 138.0 (C_{ipso}), 133.2, 132.1, 123.6, 121.8 (C_{Ar}), 56.0 (MeO), 27.3 (CH_2 from Et), 27.1 (CH_2 from Et), 11.4 (CH_3 from Et), 10.0 (CH_3 from Et).

Results and discussion

For this study we addressed the model complex *trans*-$[PtCl_4(EtCN)_2]$ bearing a platinum(IV) center, which provides a very high activation of the ligated nitriles[1b,6,15a] and exhibits rather good solubility in the most common organic solvents; an X-ray structure of this complex was determined in the framework of this project (Fig. S1, ESI†). As weak (*H*)*N*-nucleophiles we employed the isomeric *o*-, *m*-, and *p*-nitroanilines (*o*-, *m*-, and *p*-NAs) that are commercially available and soluble in organic solvents.

Reactions of *trans*-$[PtCl_4(EtCN)_2]$ with NAs

The complex *trans*-$[PtCl_4(EtCN)_2]$ reacts with all isomeric NAs at RT giving different products depending on the molar ratio of the reactants and the position of the NO_2 substituent in NAs (Scheme 1). We observed two main directions of the reaction between *trans*-$[PtCl_4(EtCN)_2]$ and NAs, *viz.*, nucleophilic addition to the C≡N bond (Scheme 1, routes A and B) and substitution of the nitrile ligand (route D, see ESI†). Lowering the reaction temperature to −14 °C leads to decreasing the reaction rate with no substantial changes in the ratio between the substitution and the addition products. Increasing the temperature to 38 °C gives rise to the increase of the substitution product fraction. However, the reaction at the higher temperature is accompanied with other side processes, giving a broad mixture of unidentified products. Therefore, the reaction was conducted at RT.

Thus, the reaction of *trans*-$[PtCl_4(EtCN)_2]$ with *o*-NA in CH_2Cl_2 at both 1 : 1 and 1 : 2 molar ratios leads exclusively to the known[29] disubstitution product *cis*/*trans*-**1** and this reaction proceeds longer (3 d) than the reactions with *m*- (1 d) and *p*-NAs (1 d). The reaction of *trans*-$[PtCl_4(EtCN)_2]$ and *m*-NA at a 1 : 1 molar ratio proceeds smoothly at RT and completes for 1 d, providing previously unreported amidine complex **4** as the major product (NMR yield *ca.* 90%; Scheme 1, A), while disubstitution product *cis*/*trans*-**2** (Scheme 1, D) is formed in minor quantities (NMR yield *ca.* 5%; isolated yield *ca.* 3%). When this reaction is performed in a 1 : 2 molar ratio of the reactants, it also requires 1 d at 20–25 °C to complete and leads to bis-amidine complex **5** (72%; Scheme 1, B) along with small amounts of *cis*/*trans*-**2** (*ca.* 3%).

Eventually, *p*-NA reacts with *trans*-$[PtCl_4(EtCN)_2]$ in a 1 : 1 molar ratio for 1 d, furnishing **6** (NMR yield *ca.* 8%) and disubstitution product *cis*/*trans*-**3**[29] (NMR yield *ca.* 46%; isolated yield 44%). Increasing the molar ratio to 1 : 2 leads to selective generation of *cis*/*trans*-**3** (92%). The experimental details and characterization of nitroaniline complexes *cis*/*trans*-**1–3** are given in the ESI.†

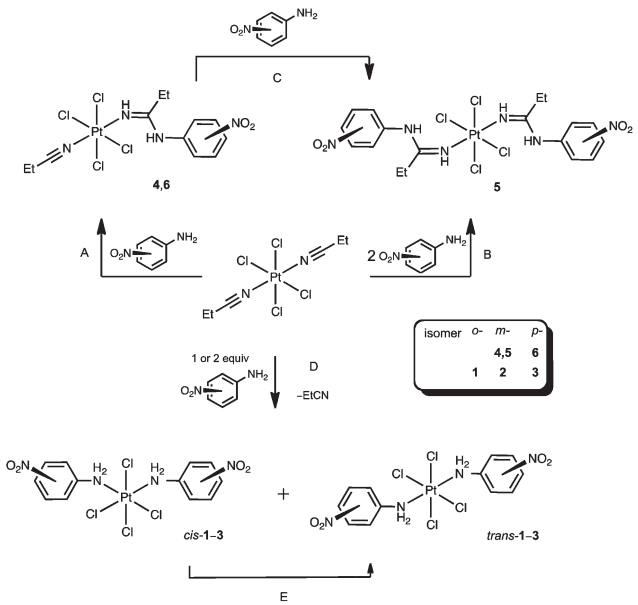
Reactivity of the amidine complexes

(i) Cyclometalation. Despite the fact that amidine complexes **4** and **5** are stable below 4 °C they undergo cyclometalation both in the solid phase (50 °C, 7 d) and in solution (CH_2Cl_2, 30 °C, 10 d for **4** and MeOH, 50 °C, 1 d for **5**) (Scheme 2); this transformation was monitored by TLC and ^1H NMR. Liberation of the propiononitrile or generation of hydration products were not observed.

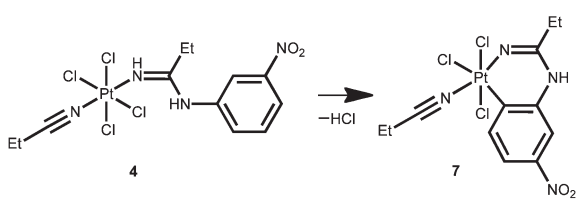
Complex **5**, bearing two amidine ligands, undergoes a stepwise cyclometalation *via* generation of *mono*-cyclometalated product **8** (67%) followed by cyclization of the second ligand to furnish bis-cyclometalated complex **9** (yield 25% in acetone solution, 20% in the solid phase) (Scheme 3).

The first stage of the cyclometalation proceeds rather rapidly (MeOH solution, 50 °C, 1 d), while the second step requires longer time (MeOH, 50 °C, 12 d or in the solid phase at 100 °C for 3 d), yielding a broad mixture of degradation products, where **9** was detected by ESI-MS, ^1H and $^{13}C\{^1H\}$ NMR methods, but was not isolated as a pure compound.

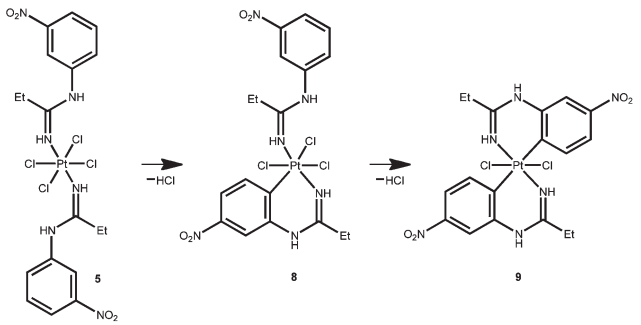
It is worth mentioning that a similar cyclization furnishing cyclometalated *N*-aryl amidines was observed earlier for the reaction of MeCN with the anilines $NH_2C_6H_4R$-*p* (R = H, CH_3, OCH_3) at a Ru^{II} center.[30] The cycloruthenation proceeds faster (1.5 h) than the cycloplatination of **5**, but requires elevated



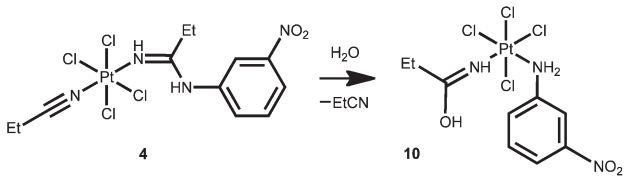
Scheme 1 Reactions of *trans*-$[PtCl_4(EtCN)_2]$ with NAs.



Scheme 2 The cyclometalation of **4**.



Scheme 3 The stepwise cyclometalation of **5**.

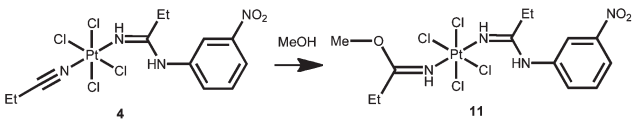


Scheme 4 The hydration of **4** accompanied by the elimination of the nitrile.

temperatures (100–110 °C) and a considerable excess of the appropriate aniline, which was used as a media for the reaction. In addition, the cycloruthenation – similar to the vast majority of cyclometalations – proceeds only in the liquid phase.[30,31] In contrast, the solid state cyclometalation is studied very little and, to the best of our knowledge, the solid state cyclometalation of amidines was not previously observed.[32] Hence, the solid state conversion of *N*-aryl amidine in **4** and **8** represents the first example of a solid state cyclometalation in amidine chemistry and the second example in imine chemistry.[32]

(ii) Nitrile hydration in **4**. Complex **4** heated at 50 °C in undried $CHCl_3$ undergoes hydration accompanied with the elimination of the nitrile (Scheme 4). Complex **10**, bearing both *m*-NA and the iminole ligands in the *cis*-position, was isolated as the final product (68%). Concurrently, the free propiononitrile was detected in the reaction mixture by ^{1}H NMR. *Bis*-amidine complex **5** does not undergo a similar elimination.

At least two mechanisms for generation of **10** and the liberation of EtCN are possible but experimental evidence supporting any of them have not yet been obtained and these works require further investigation. The first plausible mechanism consists of the elimination of the aniline *via* cleavage of the C–N bond in the amidine ligand followed by replacement of the coordinated nitrile by free *m*-NA. The Pt^{IV}-mediated hydration of the other nitrile ligand occurs as an independent process. This mechanism suggests the reversibility of the nucleophilic addition of *m*-NA, but if the equilibrium exists, it is strongly shifted to the addition products, because no products originating from the *retro*-addition were observed when **4** and **6** were kept in anhydrous solvents. A relevant reversibility was observed earlier for another imino ligand derived from a platinum-mediated nitrile–pyrazole coupling.[5a] The second plausible mechanism suggests the nucleophilic attack of H_2O on the amidine ligand followed by formation of the platinum-bound carboxamide and free nitroaniline, which coordinates to Pt^{IV} with liberation of EtCN.



Scheme 5 Methanolysis of the EtCN ligand in **4**.

The hydration of the nitrile ligand is platinum(IV)-mediated. It is well known that nitriles bound to a Pt^{IV} center are highly reactive toward hydration. Thus, the complex $[PtCl_5(EtCN)]^-$ hydrolyzed in the solid phase even in wet air at RT,[33] and the hydration of $[PtCl_4(RCN)_2]$ (R = Me, Et) occurs with water in undried solvents. Nevertheless, as stated above, complex **4** bearing the nitrile ligand is stable in air below 4 °C, in contrast to the starting $[PtCl_4(EtCN)_2]$. Probably its inertness is caused by the amidine ligand, which seems to be a better electron donor than the nitrile. This makes the platinum center of **4** less electrophilic.

(iii) Addition of Methanol. Compound **4** dissolved in neat MeOH converts to mixed-ligand complex **11** (RT, 1 d, 94%) (Scheme 5). The formation of $[PtCl_4(NH_2C_6H_4NO_2\text{-}m)\{NH{=}C(OMe)Et\}]$, which is structurally similar to **10**, was not observed at RT, or at 50 °C.

The literature data on other platinum complexes[15e,34] indicates that the R′OH–RCN coupling depends upon, first, the oxidation state of the metal and, second, the ligand environment in the Pt species. In the case of higher oxidation states (*i.e.* platinum(IV) center), the R′OH–RCN coupling does not require the use of a base, which is instead required for the lower oxidation state (*i.e.* platinum(II) center[34b]). The observed addition of MeOH gives an another example of the metal-mediated addition of alcohols to nitriles activated through coordination to Pt^{IV}, and the reaction is conducted under mild conditions and it does not require addition of a base for activation of the nucleophile.[34b]

Characterization of 4–11

Compounds **4–8**, **10**, and **11** were characterized by C, H, and N elemental analyses, high resolution ESI-MS, IR, ^{1}H and ^{13}C{^{1}H} NMR spectroscopic techniques. Complex **9**, which was not isolated as a pure compound, was identified in the reaction mixture by ESI-MS and ^{1}H and ^{13}C{^{1}H} NMR spectroscopies.

In the ESI^--MS of **4–10**, the observed peaks were attributed to $[M - H]^-$, while in the ESI^+-MS of **11** the peaks of $[M + Na]^+$ were detected; in all cases, the experimental isotopic patterns agree well with the calculated ones. In the IR spectrum of amidine complexes **4–8**, **10**, **11**, strong stretches in the range 1615–1659 cm^{-1} were assigned to the ν(C=N) vibrations and medium intensity bands at 3289–3302 and 3337–3435 cm^{-1} to ν(N–H).

One weak band at *ca.* 2330 cm^{-1} was attributed to ν(C≡N) in the nitrile containing species **4**, **5**, and **7**. In the ^{1}H NMR spectra of **4–6**, **10**, **11**, the signals from the imine NH's were detected at 6.94–5.78 ppm. High-field shift of NH's was observed in the ^{1}H NMR spectra for cyclometalated complexes **7–9** (NH's signals were detected at 4.42–4.14 ppm).

Complexes *trans*-**1** (Fig. S2, ESI†), *trans*-**2** (Fig. S3, ESI†), **4** (Fig. 1), **5** (Fig. 2), **6** (Fig. S4, ESI†), **8** (Fig. 3), **10** (Fig. S5,

ESI†), and **11** (Fig. S6, ESI†) were also characterized by X-ray diffraction.

All compounds, apart from **8**, have slightly distorted octahedral geometries with two N-donor ligands in the *trans*-position. Complex **8** exhibits a slightly distorted octahedral geometry with three chlorides in the *mer*-orientation. In **4**, **5**, **6**, **8**, and **11**, the C(1)N(1) (1.288(14)–1.303(7) Å) bond lengths of the amidine ligand are slightly longer than the typical C=N distances [1.269(2) Å] and C(1)N(3) [1.323(7)–1.343(5) Å] shorter than the single C–N bond [1.443(4) Å],[35] correspondingly. Comparison of these values suggests a moderate degree of delocalization in the NCN amidine fragment, which was also indicated earlier for relevant (amidine)Pt^{IV} complexes.[6,11] The NCN fragments are planar with a sum of angles around the C(1) carbon close to 360°. In **4**, **5**, **6**, **8**, and **11**, the amidine ligands adopt the (*Z*)-configuration, which is stabilized by the Cl(1)···HN hydrogen bonding. The C(10)N(2) bond of the nitrile ligands in **4** [1.160(12) Å] and in **6** [1.128(8) Å] exhibits values typical for the nitrile C≡N triple bond [1.139(4)].[36] In **8**, the metalacycle is approximately planar. The bond length of the double C(10)N(2) bond is 1.299(6) Å which is equal, within 3σ, to the typical value of 1.269(2) Å,[35] the bond length of the single C(10)N(4) bond is 1.349(6) Å, which is slightly smaller than the typical value of 1.443(4) Å.[35] In **4**, **5**, **6**, **8**, and **11**, the hydrogen atoms from the amido groups are involved in an intramolecular N–H···Cl hydrogen bonding [the shortest N1–H1···Cl1 of 2.7083(12) Å is in **6**, the longest N1–H1···Cl3 of 2.9729(27) is in **4**]. In **10**, the hydrogen of the hydroxo group is involved in intra- and intermolecular H-bondings with the chloride ligands; the shortest donor–acceptor distances (N···Cl) are between 3.0179(25) and 3.0238(23) Å); another H-bond (2.7487(33) Å) is between the hydrogens of the NH_2 group and the oxygen atom of the hydroxo group. In *trans*-**1**, there are two H-bonds through the coordinated NH_2 group with the oxygen atoms from the *o*-NO_2 group of the same NA and the nitro-group of the other molecule (with donor–acceptor N···O distances 2.6854(23) and 3.0615(26) Å, respectively), while in *trans*-**2**, the H-bond of 2.9682(27) is between the Cl ligands and NH_2.

Final remarks

The results from this work may be considered from a few perspectives. First, we demonstrated that platinum(IV), known as one of the strongest activators of the nitrile functionality,[6,15*a*,37] accelerates coupling of propiononitrile ligands even with such weak nucleophiles as nitroanilines. It should be noticed that the metal-free coupling of nitriles even with strong *H*(*N*)-nucleophiles proceeds only when the nitrile bears a strong electron-acceptor group R, *e.g.*, CCl_3.[1*a*]

Second, the direction of the reaction between the (nitrile)Pt^{IV} complex and the nitroanilines depends on the position of the NO_2 group in the benzene ring, *viz.* on basicity and nucleophilicity of NA (values of pK_a[38] and σ,[39] respectively: −0.3/– for *o*-NA; 2.5 and 1.25 for *m*-NA; 1.0 and 0.71 for *p*-NA). The interplay of *m*-NA with *trans*-[$PtCl_4(EtCN)_2$] gives the amidine complexes as the major products, while *o*- and *p*-NAs, where the amino- and nitro-groups form the conjugated system, react with *trans*-[$PtCl_4(EtCN)_2$], producing the nitroaniline complexes as the major (or even the only) products of the reaction. Two competitive processes are possible in the [$PtCl_4(EtCN)_2$] and NA reaction – the kinetically controlled addition to the C≡N bond and thermodynamically favorable substitution of the nitrile ligand by NA. The increasing nucleophilicity of NAs generates the addition products, and, on the contrary, decreasing nucleophilicity leads to the substitution products.

Third, we described the second example of cyclometalation of *N*-aryl substituted amidine, which, to the best of our knowledge, were previously observed only for a Ru^{II}-based system.[30]

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Notes and references

1 (*a*) V. Y. Kukushkin and A. J. L. Pombeiro, *Chem. Rev.*, 2002, **102**, 1771–1802; (*b*) V. Y. Kukushkin and A. J. L. Pombeiro, *Inorg. Chim. Acta*, 2005, **358**, 1–21; (*c*) N. A. Bokach, M. L. Kuznetsov and V. Y. Kukushkin, *Coord. Chem. Rev.*, 2011, **255**, 2946–2967; (*d*) N. A. Bokach and V. Y. Kukushkin, *Russ. Chem. Rev.*, 2005, **74**, 153–170.

2 (*a*) T. J. Ahmed, S. M. M. Knapp and D. R. Tyler, *Coord. Chem. Rev.*, 2011, **255**, 949–974; (*b*) F. F. Fleming and Q. Wang, *Chem. Rev.*, 2003, **103**, 2035–2077; (*c*) R. A. Michelin, M. Mozzon and R. Bertani, *Coord. Chem. Rev.*, 1996, **147**, 299–338; (*d*) R. A. Michelin, P. Sgarbossa, S. M. Sbovata, V. Gandin, C. Marzano and R. Bertani, *ChemMedChem*, 2011, **6**, 1172–1183.

3 (*a*) M. M. Green and H. A. Wittcoff, *Organic Chemistry Principles and Industrial Practice*, Wiley-VCH, Weinheim, 2003, p. 321; (*b*) K. L. Breno, T. J. Ahmed, M. D. Pluth, C. Balzarek and D. R. Tyler, *Coord. Chem. Rev.*, 2006, **250**, 1141–1151; (*c*) S. Prasad and T. C. Bhalla, *Biotechnol. Adv.*, 2010, **28**, 725–41.

4 (*a*) C. Marzano, S. M. Sbovata, F. Bettio, R. A. Michelin, R. Seraglia, T. Kiss, A. Venzo and R. Bertani, *J. Biol. Inorg. Chem.*, 2007, **12**, 477–493; (*b*) C. Marzano, S. M. Sbovata, V. Gandin, D. Colavito, E. Del Giudice, R. A. Michelin, A. Venzo, R. Seraglia, F. Benetollo, M. Schiavon and R. Bertani, *J. Med. Chem.*, 2010, **53**, 6210–6127; (*c*) C. Marzano, S. M. Sbovata, V. Gandin, R. A. Michelin, A. Venzo, R. Bertani and R. Seraglia, *J. Inorg. Biochem.*, 2009, **103**, 1113–1119; (*d*) S. M. Sbovata, F. Bettio, C. Marzano, M. Mozzon, R. Bertani, F. Benetollo and R. A. Michelin, *Inorg. Chim. Acta*, 2008, **361**, 3109–3116; (*e*) A. Casini, C. Gabbiani, G. Mastrobuoni, R. Z. Pellicani, F. P. Intini, F. Arnesano, G. Natile, G. Moneti, S. Francese and L. Messori, *Biochemistry*, 2007, **46**, 12220–12230; (*f*) M. Coluccia and G. Natile, *Anti-Cancer Agents Med. Chem.*, 2007, **7**, 111–123.

5 (*a*) A. V. Khripun, V. Y. Kukushkin, S. I. Selivanov, M. Haukka and A. J. L. Pombeiro, *Inorg. Chem.*, 2006, **45**, 5073–5083; (*b*) M. Arroyo, D. Miguel, F. Villafañe, S. Nieto, J. Pérez and L. Riera, *Inorg. Chem.*, 2006, **45**, 7018–7026; (*c*) C.-C. Hsieh, C.-J. Lee and Y.-C. Horng, *Organometallics*, 2009, **28**, 4923–4928; (*d*) X. Liu and W. Chen, *Dalton Trans.*, 2012, **41**, 599–608; (*e*) E. Reisner, V. B. Arion, A. Rufińska, I. Chiorescu, W. F. Schmid and B. K. Keppler, *Dalton Trans.*, 2005, 2355–2364; (*f*) B. Longato, D. Montagner, G. Bandoli and E. Zangrando, *Inorg. Chem.*, 2006, **45**, 1805–1814.

6 N. A. Bokach, N. P. Konovalova, Y. Wang, Y. E. Moskalenko, A. V. Gribanov and V. Y. Kukushkin, *Dalton Trans.*, 2010, **39**, 4619–4623.

7 S. M. Sbovata, R. A. Michelin, M. Mozzon, A. Venzo, R. Bertani and F. Benetollo, *Inorg. Chim. Acta*, 2010, **363**, 487–494.
8 D. Nieto, A. M. González-Vadillo, S. Bruña, C. J. Pastor, A. E. Kaifer and I. Cuadrado, *Chem. Commun.*, 2011, **47**, 10398–10400.
9 D. Montagner, E. Zangrando, G. Borsato, V. Lucchini and B. Longato, *Dalton Trans.*, 2011, **40**, 8664–8674.
10 (*a*) M. R. Tyan, N. A. Bokach, M.-J. Wang, M. Haukka, M. L. Kuznetsov and V. Y. Kukushkin, *Dalton Trans.*, 2008, 5178–5188; (*b*) F. P. Intini, R. Z. Pellicani, A. Boccarelli, R. Sasanelli, M. Coluccia and G. Natile, *Eur. J. Inorg. Chem.*, 2008, 4555–4561; (*c*) U. Belluco, F. Benetollo, R. Bertani, G. Bombieri, R. A. Michelin, M. Mozzon, O. Tonon, A. J. L. Pombeiro and M. F. C. Guedes da Silva, *Inorg. Chim. Acta*, 2002, **334**, 437–447; (*d*) D. Cornacchia, R. Z. Pellicani, F. P. Intini, C. Pacifico and G. Natile, *Inorg. Chem.*, 2009, **48**, 10800–10810; (*e*) T. Perera, F. R. Fronczek, P. A. Marzilli and L. G. Marzilli, *Inorg. Chem.*, 2010, **49**, 7035–7045.
11 A. V. Makarycheva-Mikhailova, V. Y. Kukushkin, A. A. Nazarov, D. A. Garnovskii, A. J. L. Pombeiro, M. Haukka, B. K. Keppler and M. Galanski, *Inorg. Chem.*, 2003, **42**, 2805–2813.
12 (*a*) Y. N. Kukushkin, N. P. Kiseleva, E. Zangrando and V. Y. Kukushkin, *Inorg. Chim. Acta*, 1999, **285**, 203–207; (*b*) L. Maresca, G. Natile, F. P. Intini, F. Gasparrini, A. Tiripicchio and M. Tiripicchio-Camellini, *J. Am. Chem. Soc.*, 1986, **108**, 1180–1185; (*c*) Z.-M. Hao and X.-M. Zhang, *Inorg. Chem. Commun.*, 2006, **9**, 57–59; (*d*) V. Mirkhani, I. Mohammadpoor-Baltork, M. Moghadam, S. Tangestaninejad, M. Abdollahi-Alibeik and H. Kargar, *Appl. Catal., A*, 2007, **325**, 99–104; (*e*) A. Syamala and A. R. Chakravarty, *Inorg. Chem.*, 1991, **30**, 4699–4704.
13 A. V. Makarycheva-Mikhailova, E. A. Tronova and V. Y. Kukushkin, *Russ. Chem. Bull.*, 2005, **54**, 610–614.
14 W. Li, M. Xue, F. Xu, J. Tu, Y. Zhang and Q. Shen, *Dalton Trans.*, 2012, **41**, 8252.
15 (*a*) D. S. Bolotin, N. A. Bokach, M. Haukka and V. Y. Kukushkin, *ChemPlusChem*, 2012, **77**, 31–40; (*b*) A. S. Kritchenkov, N. A. Bokach, M. Haukka and V. Y. Kukushkin, *Dalton Trans.*, 2011, **40**, 4175–4182; (*c*) A. S. Kritchenkov, N. A. Bokach, M. L. Kuznetsov, F. M. Dolgushin, T. Q. Tung, A. P. Molchanov and V. Y. Kukushkin, *Organometallics*, 2012, **31**, 687–699; (*d*) A. L. Mindich, N. A. Bokach, F. M. Dolgushin, M. Haukka, L. A. Lisitsyn, A. P. Zhdanov, K. Y. Zhizhin, S. A. Miltsov, N. T. Kuznetsov and V. Y. Kukushkin, *Organometallics*, 2012, **31**, 1716–1724; (*e*) Q. Wang, P. V. Gushchin, N. A. Bokach, M. Haukka and V. Y. Kukushkin, *Inorg. Chim. Acta*, 2012, **383**, 190–193.
16 I. V. Alabugin, M. Manoharan, M. Buck and R. J. Clark, *THEOCHEM*, 2007, **813**, 21–27.
17 K. V. Luzyanin, M. Haukka, N. A. Bokach, M. L. Kuznetsov, V. Y. Kukushkin and A. J. L. Pombeiro, *J. Chem. Soc., Dalton Trans.*, 2002, 1882–1887.
18 P. Svensson, K. Lövqvist, V. Y. Kukushkin and Å. Oskarsson, *Acta Chem. Scand.*, 1995, **49**, 72–75.
19 *Bruker AXS, APEX2 – Software Suite for Crystallographic Programs*, Bruker AXS, Inc., Madison, WI, USA, 2009.
20 A. J. M. Duisenberg, L. M. J. Kroon-Batenburg and A. M. M. Schreurs, *J. Appl. Crystallogr.*, 2003, **36**, 220–229.
21 W. Otwinowski and Z. Minor, Processing of X-ray diffraction data collected in oscillation mode, in *Methods in Enzymology, Macromolecular Crystallography, Part A*, ed. C. W. Carter and J. Sweet, Academic Press, New York, USA, 1997, vol. 276, pp. 307–326.
22 G. M. Sheldrick, *Acta Crystallogr., Sect. A: Found. Crystallogr.*, 2008, **A64**, 112–122.
23 G. Palatinus and L. Chapuis, *J. Appl. Crystallogr.*, 2007, **40**, 786–790.
24 R. Altomare, A. Burla, M. C. Camalli, M. C. Giacovazzo, C. Guagliardi, A. Moliterni, A. G. G. Polidori and G. Spagna, *J. Appl. Crystallogr.*, 1999, **32**, 115–119.
25 M. C. Burla, R. Caliandro, M. Camalli, B. Carrozzini, G. L. Cascarano, L. De Caro, C. Giacovazzo, G. Polidori, D. Siliqi and R. Spagna, *J. Appl. Crystallogr.*, 2007, **40**, 609–613.
26 O. V. Dolomanov, L. J. Bourhis, R. J. Gildea, J. A. K. Howard and H. Puschmann, *J. Appl. Crystallogr.*, 2009, **42**, 339–341.
27 G. M. Sheldrick, *SADABS – Bruker AXS scaling and absorption correction*, Bruker AXS, Inc., Madison, Wisconsin, USA, 2008.
28 Bruker AXS; G. M. Sheldrick, *SHELXTL*, Bruker AXS, Inc., Madison, Wisconsin, USA, 2008.
29 Y. N. Kukushkin, T. B. Pakhomova and N. P. Kiseleva, *Russ. J. Gen. Chem.*, 1997, **67**, 337–339.
30 P. Banerjee, S. Das, P. E. Fanwick and S. Goswami, *J. Organomet. Chem.*, 2006, **691**, 2915–2923.
31 (*a*) M. Albrecht, *Chem. Rev.*, 2010, **110**, 576–623; (*b*) S. U. Pandya, K. C. Moss, M. R. Bryce, A. S. Batsanov, M. A. Fox, V. Jankus, H. A. Al Attar and A. P. Monkman, *Eur. J. Inorg. Chem.*, 2010, 1963–1972.
32 Y. Y. Scaffidi-Domianello, A. A. Nazarov, M. Haukka, M. Galanski, B. K. Keppler, J. Schneider, P. Du, R. Eisenberg and V. Y. Kukushkin, *Inorg. Chem.*, 2007, **46**, 4469–4482.
33 M. L. Kuznetsov, N. A. Bokach, V. Y. Kukushkin, T. Pakkanen, G. Wagner and A. J. L. Pombeiro, *J. Chem. Soc., Dalton Trans.*, 2000, 4683–4693.
34 (*a*) A. M. Gonzalez, R. Cini, F. P. Intini, C. Pacifico, G. Natile and V. E. Orabona, *Inorg. Chem.*, 2002, **41**, 470–478; (*b*) N. A. Bokach, V. Y. Kukushkin, M. L. Kuznetsov, D. A. Garnovskii, G. Natile and A. J. L. Pombeiro, *Inorg. Chem.*, 2002, **41**, 2041–2053.
35 X.-Q. Cai, X.-N. Xie, X.-W. Yan, K.-J. Zhao and M.-R. Li, *Z. Kristallogr.*, 2009, **224**, 213–214.
36 G. Laus, K. Wurst, U. I. E. Horvath, H. Schmidhammer and H. Schottenberger, *Z. Kristallogr.*, 2004, **219**, 499.
37 N. A. Bokach, S. L. Ioffe, F. M. Dolgushin, M. Y. Antipin, V. A. Tartakovskii and V. Y. Kukushkin, *Inorg. Chem. Commun.*, 2009, **12**, 173–176.
38 P. M. Dewick, *Essentials of Organic Chemistry: for Students of Pharmacy, Medicinal Chemistry and Biological Chemistry*, John Wiley & Sons, Chichester, 2006, p. 142.
39 A. J. Gordon and R. A. Ford, *Chemist's Companion – A Handbook of Practical Data, Techniques and References*, Wiley, New York, 1972, Mir, Moscow, 1976 (Russian translation), p. 172.

