Journal of Organo metallic Chemistry

Intramolecular hydrogen bonding stabilizes *trans*-configuration in a mixed carbene/ isocyanide Pd^{II} complexes

Vladimir N. Mikhaylov, Viktor N. Sorokoumov, Alexander S. Novikov, Maria V. Melnik, Alexander G. Tskhovrebov, Irina A. Balova

PII: S0022-328X(20)30075-9

DOI: https://doi.org/10.1016/j.jorganchem.2020.121174

Reference: JOM 121174

To appear in: Journal of Organometallic Chemistry

Received Date: 9 January 2020

Revised Date: 6 February 2020

Accepted Date: 7 February 2020

Please cite this article as: V.N. Mikhaylov, V.N. Sorokoumov, A.S. Novikov, M.V. Melnik, A.G. Tskhovrebov, I.A. Balova, Intramolecular hydrogen bonding stabilizes *trans*-configuration in a mixed carbene/isocyanide Pd^{II} complexes, *Journal of Organometallic Chemistry* (2020), doi: https://doi.org/10.1016/j.jorganchem.2020.121174.

This is a PDF file of an article that has undergone enhancements after acceptance, such as the addition of a cover page and metadata, and formatting for readability, but it is not yet the definitive version of record. This version will undergo additional copyediting, typesetting and review before it is published in its final form, but we are providing this version to give early visibility of the article. Please note that, during the production process, errors may be discovered which could affect the content, and all legal disclaimers that apply to the journal pertain.

© 2020 Published by Elsevier B.V.

Intramolecular Hydrogen Bonding Stabilizes *Trans*-Configuration in a Mixed Carbene/Isocyanide Pd^{II} Complexes

Vladimir N. Mikhaylov,^a Viktor N. Sorokoumov,^a Alexander S. Novikov,^a Maria V. Melnik,^a Alexander G. Tskhovrebov,^{b,c*} and Irina A. Balova^{a*}

a) Saint Petersburg State University, Universitetskaya Nab. 7/9, 199034 Saint Petersburg, Russian Federation

b) N.N. Semenov Federal Research Center for Chemical Physics, Russian Academy of Sciences, Ul. Kosygina 4, Moscow, Russian Federation

c) Peoples' Friendship University of Russia, 6 Miklukho-Maklaya Street, Moscow, 117198, Russian Federation

Abstract

Aromatic amidines **1a-e** undergo facile reaction with one isocyanide in PdCl₂(CNBu^{*t*})₂ giving carbene complexes **2b-d** (**Scheme 2**) in high isolated yields (79–95%). The structures of **2b–d** were confirmed by the ¹H and ¹³C NMR spectroscopies, high resolution electrospray ionization mass spectrometry (HRESI-MS), IR, the elemental analyses (C, H, N), and X-ray diffraction analysis for **2c**, which revealed that the carbene and unreacted isocyanide ligands were located in a mutually *trans* position. Such arrangement was unexpected since it did not fit *trans* effect rule. Stabilization of the unfavorable isomer was rationalized by intramolecular hydrogen bonding. The nature of the intramolecular non-covalent interactions, which were responsible for the stabilization of the *trans*-isomer, was studied theoretically using DFT calculations and topological analysis of the electron density distribution within the framework of Bader's theory (QTAIM method).

Keywords

Carbenes, palladium complexes, isocyanides, amidines, hydrogen bonding.

Introduction

The Pd-catalyzed C–C and C–N coupling reactions have recently emerged as an indispensable tool in the organic synthesis.[1–3] Modern preparative methods heavily rely on the Suzuki–Miyaura, Sonogashira and Mizoroki–Heck and other cross-coupling processes.[4] In the last decades a research in the area of the Pd-catalyzed coupling reactions experienced an explosive growth which resulted in the development on the numerous well-defined catalysts. Among these systems the phosphine and N-heterocyclic carbene (NHC) complexes appeared to be among the most promising ones.[5–7] Although these systems proved to be highly efficient, they still possess several disadvantages. Homogeneity of the aforementioned catalysts does not allow a facile catalyst recovery and, consequently, their application in the industrial environment.

We have recently demonstrated that the palladium-mediated coupling between nucleophilesupported Merrifield resin and coordinated isocyanides is an efficient strategy for the expedient synthesis of the structurally elaborated acyclic diaminocarbene palladium (ADC-Pd) complexes.[8] This methodology allows a facile synthesis of the ADC-Pd complexes with easily tunable sterical and electronic parameters. Synthesis of relevant protic NHC complexes was described in excellent reviews by Hahn.[9,10]

In the course of our systematic studies on the synthesis of the new Pd-carbene complexes via nucleophilic coupling between the coordinated isocyanides and N-nucleophiles we found that the addition of various aromatic amidines to the Pd-bound isocyanide in $PdCl_2(CNBu')_2$ results in the formation of *trans*-PdCl(CNBu')(ADC) complexes.[11–15] At the first glance this seemed counterintuitive since it did not fit the classic Chernyaevs' trans effect theory.[16] Our investigation demonstrated that the unfavorable *trans*-isomer is stabilized by the intramolecular hydrogen bonding. Herein, we describe a facile synthesis of the Pd-complexes bearing chelate carbene ligand via amidine-isocyanide coupling and discuss unusual intramolecular hydrogen bond-stabilized mixed isocyanide carbene complexes.

Experimental Part

General remarks. GC analyses was performed on a Kristall 5000.2 instrument (Chromatec) with a flame ionization detector (FID) (column: Macherey-Nagel MN OptiMA-1 25 mx 0.32 mm 0.35 mkm). Infrared spectra (4000–200 cm⁻¹) were recorded on a Bruker Tensor 27 instrument as KBr pellets. NMR spectra were recorded at ambient temperature with a Bruker 400 WB Avance spectrometer (Bruker Ltd.) at 400.13 (¹H) and 100.61 (¹³C) MHz. Chemical shifts (δ) are given in ppm relative to the resonances of solvents (¹H, δ 7.26 for CDCl3; ¹³C, δ 77.16 for CDCl₃). Coupling constants (J) are given in Hz. Multiplicities of signals are described as follows: s = singlet, d = doublet, t = triplet, m = multiplet. Unless stated otherwise, all commercially available compounds (Alfa Aesar, Aldrich, TCI, Strem Chemicals) were used as received.

Computational details. The Hirshfeld molecular surface for the X-ray structure of 2c was generated using the CrystalExplorer program (version 17.5).[17] The normalized contact distances, d_{norm} ,[18] based on Bondi's van der Waals radii,[19] were mapped into the

Hirshfeld surface. In the color scale, negative values of d_{norm} are visualized by the red color indicating contacts shorter than the sum of van der Waals radii. The white color denotes intermolecular distances close to van der Waals contacts with d_{norm} equal to zero. In turn, contacts longer than the sum of van der Waals radii with positive d_{norm} values are colored with blue.

The full geometry optimization of all model structures has been carried out at the DFT level of theory using the M06 functional[20] with the help of Gaussian-09 program package.[21] The calculations were carried out using the quasi-relativistic energy-consistent pseudopotentials of the Stuttgart/Cologne group that described 28 core electrons and the appropriate contracted basis sets[22] for palladium atoms (MWB28) and the standard 6-31G(d) basis sets for other atoms. No symmetry restrictions have been applied during the geometry optimization procedure. The Hessian matrices were calculated analytically in all cases to prove the location of correct minima on the potential energy surfaces (no imaginary frequencies) and to estimate the thermodynamic parameters, the latter being calculated at 25 °C (**Table S8**). The topological analysis of the electron density distribution with the help of the "atoms in molecules" (QTAIM) method[23] has been performed by using the Multiwfn program (version 3.6).[24] The Cartesian atomic coordinates for optimized equilibrium geometries of model structures are presented in **Table S9**.

Synthetic part.



General procedure for the synthesis of *N*-substituted amidines.

Scheme 1. Synthesis of amidines.

Amidines were synthesized according to slightly modified literature procedures (Scheme 1).[25–27] Aniline (6.0 mmol, 1.20 eq) and a corresponding nitrile (5.0 mmol, 1 eq) were stirred for 15 min at room temperature in the pressure tube (75 mL). Further, AlCl₃ (5.0 mmol, 1.00 eq) was added in one portion, the tube was sealed, and the mixture was stirred at 140 °C for 15 h. Cold water (50 mL) was added. To the formed suspension, concentrated solution of NaOH was added till pH reached 14 (pH was controlled using a universal paper indicator). The aqueous layer was extracted with CHCl₃ (3×30 mL). The combined organic layers were dried over Na₂SO₄, filtered and concentrated under reduced pressure. The residue was purified by double recrystallization from hexane or a mixture of hexane/ethyl acetate or using preparative column chromatography. Analytical data were in excellent agreement with the previously reported.

1a. Aniline (6.0 mmol, 560 mg), benzonitrile (5.0 mmol, 516 mg) were used. Yield: 707 mg (72%). The compound was purified by the double recrystallization from hexane/ethyl acetate.

1b. Aniline (6.0 mmol, 560 mg), acetonitrile (5.0 mmol, 205 mg) were used. Yield: 235 mg (35%). The compound was purified by the double recrystallization from hexane/ethyl acetate.

1c. Aniline (6.0 mmol, 560 mg), 4-methoxybenzonitrile (5.0 mmol, 666 mg) were used. Yield: 238 mg (21%). The compound was purified by the double recrystallization from hexane/ethyl acetate.

1d. 2-Isopropylaniline (6.0 mmol, 751 mg), benzonitrile (5.0 mmol, 516 mg) were used. Yield: 822 mg (69%). The compound was purified by the double recrystallization from hexane/ethyl acetate.

1e. Aniline (6.0 mmol, 560 mg), pivalonitrile (5.0 mmol, 415 mg) were used. Yield: 388 mg (44%). The compound was purified by the recrystallization from hexane.

1f. p-Anisidine (6.0 mmol, 780 mg), pivalonitrile (5.0 mmol, 416 mg) were used. Yield: 371 mg (36%). The compound was purified by column chromatography with hexane/ethyl acetate (1:10) as an eluent.

General procedure for the synthesis of ADC-Pd^{II} complexes.

PdCl₂(CNBu^{*t*})₂ (**2**) (0.1 mmol, 34 mg), corresponding amidine (**1a-f**) (0.1 mmol) and Et₃N (1 mmol, 101 mg) were dissolved in 2 mL of THF and stirred for 6 h for **2a**, **2c**– **2f** or 2 h for **2b**. The reaction mixture was cooled to 0 °C, filtered from precipitated Et₃N hydrochloride, washed with cold THF (3×2 mL), evaporated under reduced pressure. An oily residue was washed with Et₂O (2 mL) to give a powder, which was filtered and crystallized by the slow diffusion of pentane into CH₂Cl₂ solution at 10 °C.



trans-2a+cis-2a*. Yield 47 mg (93%).
¹H NMR (300 MHz, CDCl₃): δ 7.76 (s, NH), 6.56-7.30 (m, 7H+7H*), 6.63 (d, J = 3.6 Hz, 2H), 6.60 (d, J = 3.6 Hz, 2H*), 5.60 (s, NH*), 3.72 (s, 3H + 3H*), 1.58 (s, 9H*), 1.51 (s, 9H*),

1.47 (s, 9H), 1.16 (s, 9H). trans-2a:cis-2a 1.63:1.00.



trans-2b+*cis*-2b*. Yield 39 mg (89%). ¹H NMR (300 MHz, CDCl₃): δ 7.66 (s, NH), 7.15–7.33 (m, 3H+3H*), 7.00 (d, J = 7.2 Hz, 2H), 7.12 (d, J = 7.5 Hz, 2H*), 5.51 (s, NH*), 1.93 (s, 3H*), 1.90 (s, 3H), 1.56 (s, 9H*, C(CH₃)₃), 1.47 (s,

9H*, C(CH₃)₃), 1.43 (s, 9H, C(CH₃)₃), 1.10 (s, 9H, C(CH₃)₃); *trans*-2b+*cis*-2b. ¹³C NMR (101 MHz, CDCl₃): δ 191.76 (C_{carbene}), 189.39 (C_{carbene}) 183.23, 182.73,150.65, 146.51, 128.86, 128.27, 125.78, 125.54, 125.48, 125.36, 55.88 (C(CH₃)₃), 54.62 (C(CH₃)₃), 30.14 (C(CH₃)₃), 29.58 (C(CH₃)₃), 29.13 (C(CH₃)₃), 28.84 (C(CH₃)₃), 17.70 (N=C(N)-CH₃), 16.83 (N=C(N)-CH₃) (isocyanide carbon atoms were not detected; IR (KBr, cm⁻¹): v(N-H) 3296, v(C-H) 2971, v(C=N) 2206, v(N=C_{carbene}=N) 1525; ESI/MS (m/z, 100V, MeCN): calculated [C₁₈H₂₈ClN₄Pd+H⁺] = 441.1037, found [*M*+H⁺] = 441.1033. *trans*-2b:*cis*-2b 1.33:1.00.



trans-2c+*cis*-2c*. Yield 44 mg (79%). ¹H NMR (300 MHz, CDCl₃) δ 7.76 (s, NH), 6.56-7.30 (m, 7H+7H*), 6.63 (d, *J* = 3.6 Hz, 2H), 6.60 (d, *J* = 3.6 Hz, 2H*), 5.60 (s, NH*), 3.72 (s, 3H + 3H*), 1.58 (s, 9H*, C(CH₃)₃), 1.51 (s, 9H*, C(CH₃)₃), 1.47 (s, 9H, C(CH₃)₃),

1.16 (s, 9H, C(CH₃)₃); *trans*-2c+*cis*-2c. ¹³C NMR (75 MHz, CDCl₃): δ 189.60 (C_{carbene}), 187.42 (C_{carbene}), 160.60, 160.36, 151.32, 146.85, 133.05, 132.72, 128.58, 127.96, 126.81, 126.31, 125.01, 124.65, 112.68, 112.62, 55.86 (C(CH₃)₃), 55.11(-OCH₃), 54.69 (C(CH₃)₃), 30.17 (C(CH₃)₃), 29.64 (C(CH₃)₃), 29.29 (C(CH₃)₃), 28.99 (C(CH₃)₃) (isocyanide carbon atoms were not detected); **IR** (KBr, cm⁻¹): v(N-H) 3279, v(C-H) 2981 , v(C=N) 2209, v(N=C_{carbene}= N) 1534, 1498; **ESI/MS** (m/z, 100V, MeCN): calculated [C₂₄H₃₁ClN₄OPd-Cl] = 497.1533, found [*M*-Cl]⁺ = 497.1542. *trans*-2c:*cis*-2c 1.38:1.00.



trans-2d+*cis*-2d*. Yield 52 mg (95%). ¹H NMR (400 MHz, CDCl₃): δ 7.76 (s, 1H, NH), 7.34-7.01 (m, 9H+9H*, Ar), 5.64 (s, 1H, NH*), 3.32 (sept, J = 6.8 Hz, 1H), 3.16 (sept, J = 6.9 Hz, 1H*), 1.93 (s,

3H*), 1.90 (s, 3H,), 1.58 (s, 9H*, C(CH₃)₃), 1.53 (s, 9H*, C(CH₃)₃), 1.49 (s, 9H, C(CH₃)₃), 1.24 (d, J = 6.8 Hz, 6H*), 1.21 (d, J = 6.8 Hz, 6H*), 1.08 (s, 9H, C(CH₃)₃), 0.72 (d, J = 6.8 Hz, 6H*); *trans*-2d+*cis*-2d. ¹³C NMR (101 MHz, CDCl₃): δ 190.10 (C_{carbene}), 188.1 (C_{carbene}), 179.81, 148.19, 145.22, 143.87, 142.44, 142.27, 132.69, 132.48, 130.80,

130.53, 129.80, 129.49, 127.21, 127.17, 126.78, 126.25, 126.21, 126.01, 125.78, 125.61, 125.24, 55.91 ($C(CH_3)_3$), 54.74 ($C(CH_3)_3$), 30.17 ($C(CH_3)_3$), 29.60 ($C(CH_3)_3$), 29.30 ($C(CH_3)_3$), 28.98 ($C(CH_3)_3$), 27.78, 27.26, 23.79, 22.50, 22.32 (isocyanide carbon atoms were not detected); **IR** (KBr, cm⁻¹): v(N-H) 3277, v(C-H) 2962, v(C=N) 2211, v(N=C_{carbene}= N) 1533, 1509; **ESI/MS** (m/z, 100V, MeCN): calculated [$C_{26}H_{35}CIN_4Pd-CI$]⁺ = 509.1897, found [*M*-CI]⁺ = 509.1923. *trans*-2d:*cis*-2d 2.33:1.00.

Results and Discussion

We started our studies with the optimization of the homogeneous reaction between *N*-phenylbenzamidine and $PdCl_2(CNBu^t)_2$. In our preliminary report the yield of the desired complex was rather low.[28] We now found that the addition of Et_3N to the reaction mixture significantly increases the reaction time and the yield of the carbene complex (99% NMR yield after 2 hours at room temperature and 93% isolated yield). Further, we tested our methodology for other amidines **1a-e**, which were synthesized from the corresponding anilines and nitriles by their coupling in the presence of $AlCl_3$ (**Scheme 1**).

Amidines **1a-e** undergo facile coupling with the Pd-bound isocyanide in $PdCl_2(CNBu^t)_2$ giving carbene complexes **2b-d** (**Scheme 2**) in high isolated yields (79–95%). Interestingly, the utilization of sterically hindered amidines **1e** and **1f** not gave the desired carbenes.

8



Scheme 2. Synthesis of mixed carbene/isocyanide Pd^{II} complexes.

The structures of **2b–d** were confirmed by the ¹H and ¹³C NMR spectroscopies, high resolution electrospray ionization mass spectrometry (HRESI-MS), IR, the elemental analyses (C, H, N), and X-ray diffraction analysis for **2c** (**Figure 1**).



Figure 1. View of 2c with the atomic numbering scheme.

Complex **2c** contains acyclic diaminocarbene complex and unreacted isocyanide ligand in *trans* configuration. We carried out the Hirshfeld surface analysis for the X-ray structure of **2c** to understand what kind of intermolecular contacts gives the most significant contribution in

the crystal packing (**Figure 2**). The partial contributions of different interatomic contacts to the molecular Hirshfeld surface of 2c are following: H…H 62.3%, C…H 17.8%, Cl…H 9.2%, O…H 4.1%, N…H 3.5%, Pd…H 3.1%, and C…C 0.1%. Thus, the Hirshfeld surface analysis for the X-ray structure of 2c reveals that crystal packing is mainly determined by intermolecular H–H contacts.



Figure 2. Total molecular Hirshfeld surface for **2c** and molecular Hirshfeld surfaces with selectively highlighted sections, which are formed due to the corresponding interatomic contacts.

The IR spectra of **2a-d** feature characteristic bands at 2206–2211 cm⁻¹ which correspond to C=N stretching vibrations from unreacted isocyanide ligand. Interestingly, **2c** features an intramolecular hydrogen bond between the chloride and the N–H proton from the carbene in the crystal. Careful analysis of the ¹H and ¹³C NMR spectra revealed an existence of **2a-d** in two isomeric forms in CDCl₃ solutions (**Scheme 3**). Additional 2D experiments (NOESY, COSY) unambiguously confirmed the presence of both *cis-* and *trans-*isomers and the dominance of the *trans-*form in the liquid. It is worth mentioning here that the *cis*

arrangement is usually preferential for this kind of systems.[4,12–14,28,29] Unfavorable *trans*-configuration in **2a-d** might be stabilized by the intramolecular hydrogen bonding.



Scheme 3. Isomerization of mixed carbene/isocyanide Pd^{II} complexes in the solution.

The ratio between the *cis*- and *trans*-isomers did not change significantly when the substituent R^1 at amidine backbone was varied while the equilibrium shifted to the *trans*-form when the substituent R^2 at the coordinate N atom was changed from Ph to *o*-Pr^{*i*}Ph (**Scheme** 3).

¹H NMR spectra of Pd-ADCs exhibited singlets which corresponded to the NHprotons of the ADC fragment ($\delta = 7.76$ ppm for *trans* forms of **2a**, **2c**, **2d** and $\delta = 5.60-5.64$ ppm for *cis* isomers of **2a**, **2c**, **2d**). Chemical shifts of the NH-protons in **2a**, **2c**, **2d** are identical for the *trans* isomers and low-field-shifted by *ca*. 2 ppm compared to the other isomer. This data also indicates on the formation of the intramolecular hydrogen bond.[30]

In addition, we investigated an influence of the solvent polarity on the equilibrium in our carbene systems. For this purpose, we compared ¹H NMR spectra of **2a** in CCl₄, CDCl₃, acetone- d_6 and DMSO- d_6 . For these solvents we observed a dominance of the *trans*-isomer in less polar solvents (CCl₄ – 91%, CDCl₃ – 62%, acetone- d_6 – 51%, a B DMSO- d_6 – 21%). Thus, a relative amount of the form stabilized by the intramolecular hydrogen bond decreases

in more polar solvents probably due to the competition between the intramolecular and intermolecular (with an appropriate solvent) hydrogen bonding.

Further, we performed DFT calculations and full geometry optimization of four different isomers of 2c to compare their relative stability from a theoretical point of view (**Figure 3**, **Tables S8** and **S9**). The isomer *trans*-2c featuring intramolecular N–H···Cl hydrogen bonding was found to be the most stable one.



Figure 3. Optimized equilibrium geometries of four different isomers of 2c and relative values of their Gibbs free energies (in kcal/mol).

Thus, intramolecular hydrogen bonding stabilizes otherwise unfavorable *trans* arrangement in the mixed carbene isocyanide complex. In order to better understand the situation, we carried out topological analysis of the electron density distribution within the framework of Bader's theory (QTAIM method)[31] for the optimized equilibrium model structure *trans*-2c (Tables 1 and S9). The contour line diagram of the Laplacian of electron density distribution $\nabla^2 \rho(\mathbf{r})$, bond paths, and selected zero-flux surfaces for N–H···Cl non-

covalent interactions in the optimized equilibrium model structure *trans*-2c are shown in Figure 4.

$\rho(\mathbf{r})$	$\nabla^2 \rho(\mathbf{r})$	λ_2	H _b	V(r)	G(r)	l	WI	E _{int} ^a	E _{int} ^b
0.020	0.068	-0.029	0.001	-0.016	0.016	2.326	0.04	5.0	4.3
$^{a} E_{int} = -V(\mathbf{r})/2[32]$									
^b $E_{int} = 0.429G(\mathbf{r})[33]$									

Table 1. Values of the density of all electrons – $\rho(\mathbf{r})$, Laplacian of electron density – $\nabla^2 \rho(\mathbf{r})$ and appropriate λ_2 eigenvalue (with promolecular approximation), energy density – H_b, potential energy density – V(\mathbf{r}), and Lagrangian kinetic energy – G(\mathbf{r}) (a.u.) at the bond critical point (3, –1), corresponding to N–H···Cl non-covalent interactions in the optimized equilibrium model structure *trans*-2 \mathbf{c} as well as bond length – l (Å), Wiberg bond index – WI and estimated energy – E_{int} (kcal/mol) for this contact.



Figure 4. Contour line diagram of the Laplacian of electron density distribution $\nabla^2 \rho(\mathbf{r})$, bond paths and selected zero-flux surfaces referring to N–H····Cl non-covalent interactions in the optimized equilibrium model structure *trans*-2c. Bond critical points (3, –1) are shown in blue, nuclear critical points (3, –3) – in pale brown, ring critical points (3, +1) – in orange, length units – Å.

The QTAIM analysis demonstrates the presence of appropriate bond critical point (BCP) for N-H···Cl non-covalent interactions in the optimized equilibrium model structure *trans*-2c. The low magnitude of the electron density, positive value of the Laplacian of electron density, and positive very close to zero energy density in this BCP are typical for hydrogen bonding[34–37] (Table 1). We have defined strength for this contact according to the procedures proposed by Espinosa et al.[32] and Vener et al.[33] (Table 1), and one can state that energy of these N-H···Cl non-covalent interactions (4.3-5.0 kcal/mol) is typical for moderate strength hydrogen bonding following the classification of Jeffrey (weak: <4 kcal/mol, moderate: 15-4 kcal/mol, strong: 40-15 kcal/mol).[38] The balance between the Lagrangian kinetic energy $G(\mathbf{r})$ and potential energy density $V(\mathbf{r})$ at the BCPs (3, -1) reveals the nature of these interactions, if the ratio $-G(\mathbf{r})/V(\mathbf{r}) > 1$ is satisfied, than the nature of appropriate interaction is purely non-covalent, in case the $-G(\mathbf{r})/V(\mathbf{r}) < 1$ some covalent component takes place[39]. Based on this criterion one can state that a covalent contribution in the discussed above N-H···Cl non-covalent interactions in the optimized equilibrium model structure *trans*-2c is negligible, which is additionally confirmed by very small value of Wiberg bond index for this contact (0.04) computed by using the Natural Bond Orbital (NBO) partitioning scheme.[40] The Laplacian of electron density is typically decomposed into the sum of contributions along the three principal axes of maximal variation, giving the three eigenvalues of the Hessian matrix (λ_1 , λ_2 and λ_3), and the sign of λ_2 can be utilized to

distinguish bonding (attractive, $\lambda_2 < 0$) weak interactions from non-bonding ones (repulsive, $\lambda_2 > 0$).[41] Thus, discussed N–H····Cl non-covalent interactions in the optimized equilibrium model structure *trans*-2c are attractive.

In summary, here we reported novel mixed-ligand Pd^{II} carbene/isocyanide complexes. We showed that intramolecular hydrogen bonding stabilizes otherwise unfavorable *trans* arrangement in these compounds. Solution NMR studies revealed that a relative amount of the *trans*-form decreases in more polar solvents due to the competition between the intramolecular and intermolecular (with an appropriate solvent) hydrogen bonding. The energy of these N–H···Cl non-covalent interactions (4.3–5.0 kcal/mol) is typical for moderate strength hydrogen bonding.

Acknowledgments. The synthetic and analytic work of VNM is supported by the Russian Science Foundation under Grant No. 19-73-00228. AGT is grateful to the FRCCP RAS State task AAAA-A19-119012990175-9 for the financial support. The Hirshfeld surface analysis, DFT calculations and QTAIM analysis were performed as part of the Russian Science Foundation project No. 19-73-00001. We acknowledge the RUDN University Program 5-100. Scientific research was performed at the resource centers of Saint Petersburg State University: Centre of Magnetic Resonance, Centre for Chemical Analysis and Materials Research, Centre for X-ray Diffraction Studies, Center of Physical methods of surface investigation.

References

- C.C.C. Johansson Seechurn, M.O. Kitching, T.J. Colacot, V. Snieckus, Angew. Chemie - Int. Ed. 51 (2012) 5062–5085.
- [2] A. Chartoire, S.P. Nolan, RSC Catal. Ser. 2015-Janua (2015) 139–227.
- [3] P. Ruiz-Castillo, S.L. Buchwald, Chem. Rev. 116 (2016) 12564–12649.

- [4] V.P. Boyarskiy, K. V. Luzyanin, V.Y. Kukushkin, Coord. Chem. Rev. 256 (2012) 2029–2056.
- [5] N. Marion, S.P. Nolan, Acc. Chem. Res. 41 (2008) 1440–1449.
- [6] L.M. Slaughter, Catalysis with Acyclic Aminocarbene Ligands: Alternatives to NHCs with Distinct Steric and Electronic Properties, in: N-Heterocyclic Carbenes Eff. Tools Organomet. Synth., Wiley-VCH Verlag GmbH & Co. KGaA, Weinheim, Germany, 2014: pp. 499–524.
- [7] V.N. Mikhaylov, V.N. Sorokoumov, I.A. Balova, Russ. Chem. Rev. 86 (2017) 459–473.
- [8] V.N. Mikhaylov, V.N. Sorokoumov, D.M. Liakhov, A.G. Tskhovrebov, I.A. Balova, Catalysts. 8 (2018).
- [9] M.C. Jahnke, F.E. Hahn, Coord. Chem. Rev. (2015).
- [10] S. Kuwata, F.E. Hahn, Chem. Rev. (2018).
- [11] A.G. Tskhovrebov, K. V. Luzyanin, M. Haukka, V.Y. Kukushkin, J. Chem. Crystallogr. 42 (2012) 1170–1175.
- [12] A. Tskhovrebov, M. Haukka, Acta Crystallogr. Sect. E Struct. Reports Online. 68 (2012).
- [13] K. V. Luzyanin, A.G. Tskhovrebov, M.F.C. Guedes da Silva, M. Haukka, A.J.L.Pombeiro, V.Y. Kukushkin, Chem. A Eur. J. 15 (2009) 5969–5978.
- [14] A.G. Tskhovrebov, K. V. Luzyanin, F.M. Dolgushin, M.F.C. Guedes Da Silva, A.J.L.Pombeiro, V.Y. Kukushkin, Organometallics. 30 (2011) 3362–3370.
- [15] A.G. Tskhovrebov, N.A. Bokach, M. Haukka, V.Y. Kukushkin, Inorg. Chem. 48 (2009) 8678–8688.
- [16] G.B. Kauffman, J. Chem. Educ. 54 (1977) 86–89.
- [17] M.A. Spackman, D. Jayatilaka, CrystEngComm. 11 (2009) 19–32.

- [18] J.J. McKinnon, D. Jayatilaka, M.A. Spackman, Chem. Commun. (2007) 3814–3816.
- [19] A. Bondi, J. Phys. Chem. 70 (1966) 3006–3007.
- [20] Y. Zhao, D.G. Truhlar, Theor. Chem. Acc. 120 (2008) 215–241.
- [21] M.J. Frisch, G.W. Trucks, H.B. Schlegel, G.E. Scuseria, M.A. Robb, J.R. Cheeseman, G. Scalmani, V. Barone, B. Mennucci, G.A. Petersson, H. Nakatsuji, M. Caricato, X. Li, H.P. Hratchian, A.F. Izmaylov, J. Bloino, G. Zheng, J.L. Sonnenberg, M. Hada, M. Ehara, K. Toyota, R. Fukuda, J. Hasegawa, M. Ishida, T. Nakajima, Y. Honda, O. Kitao, H. Nakai, T. Vreven, J.A. Montgomery Jr., J.E. Peralta, F. Ogliaro, M. Bearpark, J.J. Heyd, E. Brothers, K.N. Kudin, V.N. Staroverov, R. Kobayashi, J. Normand, K. Raghavachari, A. Rendell, J.C. Burant, S.S. Iyengar, J. Tomasi, M. Cossi, N. Rega, J.M. Millam, M. Klene, J.E. Knox, J.B. Cross, V. Bakken, C. Adamo, J. Jaramillo, R. Gomperts, R.E. Stratmann, O. Yazyev, A.J. Austin, R. Cammi, C. Pomelli, J.W. Ochterski, R.L. Martin, K. Morokuma, V.G. Zakrzewski, G.A. Voth, P. Salvador, J.J. Dannenberg, S. Dapprich, A.D. Daniels, □. Farkas, J.B. Foresman, J. V Ortiz, J. Cioslowski, D.J. Fox, Gaussian 09 Revis. C.01. (2010) Gaussian Inc., Wallingford CT.
- [22] D. Andrae, U. Häußermann, M. Dolg, H. Stoll, H. Preuß, Theor. Chim. Acta. 77 (1990)123–141.
- [23] R.F.W. Bader, Chem. Rev. 91 (1991) 893–928.
- [24] T. Lu, F. Chen, J. Comput. Chem. 33 (2012) 580–592.
- [25] Y. Wang, H. Wang, J. Peng, Q. Zhu, Org. Lett. 13 (2011) 4604–4607.
- [26] Y.F. Wang, H. Chen, X. Zhu, S. Chiba, J. Am. Chem. Soc. 134 (2012) 11980–11983.
- [27] B.C. Hamper, A.S. Kesselring, R.C. Chott, S. Yang, J. Comb. Chem. 11 (2009) 469–480.
- [28] A.G. Tskhovrebov, K. V. Luzyanin, M.L. Kuznetsov, V.N. Sorokoumov, I.A. Balova,

M. Haukka, V.Y. Kukushkin, Organometallics. 30 (2011) 863–874.

- [29] K. V. Luzyanin, A.G. Tskhovrebov, M. Carolina Carias, M. Fátima C Guedes Da Silva, A.J.L. Pombeiro, V.Y. Kukushkin, Organometallics. 28 (2009) 6559–6566.
- [30] M. Petrova, R. Muhamadejev, B. Vigante, G. Duburs, E. Liepinsh, R. Soc. Open Sci. 5 (2018).
- [31] R.F.W. Bader, Oxford Univ. Press. Oxford Henkelman G, Arnaldsson A, Jónsson H A
 Fast Robust Algorithm Bader Decompos. Charg. Density. Comput Mater Sci. 36 (1990) 354–360.
- [32] E. Espinosa, E. Molins, C. Lecomte, Chem. Phys. Lett. 285 (1998) 170–173.
- [33] M. V. Vener, A.N. Egorova, A. V. Churakov, V.G. Tsirelson, J. Comput. Chem. 33 (2012) 2303–2309.
- [34] A.G. Tskhovrebov, A.S. Novikov, O. V. Odintsova, V.N. Mikhaylov, V.N.
 Sorokoumov, T. V. Serebryanskaya, G.L. Starova, J. Organomet. Chem. 886 (2019) 71–75.
- [35] D.M. Ivanov, A.S. Novikov, G.L. Starova, M. Haukka, V.Y. Kukushkin, CrystEngComm. 18 (2016) 5278–5286.
- [36] A.G. Tskhovrebov, A.A. Vasileva, R. Goddard, T. Riedel, P.J. Dyson, V.N. Mikhaylov, T. V. Serebryanskaya, V.N. Sorokoumov, M. Haukka, Inorg. Chem. 57 (2018) 930–934.
- [37] O. V. Repina, A.S. Novikov, O. V. Khoroshilova, A.S. Kritchenkov, A.A. Vasin, A.G. Tskhovrebov, Inorganica Chim. Acta. 502 (2020).
- [38] T. Steiner, Angew. Chemie Int. Ed. 41 (2002) 48–76.
- [39] E. Espinosa, I. Alkorta, J. Elguero, E. Molins, J. Chem. Phys. 117 (2002) 5529–5542.
- [40] E.D. Glendening, C.R. Landis, F. Weinhold, Wiley Interdiscip. Rev. Comput. Mol. Sci. 2 (2012) 1–42.

- [41] E.R. Johnson, S. Keinan, P. Mori-Sánchez, J. Contreras-García, A.J. Cohen, W. Yang,
 - J. Am. Chem. Soc. 132 (2010) 6498-6506.

Journal Prevention

Journal Pre-proof Highlights

- Synthesis of novel mixed-ligand Pd^{II} carbene/isocyanide complexes. 0
- Stabilization of otherwise unfavorable trans arrangement in carbene/isocyanide 0 systems by intramolecular hydrogen bonding.
- X-ray diffraction analysis of the new material. 0
- Theoretical study of the nature and energies of intramolecular non-covalent 0

. of .

Declaration of interests

☐ The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests:

Journal Prerk