

X-Ray diffraction study of fluorine-functionalized thiosemicarbazones and cyclometallated compounds[†]

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Abstract:

In this work the X-Ray diffraction study of fluorine-functionalized thiosemicarbazone ligands and their corresponding cyclometallated compounds is discussed. The results are in agreement with previous characterization by IR spectroscopy, ¹H and ¹⁹F NMR spectroscopy.

Suitable crystals were obtained for a thiosemicarbazone ligand and a cyclometallated compound. The crystal structure analyses are in accordance with the proposed structures: a thiosemicarbazone ligand fluorine-functionalized and a cyclometallated compound in which the thiosemicarbazone is a tridentate [C, N, S] ligand. A comparative study of bond distances and angles is shown, providing information about the coordination of the ligand to the metal center.

Keywords:

X-Ray, thiosemicarbazone, palladium, cyclometallation, fluorine

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1. Introduction

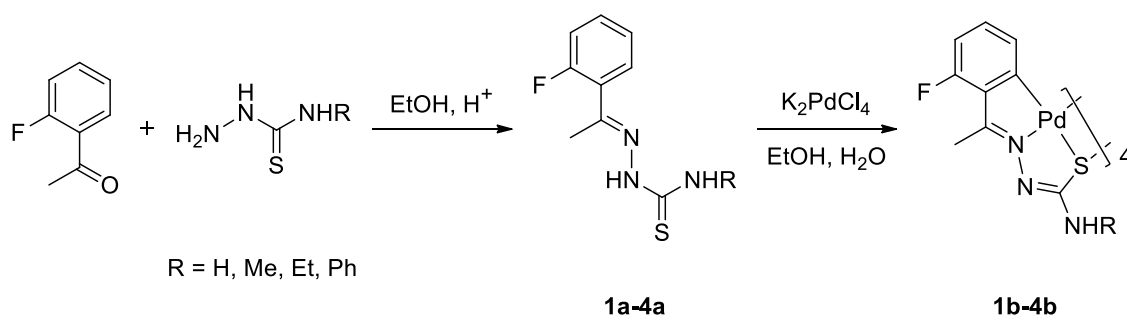
In this work fluorine-thiosemicarbazone ligands are used to synthesize cyclometallated palladium compounds. The fluorine functionality increases their solubility, that is one of the main issues when dealing with this type of species[1,2].

The ligands are widely used in coordination and organometallic chemistry due to the number of different heteroatoms and their versatile coordination to metal centers[3], generating a wide range of compounds. In addition, these ligands are relevant in the biological field; the free ligands themselves possess a certain degree of biological activity[4,5], usually enhanced by coordination to one or more metal atoms[6,7].

Furthermore, cyclometallated compounds are a large family of complexes which contain a chelate ring comprising a coordinated heteroatom-metal bond a σ carbon-metal bond[8,9]. The metalated atom may be an aromatic[10,11] or alkenyl[12] sp² carbon or a sp³ carbon[13]. Many of these compounds are used in catalysis, and they give really good results in cross-coupling reactions with carbon-carbon bond formation (Suzuki-Miyaura[14,15] and Mizoroki-Heck[16,17]) and carbon-nitrogen bond formation (Buchwald-Hartwig[18,19]). Likewise, their biological activity has been shown to be quite high and it has been tested for a huge variety of metals and ligands[20-23].

2. Results and discussion

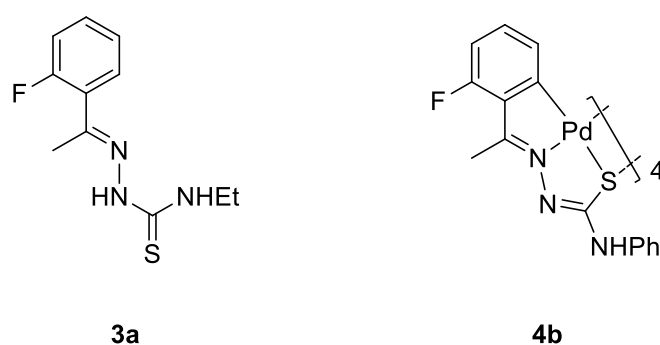
X-Ray diffraction study of a thiosemicarbazone ligand and the ensuing palladium cyclometallated product is discussed (see Scheme 1). The results agree with a previous characterization by IR, ^1H NMR and ^{19}F NMR spectroscopies[24]. In addition, a structural study and comparison between the two structures was carried out.



Scheme 1. Reaction sequence leading to the synthesis of cyclometallated complexes containing fluor atoms

2.1. X-Ray diffraction study

Suitable crystals for compounds were obtained by slow evaporation of a DMSO–acetone (**3a**) or chloroform (**4b**) solutions, shown in Scheme 2. The X-Ray diffraction study showed the proposed structures. The structures were solved by direct methods and refined by full matrix least squares on F^2 . Hydrogen atoms were included in calculated positions. Refinement converged at a final $R_1 = 0.0302$ and $wR_2 = 0.0712$ (compound **3a**) and $R_1 = 0.0299$ and $wR_2 = 0.0625$ (compound **4b**) with allowance for thermal anisotropy of all non-hydrogen atoms. The structure solution and refinement were carried out using the program OLEX2[25].



Scheme 2. Compounds **3a** and **4b** were studied by X-Ray diffraction study

2.1.1. Compound 3a

Compound **3a** crystallizes in monoclinic system, $P2_1/n$ space group. The unit cell contains four molecules of thiosemicarbazone (see Figure 1).

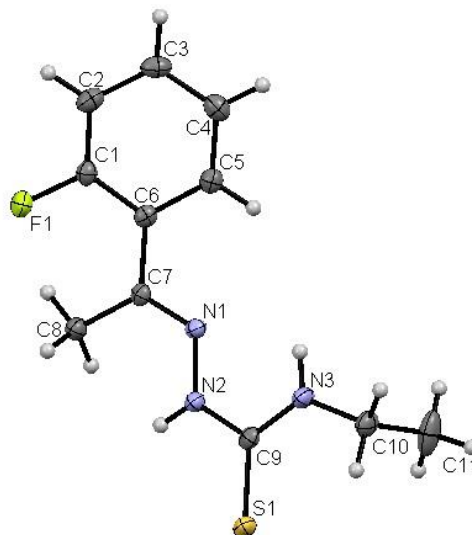


Figure 1. Molecular structure of the ligand **3a**. Thermal ellipsoids are shown at 50% probability level

The structure shows the thiosemicarbazone in the thionic form, with *E* conformation[26], probably due to the intramolecular interaction (2.179 Å) between the imine nitrogen and the thioamide proton, shown in Figure 2a.

Also, intramolecular interaction (2.378 Å) between the fluorine atom and the imine methyl group is observed. Consequently, in Figure 2b, the aromatic ring is turned away from the thiosemicarbazone plane, with a 34.34° deviation.

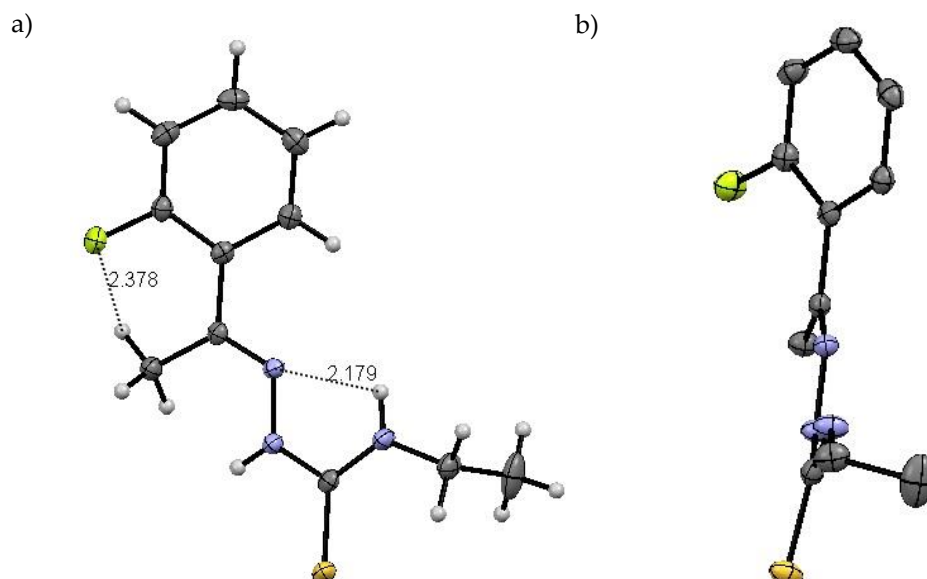


Figure 2. a) Intramolecular interactions between F(1)-H and N(1)-H. b) Deviation of the phenyl ring from the thiosemicarbazone plane

2.1.2. Compound 4b

Compound **4b** crystallizes in triclinic system, P-1 space group. The unit cell contains two cyclometallated molecules and eight chloroform molecules.

The thiosemicarbazone acts as tridentate ligand (see Figure 3a), generating two five-membered chelate rings, and the compound shows a tetranuclear structure, in Figure 3b, with the ligands assuming an antiparallel arrangement and being perpendicular to each other.

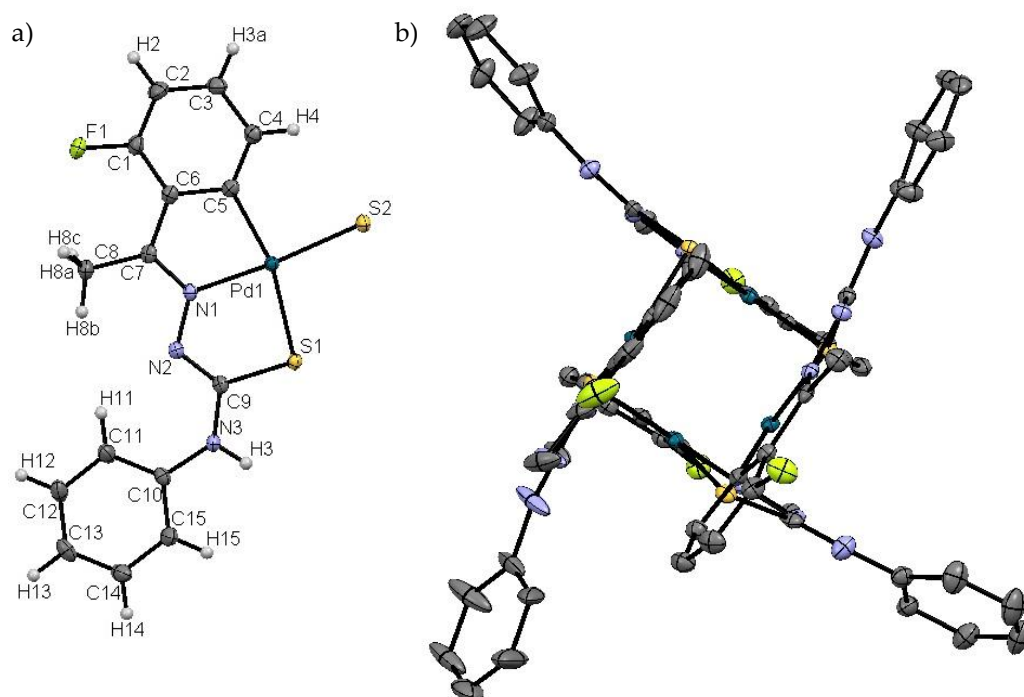


Figure 3. a) Molecular structure of a monomer of 4b. Thermal ellipsoids are shown at 50% probability level. b) Molecular structure of 4b, with antiparallel and perpendicular arrangement of each thiosemicarbazone

In one of the monomers, the palladium center (Pd1) is surrounded by the ortho aromatic carbon of the phenyl ring (C5), the imine nitrogen (N1) and two sulfur atoms (S1 and S2), exhibiting two different bonds at palladium: Pd–S_{chelate} (S1) and Pd–S_{bridging} (S2).

As in the thiosemicarbazone ligand, an intramolecular interaction *ca.* 2.5 Å (Figure 4) is observed between the fluorine atom and the imine methyl group. In this case, the aromatic ring is unable to rotate due to metallation, so the methyl group displays an eclipsed conformation.

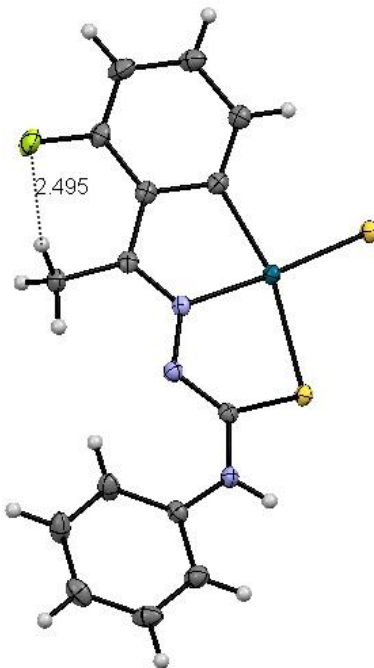


Figure 4. Intramolecular interaction of F(1)-H in compound 4b

2.1.3. Comparison between bond distances (Å) and angles (°)

A comparative study of bond distances (Table 1) and angles (Table 2) between the thiosemicarbazone ligand **3a** and the cyclometallated compound **4b** was carried out.

Table 1. Comparison between bonds in compounds 3a and 4b

Bond	3a / Å	4b / Å
N(1)-C(7)	1.2870(18)	1.304(3)
C(9)-N(2)	1.3677(18)	1.297(3)
C(9)-S(1)	1.6816(14)	1.807(3)
C(9)-N(3)	1.3297(18)	1.361(3)
C(5)-C(6)	1.399(2)	1.424(4)

The N(1)-C(7) and C(5)-C(6) bonds are somewhat longer in the cyclometallated compound due to back-bonding of the palladium metal to the N(1) and the C(5) atoms, respectively.

The C(9)-N(2) and C(9)-S(1) bond differences are because of metallation, since it occurs in the thiolic form of the thiosemicarbazone, tautomerization of the C(9)=S(1) double bond is thus needed.

The C(9)-N(3) bond is slightly longer, probably for the tautomerization of the thionic bond and the coordination of the sulfur atom.

Table 2. Comparison between angles in compounds 3a and 4b

Angle	3a /°	4b /°
C(5)-C(6)-C(7)	121.14(12)	116.3(2)
N(1)-N(2)-C(9)	117.90(11)	114.1(2)
N(2)-C(9)-S(1)	119.57(11)	125.16(19)
N(2)-C(9)-N(3)	115.62(12)	120.6(2)
N(3)-C(9)-S(1)	124.81(11)	114.08(18)

The N(2)-C(9)-S(1), N(2)-C(9)-N(3) and N(3)-C(9)-S(1) angles changes on going to the cyclometallated compound due to the tautomerization and the coordination of the sulfur atom to palladium.

The C(5)-C(6)-C(7) and N(1)-N(2)-C(9) are smaller due to the formation of the five-membered chelate ring upon cyclometallation.

2.1.4. Palladium bonds and angles in compound 4b

Table 3. Distance bonds (Å) and angles (°) around palladium metal center

Bond	/Å	Angle	/°
Pd(1)-N(1)	1.996(2)	N(1)-Pd(1)-C(5)	81.24(9)
Pd(1)-C(5)	2.003(2)	N(1)-Pd(1)-S(1)	83.31(6)
Pd(1)-S(2)	2.3060(6)	C(5)-Pd(1)-S(2)	94.39(8)
Pd(1)-S(1)	2.3729(6)	S(2)-Pd(1)-S(1)	100.81(2)
		N(1)-Pd(1)-S(2)	174.68(6)
		C(5)-Pd(1)-S(1)	164.07(8)

The bond distances at palladium are in accordance with those found in similar complexes[27-29], and the angles with a square-planar geometry of the metal center (see Table 3).

3. Conclusions

- X-Ray structural analysis was carried out for a thiosemicarbazone ligand and its cyclometallated palladium derivative.
- A comparative study allowed to determine the variations in bond distances and angles in the structure of the ligand after the cyclometallation process.
- The metal atom displays the typical square-planar geometry for palladium.

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Conflicts of Interest: “The authors declare no conflict of interest”.

Appendix A

Table A1. Crystal data and structure refinement for 3a

Identification code	3a	
Empirical formula	C ₁₁ H ₁₄ FN ₃ S	
Formula weight	239.31	
Temperature	100(2) K	
Wavelength	0.71073 Å	
Crystal system	Monoclinic	
Space group	P2 ₁ /n	
Unit cell dimensions	a = 5.8663(2) Å	α = 90°.
	b = 19.5573(6) Å	β = 105.0047(10)°.
	c = 10.5485(3) Å	γ = 90°.
Volume	1168.96(6) Å ³	
Z	4	
Density (calculated)	1.360 Mg/m ³	
Absorption coefficient	0.266 mm ⁻¹	
F(000)	504	
Crystal size	0.240 × 0.127 × 0.119 mm ³	
Theta range for data collection	2.083 to 26.366°.	
Index ranges	-6 ≤ h ≤ 7, -24 ≤ k ≤ 24, -13 ≤ l ≤ 13	
Reflections collected	32894	
Independent reflections	2399 [R(int) = 0.0527]	
Completeness to theta = 25.242°	100.0 %	
Refinement method	Full-matrix least-squares on F ²	
Data / restraints / parameters	2399 / 0 / 147	
Goodness-of-fit on F ²	1.050	
Final R indices [I > 2σ(I)]	R ₁ = 0.0302, wR ₂ = 0.0712	
R indices (all data)	R ₁ = 0.0372, wR ₂ = 0.0751	
Largest diff. peak and hole	0.246 and -0.266 e·Å ⁻³	

Table A2. Crystal data and structure refinement for 4b

Identification code	4b	
Empirical formula	C ₆₄ H ₅₂ Cl ₁₂ F ₄ N ₁₂ Pd ₄ S ₄	
Formula weight	2044.41	
Temperature	100(2) K	
Wavelength	0.71073 Å	
Crystal system	Triclinic	
Space group	P-1	
Unit cell dimensions	a = 13.6814(4) Å	α = 87.1620(10)°.
	b = 15.1512(4) Å	β = 79.4790(10)°.
	c = 19.9092(5) Å	γ = 64.1110(10)°.
Volume	3648.25(17) Å ³	
Z	2	
Density (calculated)	1.861 Mg/m ³	
Absorption coefficient	1.585 mm ⁻¹	
F(000)	2016	
Crystal size	0.180 × 0.160 × 0.070 mm ³	
Theta range for data collection	2.082 to 28.342°.	
Index ranges	-18 ≤ h ≤ 18, -20 ≤ k ≤ 20, -26 ≤ l ≤ 26	
Reflections collected	112138	
Independent reflections	18195 [R(int) = 0.0390]	

Completeness to theta = 25.242°	99.9 %
Refinement method	Full-matrix least-squares on F^2
Data / restraints / parameters	18195 / 0 / 1020
Goodness-of-fit on F^2	1.049
Final R indices [$I > 2\sigma(I)$]	$R_1 = 0.0299$, $wR_2 = 0.0625$
R indices (all data)	$R_1 = 0.0390$, $wR_2 = 0.0666$
Largest diff. peak and hole	2.352 and $-1.613 \text{ e} \cdot \text{Å}^{-3}$

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