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Structural study of a Pd-Fe hetero-trinuclear compound †

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Abstract: Cyclometallated compounds, specifically cyclopalladates, have been synthesized for years. In this work, we describe a new family of compounds in which an iron core has been introduced in addition to Pd. This novel characteristic provides interesting properties to these compounds, such as the possibility of undergoing reduction-oxidation processes due to the versatility of the iron nucleus. XRD study of the resulting crystalline structure allows explaining the compound behavior.

Keywords: Crystal-structure; Metallic; Voltammetry

1. Introduction

Thiosemicarbazones are a type of ligands obtained by condensation of the carbonyl group of an aldehyde or ketone and the amino group of a thiosemicarbazide, as is shown in Figure 1.

Figure 1. General retrosynthetic scheme of thiosemicarbazones.

These types of compounds are well-known antibacterial or antifungal agents: for example, studies for the treatment of tuberculosis were carried out in the fifties. Nowadays, studies are more focused on the synthesis of new derivatives for their use as antitumorals [1].

This work presents the synthesis and study of thiosemicarbazone family derivatives with two methoxy substituents as can be seen in Figure 2.

Figure 2. General structure of compounds **1-4**.

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2. Materials and Methods

2.1. Ligand synthesis procedure

The appropriate amount of thiosemicarbazide (5,50 mmol) was dissolved in 40 cm³ of distilled water and a small amount of hydrochloric acid (0,50 cm³) in a 100 mL round bottom flask. The addition of hydrochloric acid does not only enable solubilization but also favors the condensation reaction (Figure 3). Once the thiosemicarbazide had been completely solubilized, the corresponding ketone (1 Eq, 5,50 mmol, see Table 1) was added and the mixture stirred at room temperature for 8 hours.

In all cases, an off-white solid that could be separated by filtration appeared. This solid was thoroughly washed with water and then dried under vacuum to afford the pure thiosemicarbazone.

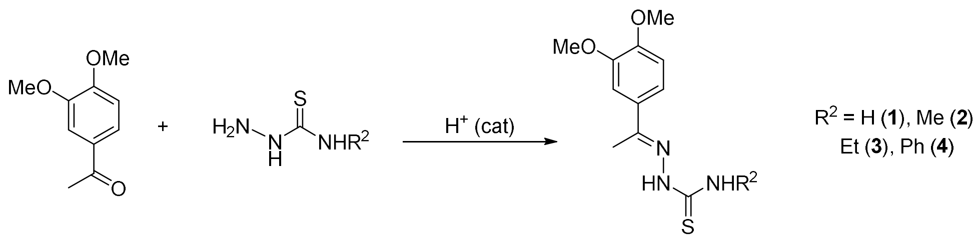

Figure 3. General synthesis scheme for ligands **1-4**.

Table 1. Amounts of reagents used in the synthesis of the thiosemicarbazone ligands (**1-4**).

Compound	Ketone (mmol)	Thiosemicarbazide (mmol)	R^2
1	5,5	5,5	H
2	5,5	5,5	Me
3	5,5	5,5	Et
4	5,5	5,5	Ph

2.2. Syntheis of palladium organometallic compounds

In a 100 mL round bottom flask, 200 mg (0,61 mmol) of potassium tetrachloropalladate were dissolved in 6 cm³ of distilled water and 40 cm³ of ethanol. The corresponding amount of ligand (1,1 Eq, 0,67 mmol, see Table 2) was added after a yellow suspension appeared, and the resulting mixture was stirred at room temperature for 24 hours.

In each case, the reaction product was obtained as a fine solid in suspension, which was separated by centrifugation, decantated, and vacuum dried to afford the pure compound (Figure 4). Said solids, regardless of R², have varied colors, ranging from yellow to orange.

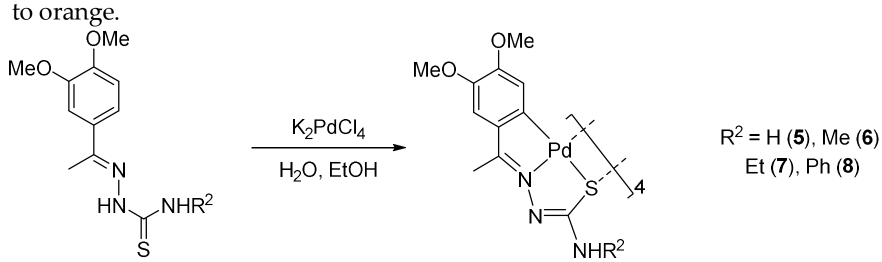

Figure 4. General synthetic scheme for the organometallic compounds (**5-8**).

Table 2. Amounts of reagents used in the synthesis of the organometallic compounds (**5-8**)

Compound	Ligand amount	R^2
5	**1** – 0,67mmol	H
6	**2** - 0,67mmol	Me
7	**3** - 0,67mmol	Et
8	**4** - 0,67mmol	Ph

2.3. Synthesis of Pd-Fe hetero-trimetallic compounds

For the synthesis of the compounds bearing 1,1'-bis(diphenylphosphino)ferrocene (dppf), a suspension of the corresponding cyclometallated compound (20 mg) in 10 cm^3 of acetone was prepared in a Radleys tube, to which the appropriate quantity of phosphine (4 Eq, see Table 3) was added. The mixture was stirred at 50 °C for 24 hours. The reaulting products appeared as orange solids that could be filtered off, washed with the minimum amount of hexanes, and dried under vacuum.

Table 3. Amounts of reagents used in the synthesis of the organometallic compounds (**9-12**).

Compound	dppf	R^2
9	0,20mmol	H
10	0,20mmol	Me
11	0,20mmol	Et
12	0,19mmol	Ph

Due to the stoichiometry of the reaction, derivatives in which the diphosphine moiety acts as a monodentate ligand would be expected, as is shown in Figure 5. However, in all cases, the results show greater preference for bidentate bridge coordination through said phosphine (Figure 6).

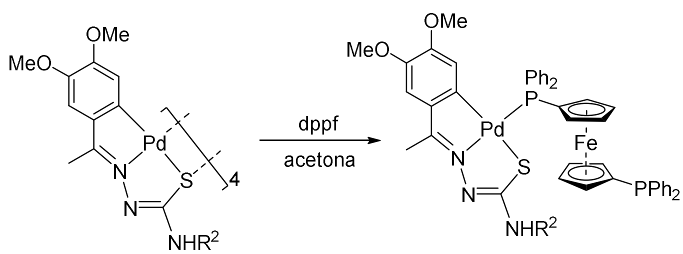

Figure 5. Expected Pd-Fe organometallic compounds.

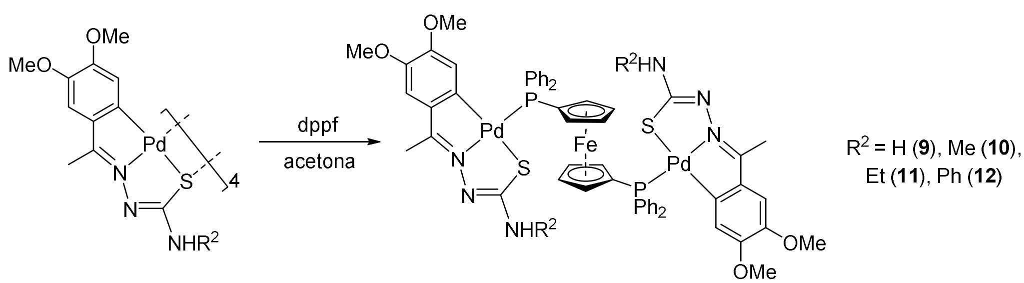

Figure 6. Obtained Pd-Fe organometallic compounds (**9-12**).

The addition of an iron nucleus to these compounds provides the possibility to them to be used for reduction-oxidation processes increasing their properties in the electrochemical field [2].

3. Results and discussion

The structural characterization of the compounds has been carried out using proton nuclear magnetic resonance. Furthermore, in the case of Pd-Fe organometallic compounds, phosphorous nuclear magnetic resonance (^{31}P-{^1H}-NMR) was required, since it provides additional information on the behavior of the phosphine.

3.1. ^{1}H and ^{31}P-{^{1}H}-NMR spectroscopy study

3.1.1. ^{1}H-NMR for ligands (**1-4**)

In all cases, the spectra of these ligands show two doublets corresponding to the H2 and H5 protons and one doublet of doublets for the H6 proton. The rest of the signals are also consistent with what would be expected for the proposed structures (Figure 7).

The data extracted from the proton nuclear magnetic resonance spectra of the ligands **1-4** are shown in Table 4.

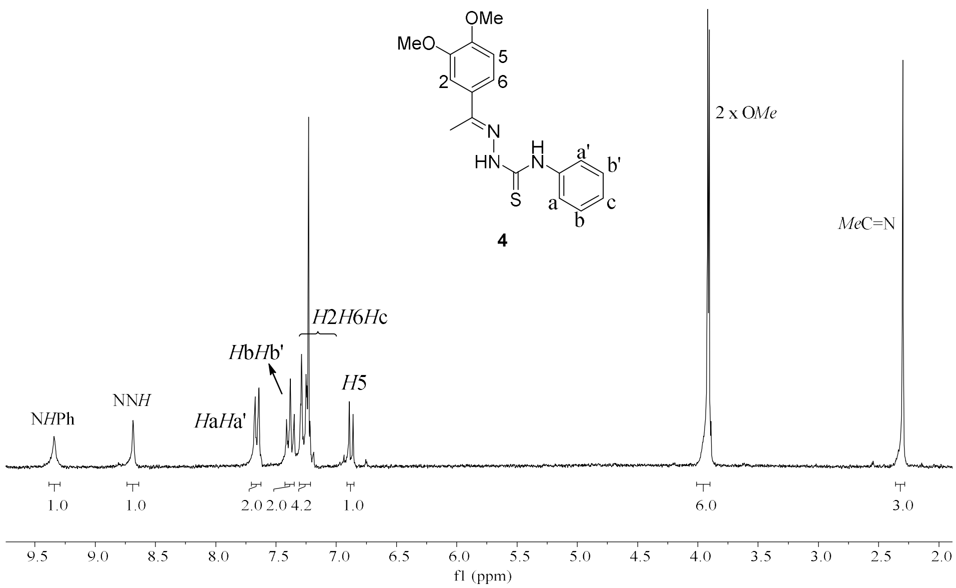

Figure 7. ^{1}H NMR spectrum (250 MHz, $CDCl_3$) of ligand **4**.

Table 4. ^{1}H NMR data of ligands **1-4**.

^{1}H NMR data	
1	^{1}H NMR (250 MHz, $CDCl_3$) δ (ppm): 8,69 (s, 1H, NN*H*); 7,31 (m, 2H, N*H*, *H*6); 7,23 (d, ^{4}J=2,1 Hz, 1H, *H*2); 6,88 (d, ^{3}J=8,3 Hz, 1H, *H*5); 6,32 (s, 1H, N*H*); 3,93 (s, 3H, O*Me*); 3,92 (s, 3H, O*Me*); 2,28 (s, 3H, *Me*C=N).
2	^{1}H NMR (250 MHz, $CDCl_3$) δ (ppm): 8,61 (s, 1H, NN*H*); 7,57 (s, 1H, N*H*Me); 7,27 (d, 1H, ^{3}J=8,7 Hz, *H*6); 7,24 (d, ^{4}J=2,1 Hz, 1H, *H*2); 6,89 (d, 1H, ^{3}J=8,7 Hz, *H*5); 3,95 (s, 3H, O*Me*); 3,93 (s, 3H, O*Me*); 3,29 (d, ^{3}J=5,6 Hz, 3H, NH*Me*); 2,26 (s, 3H, *Me*C=N).
3	^{1}H NMR (250 MHz, $CDCl_3$) δ (ppm): 8,59 (s, 1H, NN*H*); 7,54 (m, 1H, N*H*Et); 7,23 (m, 1H, *H*6); 7,21 (d, ^{4}J=2,1 Hz, 1H, *H*2); 6,87 (d, 1H, ^{3}J=8,8 Hz, *H*5); 3,92 (s, 3H, O*Me*); 3,91 (s, 3H, O*Me*); 3,76 (m, 2H, $NHCH_2CH_3$); 2,25 (s, 3H, *Me*C=N); 1,29 (t, ^{3}J=7,3 Hz, 3H, $NHCH_2CH_3$).
4	^{1}H NMR (250 MHz, $CDCl_3$) δ (ppm): 9,34 (s, 1H, N*H*Ph); 8,69 (s, 1H, NN*H*); 7,66 (d, ^{3}J=7,8 Hz, 2H, *H*a*H*a'); 7,38 (t, ^{3}J=7,8 Hz, 2H, *H*b*H*b'); 7,26 (m, 3H, *H*2*H*6*H*c); 6,88 (d, ^{3}J=8,3 Hz, 1H, *H*5); 3,92 (s, 3H, O*Me*); 3,91 (s, 3H, O*Me*); 2,30 (s, 3H, *Me*C=N).

3.1.2. ^{1}H-NMR for palladium organometallic compounds (**5-8**).

As metallation of the carbon of the aromatic ring occurs, the complexity of the signals observed in the magnetic resonance spectra is reduced: two singlets are registered in the aromatic zone and the signal that can be observed at lower field is the one corresponding to the H5 proton (Figure 8).

The data obtained from the proton magnetic resonance spectra for palladium organometallic compounds **5-8** are shown in Table 5.

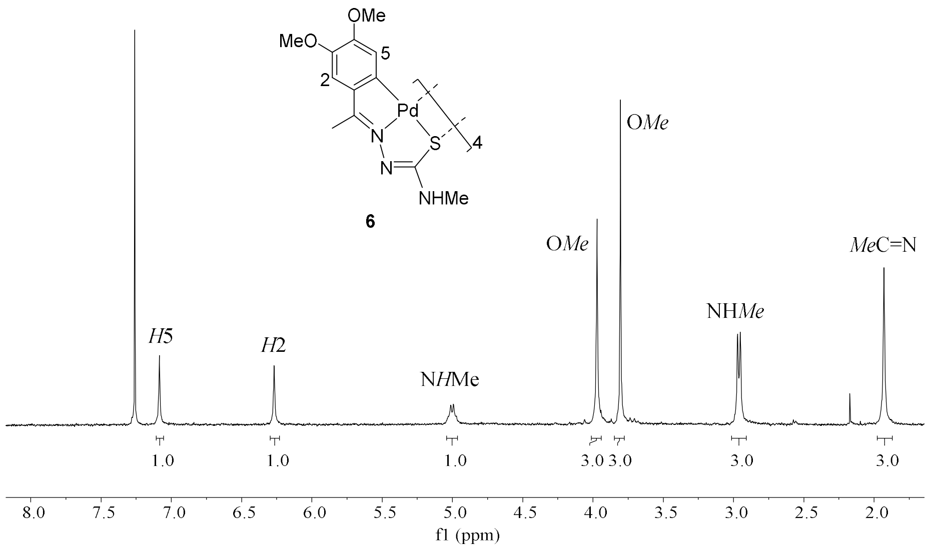

Figure 8. ^{1}H NMR spectrum (250 MHz, $CDCl_3$) of palladium organometallic compound **6**.

Table 5. ^{1}H NMR data of palladium organometallic compounds (**5-8**).

^{1}H NMR data	
5	^{1}H NMR (250 MHz, $CDCl_3$) δ (ppm): 7,04 (s, 1H, *H*5); 6,23 (s, 1H, *H*2); 5,22 (s, 2H, N*H*$_2$); 3,95 (s, 3H, O*Me*); 3,78 (s, 3H, O*Me*); 1,92 (s, 3H, *Me*C=N).
6	^{1}H NMR (250 MHz, $CDCl_3$) δ (ppm): 7,09 (s, 1H, *H*5); 6,27 (s, 1H, *H*2); 5,00 (m, 1H, N*H*Me); 3,97 (s, 3H, O*Me*); 3,81 (s, 3H, O*Me*); 2,96 (d, ^{3}J=4,9 Hz, 3H, NH*Me*); 1,93 (s, 3H, *Me*C=N).
7	^{1}H NMR (250 MHz, $CDCl_3$) δ (ppm): 7,08 (s, 1H, *H*5); 6,26 (s, 1H, *H*2); 5,03 (m, 1H, N*H*CH_2CH_3); 3,97 (s, 3H, O*Me*); 3,81 (s, 3H, O*Me*); 3,43 (m, 2H, NHC*H*$_2$$CH_3$); 1,95 (s, 3H, *Me*C=N); 1,22 (t, 3H, ^{3}J=7,2 Hz, NHCH_2C*H*$_3$).
8	^{1}H NMR (250 MHz, $CDCl_3$) δ (ppm): 7,52 (d, ^{3}J=7,6 Hz, 2H, *H*a*H*a'); 7,27 (t, ^{3}J=7,6 Hz, 2H, *H*b*H*b'); 7,01 (t, ^{3}J=7,6 Hz, 1H, *H*c); 7,00 (s, 1H, N*H*Ph); 6,94 (s, 1H, *H*5), 6,41 (s, 1H, *H*2); 3,86 (s, 3H, O*Me*); 3,51 (s, 3H, O*Me*); 1,91 (s, 3H, *Me*C=N).

3.1.3. ^{1}H-NMR and ^{31}P-{^{1}H}-NMR for Pd-Fe organometallic compounds (**9-12**).

The signal appearing at lower field is, in all cases, a singlet that corresponds to the H2 proton. When the coordination of the phosphorus nucleus occurs, the signal of proton H5 appears as a doublet because it is coupled with this nucleus. This signal (H5) and the one corresponding to the methoxy group at position four are shifted towards high-field with respect to the compound from which they derive (*vide supra*). This effect can be justified with the structural data obtained after crystal structure resolution of the compound.

The signals corresponding to the coordinated phosphine are observed in two zones: the protons of the phenyl rings appear in the aromatic zone, between 7.3 and 7.6 ppm, and the protons of the cyclopentadienyl rings appear between 4.2 and 5.1 ppm. The protons located in *ortho* with respect to the phosphorus atom are those appearing at lower field (Figure 9).

Analysis of the phosphorus NMR spectra indicates that both nuclei are equivalent since a single singlet signal can be observed; also, the position in which they appear, ca. 29 ppm, shifted to the low field with respect to the position where the free phosphine signal appears (-18.8 ppm), indicates that they are coordinated to the metal center (Figure 10).

This fact, together with the presence of a single signal for the different groups of the dinuclear compound in the proton NMR spectra, indicates that the compounds are symmetric in solution.

The data inferred from the signals of the proton and phosphorus NMR spectra of the Pd-Fe organometallic compounds **9-12** are shown in Table 6.

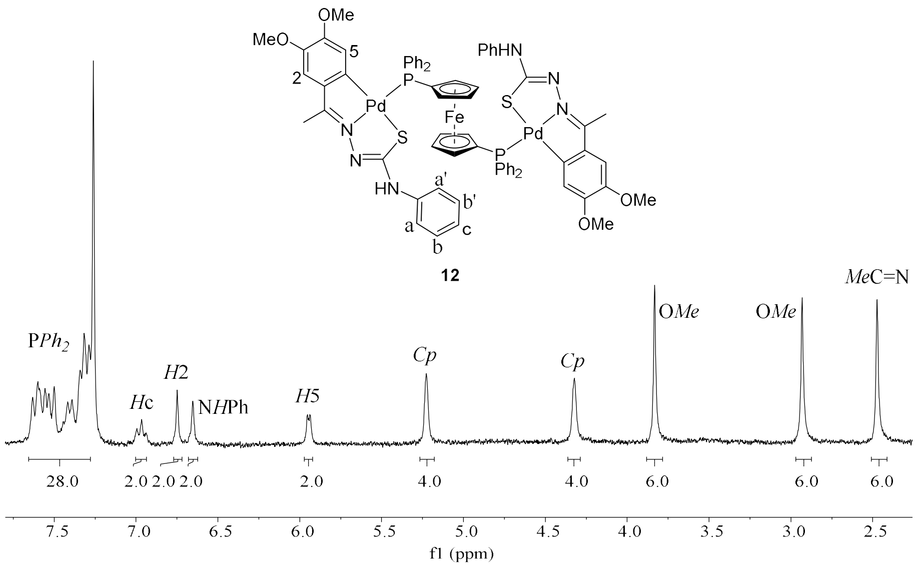

Figure 9. ^{1}H NMR spectrum (400 MHz, $CDCl_3$) of Pd-Fe organometallic compound **12**

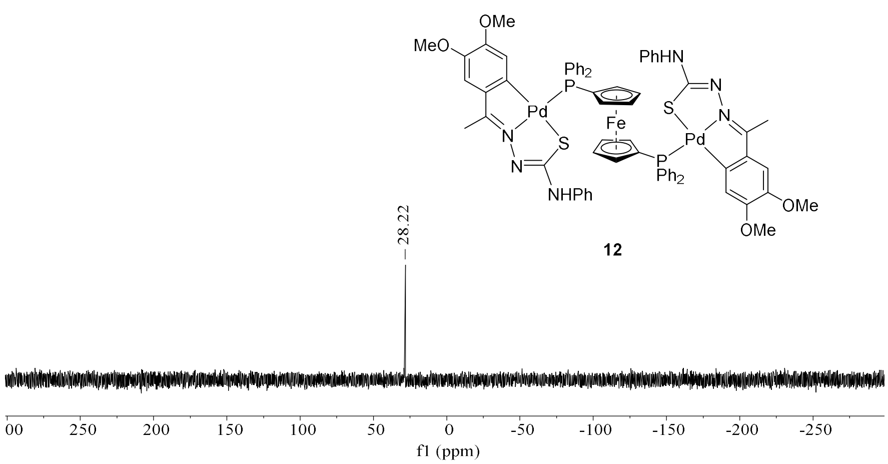

Figure 10. ^{31}P-{^{1}H}-NMR spectrum (400 MHz, $CDCl_3$) of Pd-Fe organometallic compound **12**.

Table 6. ^{1}H NMR data of Pd-Fe organometallic compounds (**9-12**).

^{1}H NMR data	
9	^{1}H NMR (400 MHz, dmso-d$_6$) δ (ppm): 7,48 (m, 12H, *m*–P*Ph*$_2$, *p*–P*Ph*$_2$); 7,37 (m, 8H, *o*–P*Ph*$_2$); 6,74 (s, 2H, *H*2); 6,55 (s, 4H, 2xN*H*$_2$); 5,77 (d, $^{4}J_{HP}$=4,1 Hz, 2H, *H*5); 5,11 (s, 4H, *Cp*); 4,19 (s, 4H, *Cp*); 3,67 (s, 6H, 2xO*Me*); 2,80 (s, 6H, 2xO*Me*); 2,27 (s, 6H, 2x*Me*C=N). ^{31}P–{^{1}H} NMR (400 MHz, dmso-d$_6$) δ (ppm): 32,45 (s).
10	^{1}H NMR (400 MHz, $CDCl_3$) δ (ppm): 7,57 (m, 8H, *m*–P*Ph*$_2$); 7,39 (t, ^{3}J=7,0 Hz, 4H, *p*–P*Ph*$_2$); 7,30 (m, 8H, *o*–P*Ph*$_2$); 6,69 (s, 2H, *H*2); 5,91 (d, $^{4}J_{HP}$=4,3 Hz, 2H, *H*5); 5,17 (s, 4H, *Cp*); 4,71 (s, 2H, 2xN*H*Me); 4,28 (s, 4H, *Cp*); 3,81 (s, 6H,

	2xO*Me*); 2,97 (d, ^{3}J=4,9 Hz, 6H, 2xNH*Me*); 2,92 (s, 6H, 2xO*Me*); 2,40 (s, 6H, 2x*Me*C=N). ^{31}P–{^{1}H} NMR (400 MHz, $CDCl_3$) δ (ppm): 28,25 (s).
11	^{1}H NMR (400 MHz, $CDCl_3$) δ (ppm): 7,43 (m, 20H, P*Ph*$_2$); 6,66 (s, 2H, *H*2); 5,88 (s, 2H, *H*5); 5,15 (s, 4H, *Cp*); 4,68 (s, 2H, 2xN*H*CH_2CH_3); 4,25 (s, 4H, *Cp*); 3,78 (s, 6H, O*me*); 3,37 (m, 4H, 2xNHC*H*$_2$$CH_3$); 2,90 (s, 6H, 2xO*Me*); 2,35 (s, 6H, 2x*Me*C=N); 1,14 (t, 6H, ^{3}J=6,8 Hz, 2xNHCH_2C*H*$_3$). ^{31}P–{^{1}H} NMR (400 MHz, $CDCl_3$) δ (ppm): 28,25 (s).
12	^{1}H NMR (250 MHz, $CDCl_3$) δ (ppm): 7,47 (m, 28H, P*Ph*$_2$, *H*a*H*a'*H*b*H*b'); 6,97 (t, ^{3}J=7,1 Hz, 2H, *H*c); 6,75 (s, 2H, *H*2); 6,65 (s, 2H, 2xN*H*Ph); 5,95 (d, $^{4}J_{HP}$=3,6 Hz, 2H, *H*5); 5,23 (s, 4H, *Cp*); 4,32 (s, 4H, *Cp*); 3,83 (s, 6H, 2xO*Me*); 2,93 (s, 6H, 2xO*Me*); 2,47 (s, 6H, 2x*Me*C=N). ^{31}P–{^{1}H} NMR (400 MHz, $CDCl_3$) δ (ppm): 28,22 (s).

3.2. X-Ray spectroscopy discussion for compound ***10***

Crystals suitable for single crystal X-ray diffraction of the compound cyclometallated with phosphine ferrocene **10** were obtained by slow evaporation of a solution in acetone.

The compound crystallizes in the triclinic system, in the space group P–1. The asymmetric unit is made up of a compound molecule and an acetone molecule (Figure 11). The two metalated ligand units lie in two almost parallel planes (with an angle between them of 2.82 °).

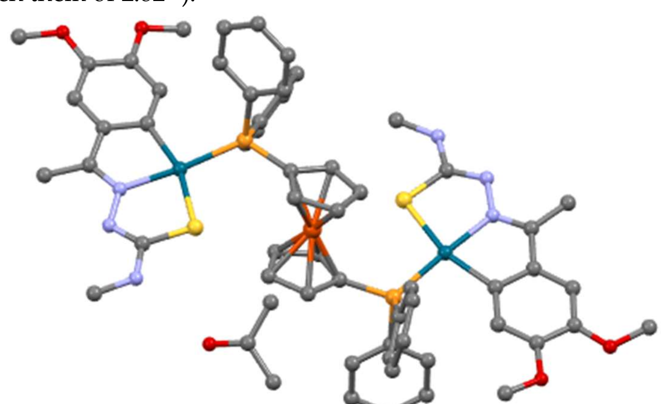

Figure 11. Crystal structure of compound **10** using a ball-and-stick model with standard CPK colors.

The distance of the imine bond C7–N1 (1,295 Å) is shorter than in the case of the cyclometallated precursor, which agrees with the results observed in the displacement of the tension vibration bands υ (C=N).

It can also be observed how one of the phenyl rings of phosphine is perpendicular to the position where the H5 proton and one of the methoxy groups meet, which explains the effects observed in the NMR spectra on these signals (Figure 12).

On the other hand, cyclopentadienyl rings are placed in a nearly eclipsed conformation despite being in a higher energy arrangement.

The data obtained from the analysis of the X-ray diffraction of the Pd-Fe organometallic compound **10** are shown in Table 7.

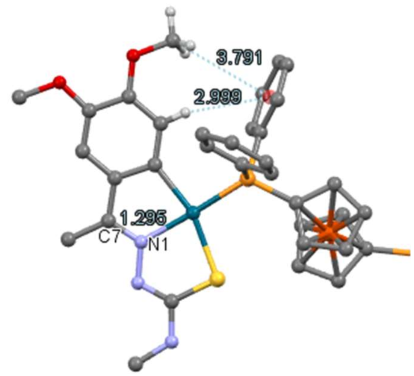

Figure 12. Interaction between Cp ring, H5 and the methoxy group.

Table 7. Crystallographic data of the Pd-Fe organometallic compound **10**.

Compound	**10**
Empirical formula	$C_{58}H_{58}FeN_6O_4P_2Pd_2S_2 \cdot C_3H_6O$
Formula weight	1355,89
Temperature	100 (2) K
Wavelength	0,71073 Å
Crystal system	Triclinic
Space group	P−1
Unit cell dimensions	a = 11,148 (5) Å ; α = 86,251 (5)° b = 12,652 (5) Å ; β = 84,791 (5)° c = 20,736 (5) Å ; γ = 78,360 (5)°
Volume	2849 (18) $Å^3$
Z	2
Calculated density	1,580 Mg/m^3
Absorption coefficient	1,061 mm^{-1}
F(000)	1384
Crystal size	0,22 x 0,15 x 0,04 mm^3
Theta range for data collection	0,987–26,373°
Limiting indexes	$-13 \le h \le 13$ $-15 \le k \le 15$ $-25 \le l \le 25$
Reflections collected	87669
Reflections unique	11617 [$R(int)$=0,0444]
Data / restraints / parameters	11617 / 0 / 888
Goodness-of-fit on F^2	1,028
Final R indexes [I>2sigma(I)]	R_1=0,0273; wR_2=0,0588
R indexes (all data)	R_1=0,0405; wR_2=0,0632
Largest diff. peak and hole	0,675 y -0,662 e/$Å^3$

4. Conclusions

The reaction of cyclometallated compounds with phosphine dppf gives rise to heterotrinuclear cyclometallated compounds that contain two metallated thiosemicarbazone ligand units separated by diphosphine.

These compounds will be tested as possible sensors using cyclic voltammetry techniques.

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Conflicts of Interest: "The authors declare no conflict of interest."

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