Coordination Dynamics and Reactivity of Palladium(II) Complexes Containing the N-Thienylidene-L/D-methionine Methyl Ester Ligand


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Coordination Dynamics and Reactivity of Palladium(II) Complexes Containing the N-Thienylidene-1/d-methionine Methyl Ester Ligand

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Metathesis reactions of the N-thienylidene-1/d-methionine methyl ester ligand (th-metMe) with suitable palladium starting complexes afforded coordination complexes of the type PdX2(th-metMe), Pd(Me)(th-metMe), and [Pd(Me)(th-metMe)(L′′′)]2Cl2 (X = Cl, Br, I; and L′′′ = MeCN, pyridine, picoline, lutidine) which were studied by NMR with respect to the fluxional behavior of the diastereomeric PdNS six-membered ring chelates. The structure of PdCl2(th-metMe) in the solid state (a = 13.318(5) Å, b = 11.365(2) Å, c = 13.579(5) Å, β = 96.66(4)°) showed a square planar coordination complex in which the ligand is chelating via the imine nitrogen (Pd−N = 2.030(7) Å) and the methionine sulfur donor atom (Pd−S = 2.283(2) Å). The square planar geometry is completed by the chlorides (Pd−Cl′′ = 2.275(3) Å (trans to the imine nitrogen) and Pd−Cl′′ = 2.322(2) Å (trans to the sulfur donor)). The dimeric [PdCl(L′′′)]2 complex (L′′′ = anionic α-methoxybenzylamine, α-(2-thienylmethylidene)amine, α′′-(methylthio)ethane) was formed by C−H activation of the chiral carbon atom of the α-amino acid moiety. The structure determination (a = 8.1887(7) Å, b = 20.5072(2) Å, c = 34.0793(7) Å, β = 91.220(7)°) revealed two stretched out ligands of which one is coordinating to Pd(1) via the methionine sulfur donor (2.268(2) Å) and α-bonded via the stereogenic chiral carbon atom (2.068(6)) and to Pd(2) via the imine nitrogen (2.074(5) Å). The second ligand coordinates to Pd(1) via the imine donor (2.074(5) Å) and to Pd(2) via the methionine sulfur (2.276(1)) and the former stereogenic carbon atom (2.060(6)). Both square planar coordination sites are occupied by the chlorides which are positioned trans to the carbon atom (2.390(2) and 2.412(2) Å for Cl(1A) and Cl(2A)). Complexes of the type [PdX(C(O)Me)(th-metMe)] and [Pd(C(O)Me)(L′′′)(th-metMe)](O2ScF3) were obtained by reaction of CO with the corresponding methyl complexes. The rates of CO insertion into the methyl−palladium bond were investigated, and it was found that the rate decreases in the order [Pd(Me)(th-metMe)(CF3SO3)] > [Pd(Me)(th-metMe)] > [Pd(Me)(Br)(th-metMe)] > [Pd(Me)(th-metMe)(MeCN)](CF3SO3) > [Pd(Me)(th-metMe)(2,6-lutidine)](CF3SO3) > [Pd(Me)(Cl)(th-metMe)] > [Pd(Me)(th-metMe)(pyridine)](CF3SO3).

Introduction

In our laboratory the N-[N-(5-methyl-2-thienyl)methylidene]-l-methionyl]histamine ligand (Figure 1) was designed in order to mimic the active site of plastocyanine.1 In the solid state this hemilabile ligand shows a polymeric structure which is formed by inter- and intramolecular hydrogen bonds.2 The ethyl methyl sulfide arm connected to the central methionine atom is stretched out and a helix geometry is formed. Upon coordination to a cationic silver(I) or copper(I) nucleus, again a helix geometry is created as each of the hemilabile ligand molecules bind to three metal ions while each metal center interacts with a suitable coordination site of three different

Figure 1. The th-met and th-th-metMe ligands.

hemilabile ligands. The geometry of the ligand backbone in the complex is only slightly changed when compared to the structure in the free ligand; this means that the tetrahedral geometry of the coordination site is mainly ligand controlled.3 This interesting feature initiated our interest in the coordination behavior of this ligand toward d8 metal centers, which should force the ligand to assume a different configuration, because of the square planar geometry of the metal site. In order to gain understanding of the coordination properties of a potentially tetradentate ligand, the coordination behavior of a

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4 Debye Institute, Universiteit Utrecht.
5 Abstract published in Advance ACS Abstracts, September 1, 1996.
Table 1. Crystal Data for 1 and 12

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<th>1</th>
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<tr>
<td>β (deg)</td>
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<td>91.22(7)</td>
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<td>1.5418 (graphite monochromated)</td>
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<td>R²</td>
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<td>0.042 (for 7941 F₀ &gt; 4σ(F₀))</td>
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<tr>
<td>R₂ (w)</td>
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*a R = ∑||F₀|| - |Fₐ|/∑|F₀|. b Rw = (∑|w[(|F₀| - |Fₐ|)]²/∑|w(F₀)|)⁰.⁵. c An ε 20 scan. A total of 3461 unique reflections were measured within the ranges 0 ≤ h ≤ 15, −13 ≤ k ≤ 0, and −15 ≤ l ≤ 15; 2547 were above the significance level of 2.5σ(0). The maximum value of (sin θ/λ) was 0.59 Å⁻¹. Unit-cell parameters were refined by a least-squares fitting procedure using 23 reflections with 72 < 2θ < 80°. Corrections for Lorentz and polarization effects were applied. The structure was solved by direct methods using the program SIMPlec.⁹ After isotropic refinement of the model, a AF synthesis revealed four peaks which were interpreted as deuterochloroform, one of the solvents used during the recrystallization. The hydrogens were calculated. Block-diagonal least-squares refinement on F, anisotropic for the non-hydrogen atoms and isotropic for the hydrogen atoms, restraining the latter in such a way that the distances to their carrier atoms remained within 1.0(3) Å, converged to R = 0.049, R₁ = 0.053, and (Δw)ₘₐₓ = 0.70. A weighting scheme w = (5.02 + F₀ + 0.029F₀⁻¹)⁻¹ was used. An empirical absorption correction¹⁰ was applied, with coefficients in the range 0.74 – 1.50. A final difference Fourier map revealed a residual electron density between −1.1 and +0.8 e Å⁻³. Scattering factors were taken from Cromer and Mann.¹¹ The anomalous dispersion of palladium and chlorine was taken into account. All calculations were performed with XTAŁ3.0,¹² unless stated otherwise. The crystal data are presented in Table 1, while the positional parameters are given in the Supporting Information.

Crystal Structure Determination of 5a-c. Brown, blade-shaped crystals suitable for X-ray structure determination were mounted on a Lindemann glass capillary and transferred into a cold nitrogen stream on an Enraf-Nonius CAD-4 diffractometer on a rotating anode (5a and 5c) or an Enraf-Nonius CAD-4 sealed tube diffractometer at room temperature (5b). Accurate unit-cell parameters and an orientation matrix were determined by least-squares refinement of the setting angles of 25 well-centered reflections (set 4) in the ranges 11.5 < θ < 14.0°.

Materials. All reactions were carried out in an atmosphere of purified nitrogen, using standard Schlenk techniques. Solvents were dried and distilled prior to use or stored under an inert atmosphere, unless noted otherwise. Ethyl acetate and triethylamine were of PA grade, PdCl₂(COD) and PtCl₂(COD) (COD = cycloocta-1,5-diene) were synthesized according to literature procedures.² 2-Thiophene-carbaldehyde was freshly distilled before use. Silica gel for column chromatography (Kieselgel 60, 70 – 330 mesh, E. Merck) was dried and activated prior to use.

Instrumentation. ¹H, ¹³C(H), and ¹⁹F NMR spectra were recorded on Bruker AMX300 and AC100 spectrometers. Chemical shift values are in ppm relative to Me₄Si (¹H and ¹³C(H)) or CFCl₃ (¹⁹F). Coupling constants are in Hz. Solid state magic angle spinning NMR experiments were performed on a Bruker AM500 using a DOTA probe (90° pulse was 5 μs). IR spectra were recorded on a Bio-Rad spectrophotometer in the range 1000 – 2200 cm⁻¹. Elemental analyses were carried out by Dornis und Kolbe.

The degree of association of 12 was calculated from vapor pressure measurements with a Hewlett-Packard 320B osmometer in dichloromethane (instrumental error amounts to 5%).

Conductivity experiments were carried out using a Consort K720 digital conductometer.

The CO insertion rates were determined using an electronic gas buret, which consists of an Inacomm Instruments 5860E/1AB38 mass flow-meter (with a range of 0.06 – 9.00 mL/min) connected to a high-pressure 20 mL glass reaction vessel. In order to avoid CO pressure drop, a 300 cm⁻³ buffer flask was connected. Data points were sampled every 1 s and processed with TURBOKIN.⁸

Crystal Structure Determination of 1. A yellow crystal with approximate dimensions 0.20 × 0.25 × 0.35 mm was used for data collection, at room temperature, on an Enraf-Nonius CAD-4 diffractometer with graphite-monochromated Cu Kα radiation (λ = 1.5418 Å) and an 0 – 28 scan. A total of 3461 unique reflections were measured within the ranges 0 ≤ h ≤ 15, −13 ≤ k ≤ 0, and −15 ≤ l ≤ 15; 2547 were above the significance level of 2.5σ(0). The maximum value of (sin θ/λ) was 0.59 Å⁻¹. Unit-cell parameters were refined by a least-squares fitting procedure using 23 reflections with 72 < 2θ < 80°. Corrections for Lorentz and polarization effects were applied. The structure was solved by direct methods using the program SIMPlec.⁹ After isotropic refinement of the model, a AF synthesis revealed four peaks which were interpreted as deuterochloroform, one of the solvents used during the recrystallization. The hydrogens were calculated. Block-diagonal least-squares refinement on F, anisotropic for the non-hydrogen atoms and isotropic for the hydrogen atoms, restraining the latter in such a way that the distances to their carrier atoms remained within 1.0(3) Å, converged to R = 0.049, R₁ = 0.053, and (Δw)ₘₐₓ = 0.70. A weighting scheme w = (5.02 + F₀ + 0.029F₀⁻¹)⁻¹ was used. An empirical absorption correction¹⁰ was applied, with coefficients in the range 0.74 – 1.50. A final difference Fourier map revealed a residual electron density between −1.1 and +0.8 e Å⁻³. Scattering factors were taken from Cromer and Mann.¹¹ The anomalous dispersion of palladium and chlorine was taken into account. All calculations were performed with XTAŁ3.0,¹² unless stated otherwise. The crystal data are presented in Table 1, while the positional parameters are given in the Supporting Information.

Crystal Structure Determination of 5a-c. Brown, blade-shaped crystals suitable for X-ray structure determination were mounted on a Lindemann glass capillary and transferred into a cold nitrogen stream on an Enraf-Nonius CAD-4 diffractometer on a rotating anode (5a and 5c) or an Enraf-Nonius CAD-4 sealed tube diffractometer at room temperature (5b). Accurate unit-cell parameters and an orientation matrix were determined by least-squares refinement of the setting angles of 25 well-centered reflections (set 4) in the ranges 11.5 < θ < 14.0°.
7.9 \times 10^{-19} \text{ cm}^3, and 11.5 < \theta < 14.0 \times 10^{-19} \text{ cm}^3 \) for (5a – c, respectively). The unit-cell parameters were checked for the higher lattice symmetry. Crystal data and details on data collection are presented in Table 2. Data were collected in the \( 0 < 2\theta < 20 \text{ scan mode}. The scan width was \( \Delta 2\theta = (a + 0.35 \times \tan \theta) \) with \( a = 0.55, 0.78, \) and 0.71 for (5a – c, respectively. Intensity data were collected up to \( \theta = 27.50^\circ \). Total data of 6189, 10 616, and 6079 reflections were collected, of which \( 97, 57, \) and 184, respectively. Data were corrected for Lp effects and for the linear decay of three periodically measured reference reflections during X-ray exposure time. An empirical absorption/extension correction was applied (DIFABS,14 correction ranges 0.72 < \( F_o < 0.74 \)).

Refinement on \( F^2 \) was carried out using full-matrix least-squares techniques (SHELXL-93);16 no observation criterion was applied during refinement. The positions of the palladium atoms were found by direct methods, and Mann.21 The anomalous scattering of palladium, chlorine, and sulfur was taken into account. All calculations were performed on a DEC5000 cluster.

**Crystal Structure Determination of 12.** An orange crystal with approximate dimensions 0.05 × 0.15 × 0.60 mm was used for data collection on an Enraf–Nonius CAD-4 diffractometer with graphite-monochromated Cu K\( \alpha \) radiation and an \( 0 \sim 2\theta \) scan. A total of 9699 unique reflections were measured within the ranges 0 ≤ \( h \leq 9, 0 \leq k \leq 24, -39 \leq \ell \leq 40; \) of these, 7941 were above the significance level of 2.5\( t \). The maximum value of \( \sigma (h\theta\ell) \) was 0.59 Å\(^{-1}\). Two reference reflections (110, 016) were measured hourly and showed no decrease during the 110 h collecting time. Unit-cell parameters were refined by a least-squares fitting procedure using 23 reflections with \( 78 < \theta < 82^\circ \). Corrections for Lorentz and polarization effects were applied. The asymmetric unit contains two independent molecules. The positions of the palladium atoms were found by direct methods. The remainder of the non-hydrogen atoms were found in a subsequent \( \Delta F \) synthesis. The hydrogen atoms were calculated. Full-matrix least-squares refinement on \( F^2 \), anisotropic for the non-hydrogen atoms and isotropic for the hydrogen atoms, restraining the latter in such a way that the distances to their carrier atoms remained within 1.09 Å, converged to \( R = 0.042, R_e = 0.064, \) and \( (\Delta F)_{max} = 0.51 \). A weighting scheme \( w = (5.8 + F_o + 0.0073F^2)^{-1} \) was used. An empirical absorption correction19 was applied, with coefficients in the range 0.61–1.55. The secondary isotropic extinction coefficient20 refined to \( G = 0.81(1) \). A final difference Fourier map revealed a residual electron density between −0.9 and +0.9 e Å\(^{-3}\). Matching the two molecules resulted in an rms of 0.19 Å. Scattering factors were taken from Cromer and Mann.21 The anomalous scattering of palladium, chlorine, and sulfur was taken into account. All calculations were performed with XTAL3.0,22 unless stated otherwise. The crystal data are presented in Table 1, and the fractional coordinates are given in the Supporting Information.

**Ligand Synthesis.** L-/D-Methionine Methyl Ester (L-/D-HmetMe). According to the procedures described,23 using L-methionine, the optical pure HCl salt of methionine methyl ester was obtained in 60% yield \((\sigma^{\text{L}}) = +21.82\). By the reaction of HCl/L-HmetMe with Et\(_2\)N (1.5 equiv) in EtOH and subsequent evaporation of the solvent, followed by extraction of the resulting white sticky solid with CH\(_2\)Cl\(_2\), L-/D-HmetMe was obtained as a yellow oil in 60% yield \((\sigma^{\text{L}}) = -2.43\).

**N-(2-Thienylmethylidene)-1-/d-/methionine Methyl Ester (th-metMe).** This ligand was obtained by reacting 2-thiophencarboxaldehyde-
hydrate (13.4 g; 120.0 mmol) with l/H-metMe (17.8 g; 109.1 mmol) in refluxing ethyl acetate (100 mL), on molecular sieves, for 18 h. After cooling of the yellow solution to room temperature and evaporation of the solvent, 28.5 g of a yellow oil was obtained. Purification was carried out by distillation of the 2-thiophenecarbaldehyde under reduced pressure (bp 373 K; 2 mmHg); yield 95% (\(\Delta T\) = +0.02). Found (calc for C\(_{12}\)H\(_{18}\)BrNO\(_2\)S\(_2\)Pd): C, 25.08 (25.23); H, 2.81 (2.89); N, 2.74 (2.68).


**Synthesis of the Complexes.** PdCl\(_2\)-(th-metMe). 1. (A) To a stirred suspension of PdCl\(_2\)(COD) (1.44 g; 4.91 mmol) in CH\(_2\)Cl\(_2\) (20 mL), was added a solution of th-metMe (1.33 g; 5.16 mmol) in CH\(_2\)Cl\(_2\) (15 mL). The mixture was stirred for at least 3 h at room temperature, after which the solvent was evaporated. The resulting yellow sticky solid was washed with Et\(_2\)O (2 x 10 mL) and dried. A yellow solid was obtained in 92% yield. Slow diffusion of Et\(_2\)O into a solution of 1 in CH\(_2\)Cl\(_2\) afforded yellow crystals.

(B) To a solution of Na\(_2\)PdCl\(_4\) in CH\(_2\)Cl\(_2\) (15 mL) was added th-metMe (1.1 equiv) in CH\(_2\)Cl\(_2\) (10 mL). After 30 min, yellow solid 1 precipitated, which was isolated by filtration and subsequently dried in vacuo. Found (calc for C\(_{12}\)H\(_{18}\)BrNO\(_2\)S\(_2\)Pd): C, 28.69 (28.72); H, 2.28 (2.29); N, 2.35 (2.36). IR (KBr, cm\(^{-1}\)) 1737 (C\(_\text{O}\)), 1607 (C\(_\text{N}\)).

PdBr\(_2\)-(th-metMe). 2. PdBr\(_2\) (0.91 g; 3.39 mmol) was suspended in a mixture of CH\(_2\)Cl\(_2\) (15 mL) and MeCN (10 mL) followed by addition of a th-metMe solution in CH\(_2\)Cl\(_2\) (13.2 mL of 0.26 M). The mixture was stirred for 18 h at room temperature, during which the color of the mixture slowly changed to yellow. The yellow mixture was filtered and subsequently reduced to 5 mL by evaporation, after which Et\(_2\)O (20 mL) was added, causing a yellow solid to precipitate. Complex 2 was isolated in quantitative yield by filtration and subsequently dried in vacuo. Found (calc for C\(_{12}\)H\(_{18}\)BrNO\(_2\)S\(_2\)Pd): C, 21.35 (21.39); H, 2.54 (2.45); N, 2.25 (2.27). IR (KBr, cm\(^{-1}\)) 1730 (C\(_\text{O}\)), 1605 (C\(_\text{N}\)).

PdCl\(_2\)(Me)(th-metMe). 4. (A) The same procedure as described for 1 was followed, using PdCl\(_2\)(Me)(COD) (1.40 g; 5.27 mmol). The yellow solid 4 was obtained in quantitative yield.

(B) Reaction of 1 (0.5 g, 1.8 mmol) with Me\(_2\)Sn (1.5 equiv) in CH\(_2\)Cl\(_2\) (10 mL) for 18 h at room temperature resulted in the formation of a yellow suspension. After filtration and evaporation of the solvent, yellow solid 4 was obtained in 95% yield. Found (calc for C\(_{12}\)H\(_{18}\)BrNO\(_2\)S\(_2\)Pd): C, 34.65 (34.79); H, 4.38 (4.42); N, 3.38 (3.40). IR (KBr, cm\(^{-1}\)) 1742 (C\(_\text{O}\)), 1621 (C\(_\text{N}\)).

PdCl\(_2\)(Me)(th-metMe). 5. Reacting 2 (0.24 g; 0.55 mmol) with Me\(_2\)Sn (0.15 g; 0.83 mmol) for 18 h at room temperature in CH\(_2\)Cl\(_2\) (15 mL) resulted in a brownish solution. Evaporation of the solvent afforded a brown solid, which was purified by column chromatography (silica gel). Using CH\(_3\)Cl as the eluent afforded a yellow fraction. Evaporation of the solvent and drying the product afforded yellow-orange complex 5 in 60% yield. Recrystallization was done in two different ways: (A) Slow diffusion of Et\(_2\)O into the reaction mixture of 5 in CH\(_2\)Cl\(_2\) afforded yellow crystals of 5a and 5c. (B) Slow evaporation of CHCl\(_3\) afforded yellow crystals of 5b. Attempts to recrystallize purified complex 5 failed. Found (calc for C\(_{12}\)H\(_{18}\)BrNO\(_2\)S\(_2\)Pd): C, 28.69 (28.72); H, 3.88 (3.71); N, 2.79 (2.57). IR (KBr, cm\(^{-1}\)) 1744 (C\(_\text{O}\)), 1621 (C\(_\text{N}\)).

13C NMR (CDCl\(_3\), 293 K, ppm): 1738 (C\(_\text{d}\)), 1617 (C\(_\text{d}\)), 153.2 (C\(_\text{d}\)), 141.7 (C\(_\text{d}\)), 137.2 (C\(_\text{d}\)).

Pd(II) Complexes Containing the th-metMe Ligand

PdCl(C(O)Me)(th-metMe), 13. A yellow solution of 4 (0.04 g; 0.16 mmol) in CD₂Cl₂ (2 mL), cooled to −78 °C, in a high-pressure tube, was put under 3 bar of CO atmosphere. The ¹H spectrum showed that the complex was formed quantitatively. Attempts to isolate the product were unsuccessful due to decomposition.

Addition of a stoichiometric amount of th-metMe to a PdCl(C(O)-Me)(COD) solution at 223 K, (vide supra) and stirring for 18 h at 223 K generated, after addition of Et₂O (25 mL), subsequent filtration, and drying in vacuo, a yellow solid quantitatively, which degraded slowly at room temperature. IR (CH₂Cl₂, 293 K, cm⁻¹): 1743 (C=O), 1622 (C=N), 1704 (Pd–COMe). IR (CH₂Cl₂, 243 K, cm⁻¹): 1739 (C=O), 1622 (C=N), 1704 (Pd–COMe).

PdX(C(O)Me)(th-metMe) (X: Br, 14; I, 15). Through a solution of 5 (0.03 g; 0.07 mmol) (or 6) in CDCl₃ (0.5 mL) was bubbled CO for at least 15 min. A slight color change was observed. The product could not be isolated due to instability. ¹³C¹H NMR of 14 (CD₂Cl₂, 293 K, δ): 21.5 (C'); 32.4 (C'); 35.1 (C'); 40.5 (Pd–COCH₃); 54.4 (C); 71.8 (C'); 128 (C'); 135 (C); 139 (C'); 139 (C'); 164.3 (C'); 170.9 (C').

Pd(C(O)Me)(L⁺)(th-metMe)(O(SCF₃)) (L⁺: MeCN, 16; Pyridine, 17; Lutidine, 18). Using the corresponding starting complexes, i.e. 8, 9, and 11, in situ (vide supra), the products were obtained by bubbling CO through the cationic alkyl solution for 15 min or by pressurising the solution of the complex in a high pressure tube or by using a gas buret. The unstable products could not be isolated.

Results

The first step in the ligand synthesis involves the formation of the optically active methyl ester of methionine. Reaction of this enantio pure ester with Et₃N resulted in the abstraction of the HCl but also in racemization of C₄. After isolation of the product by addition of Et₂O or hexane to a concentrated solution of the complex in CH₂Cl₂ or MeCN. The neutral complexes neutral complexes will be described below as well as the reactivity of the ligand in a basic medium, resulting in a C−H activation, and of the methyl complexes toward CO.

Neutral Complexes. PdX₂(th-metMe) (X = Cl, Br, I). The solid state structure of 1 (X = Cl) was determined by X-ray structure analysis. The molecular geometry of the mononuclear species comprises a square planar Pd center formed by two halide atoms and the ligand. Coordination of the ligand via the imine nitrogen and the methionine sulfur donor atoms leads to a six-membered chelate ring having a boat configuration. The Pd–Cl, Pd–N, and Pd–S bond distances observed in 1 (Table 7) are all within the expected range for an imine N and a thioether sulfur coordination.⁵,⁶,²⁵ The methyl group on the sulfur donor in 1 is positioned quasi-axial, thus giving the sulfur atom either an S or R configuration. The thiophene moiety is positioned above the coordination plane, resulting in a Pd–S² distance of 3.11 Å, which points to a nonbonding interaction between the metal center and the thioether sulfur donor (Figure 2).

The NMR spectra (Table 3) of the complexes in solution show that all the resonances are shifted to lower field as compared to the resonance values measured for the free ligand. The ¹H shift differences found for C₁H (Δδ = 0.09−0.72 ppm) and C₄H, (Δδ = 0.04−0.69 ppm) indicate that NS coordination occurs in solution, which is also supported by the downfield ¹³C¹H NMR shifts of C₁ (Δδ = 9.8 ppm) and C₄ (Δδ = 18.6 ppm) (Experimental Section). The fact that the ¹H NMR spectra of the neutral dihalopalladium complexes show a sharp as well as a broad set of resonance signals at room temperature indicates that exchange processes are occurring in solution. Unfortunately, the geometry of the isomers which are in the intermediate exchange at room temperature could not be elucidated; because of the low solubility of these complexes, low-temperature NMR could not be performed. Since no large shifts of C₄H are observed, isomerizations involving rotations around the C₅−C₈ bond, i.e. s-cis-s-trans conformations of the conjugated thienylidenemaine moiety, can be excluded because an s-cis conformation would place C₄H in the vicinity of the palladium center. Addition of excess ligand to the complex in solution

![Diagram]

does not alter the appearance of the spectra, showing that intramolecular exchange processes are operating. Variation of the halide bonded to the palladium center influences the isomer ratio; an increase of the halide ion radius decreases the amount of complex responsible for the set of sharp resonance signals: 1 (22:78%), 2 (33:67%), 3 (100:0%).

PdX(Me)(th-metMe) (X = Cl, Br, I). The structure of compound 5 was established by a crystal structure determination. Three crystals of different batches were measured, each displaying a different ratio of compounds 5 and 2. The fractions of compound 5 present in the crystals were 0.229(3), 0.545(4), and 0.829(3) for structure determinations on single crystals from batches a, b, and c, respectively. All crystals contained one solvent molecule per asymmetric unit, CH₂Cl₂ for batch a and batch c and CHCl₃ for batch b. The coordination of the ligand of compounds 5 and 2 in all batches was found to be isostuctural with that of 1; i.e., the ligand is chelate bonded via the N and S donors. The Pd–N (2.043(4) Å) bond is relatively long when compared to this distance found in 1, which can be ascribed to the larger trans influence of the methyl group. The Pd–S (2.2782(11) Å) bond is within the expected range. In Figure 2 the SS₅ configuration is shown, and again C₁H₃ is positioned under the coordination plane, i.e., directed away from the thiophene ring.

In solution, coordination of the ligand in complexes 4–6 has been elucidated by ¹H (Table 3) and ¹³C (¹H) NMR spectroscopy (Experimental Section). At room temperature the ¹H downfield shifts of the C₁H₃ (∆δ) 0.13–0.51 ppm and C₇H resonances (∆δ = 0.19–0.24 ppm) confirm the expected NS₅ coordination, similar to that of 1–3. At room temperature, the ¹H spectra have the same appearance as those of the dihalide complexes, i.e., one set of sharp and one set of broad resonance signals, indicating that the methyl complexes (4–6) are isostaucructural with the dihalide compounds (1–3). Investigation of 4 (X = Cl) by variable-temperature ¹H NMR (Figure 3, in the range 243–348 K) shows an interesting dynamic behavior. Dissolving batches a, b, and c, respectively. All crystals contained one solvent molecule per asymmetric unit, CH₂Cl₂ for batch a and batch c and CHCl₃ for batch b. The coordination of the ligand of complex 5 and 2 in all batches was found to be isostuctural with that of 1; i.e., the ligand is chelate bonded via the N and S donors. The Pd–N (2.043(4) Å) bond is relatively long when compared to this distance found in 1, which can be ascribed to the larger trans influence of the methyl group. The Pd–S (2.2782(11) Å) bond is within the expected range. In Figure 2 the SS₅ configuration is shown, and again C₁H₃ is positioned under the coordination plane, i.e., directed away from the thiophene ring.

Table 3. ¹H NMR Data for the Complexes Based on L, All Recorded at 293 K

<table>
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<tr>
<th>entry (solvent)</th>
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<th>entry (solvent)</th>
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<tr>
<td></td>
<td>C₆H₃</td>
<td>C₄H₄</td>
<td>C₃H₃</td>
<td>C₃H₆</td>
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<tr>
<td>L (CDCl₃)</td>
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<td>4.14</td>
<td>2.04</td>
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<tr>
<td>1 (CD-CN)</td>
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<td>4.40, 4.44</td>
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<td>2 (CD-CN)</td>
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<td>4.50, 4.52</td>
<td>2.08, 2.10</td>
<td>8.80, 8.86*</td>
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<tr>
<td>3 (CD-CN)</td>
<td>3.86</td>
<td>4.27*</td>
<td>2.18</td>
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</tr>
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<td>4 (CD-CN)</td>
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<td>4.76</td>
<td>2.33, 2.73</td>
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<tr>
<td>5 (CD-CN)</td>
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<td>4.27*, 4.36</td>
<td>2.33*, 2.55</td>
<td>8.57, 8.61</td>
</tr>
<tr>
<td>6 (CD-CN)</td>
<td>3.79, 3.87</td>
<td>4.27*, 4.36</td>
<td>2.33*, 2.55</td>
<td>8.57, 8.61</td>
</tr>
<tr>
<td>7 (CD-CN)</td>
<td>3.72</td>
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<td>2.41</td>
<td>8.94</td>
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<td>8 (CD-CN)</td>
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<td>2.33, 2.42, 2.53</td>
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<td>11 (CD-CN)</td>
<td>3.72</td>
<td>4.45*</td>
<td>2.49</td>
<td>8.89</td>
</tr>
</tbody>
</table>

* m = multiplet, J_H_H = see Table 6; d = doublet, 3.4 Hz < J_H_H < 4.0 Hz; dd = doublet, 4.8 Hz < J_H_H < 5.9 Hz; s = singlet; dd = double doublet. * = broad resonance; obsc = obscured by solvent or coligand resonance signals.
4 in CDCl₃ at 243 K results in mainly one set of resonance signals, pointing to the existence of one diastereomer in the solid state, which is also confirmed by solid state NMR (Experimental Section). The coupling constants observed at 243 K for C₄H (J₄H₄a = 5.28 Hz, J₄H₄b = 10.23 Hz) point to a boat conformation of the six-membered ring, analogous to the crystal structures of I and S. However, heating of this solution to 348 K results in formation of a second set of isomers, in a 1:1 ratio. When the solution is cooled to 293 K, this second set of signals is broad. These spectral data indicate the occurrence of an exchange process. Subsequent cooling of the solution to 243 K results in a decoalescence of the broad set of signals. When the solution is cooled to 293 K, this second set of signals is broad. These spectral data indicate the occurrence of an exchange process. Subsequent cooling of the solution to 243 K results in a decoalescence of the broad set of resonance signals; the C¹H₁ singlet splits into two singlets and the C⁴H resonance signal splits into two doubletts in a 3:1 ratio (J₄H₄a = 7.5 Hz (1) and 6.12 Hz (3), J₄H₄b = 5.7 Hz (1) and 8.01 Hz (3)). The free energy is associated with this process (∆G₂₄₃K = 59.7 ± 0.3 kJ·mol⁻¹ for 4, ∆G₃₀₈K = 61.0 ± 0.4 kJ·mol⁻¹ for S, and ∆G₃₀₈K = 61.8 ± 0.4 kJ·mol⁻¹ for 6) is comparable to the values found for monodentate thioethers such as N-acetyl-1-methionine bonded to Pd (63.7 kJ·mol⁻¹). These results indicate that, in the case of the th-metMe palladium complexes, the inversion is accompanied by a change in the chelate ring conformation, since a much lower ∆G value, when compared to that of the (N-acetyl-1-methionine)platinum complex, is expected. The coupling constants of C⁴H for the two diastereomers observed at 243 K indicate a conformational change of the chelate ring. Since for both a flattened boat and an envelope ring conformation different couplings would be observed, two chair diastereomers are proposed that differ with respect to the position of C¹H₁.

These results suggest the presence of three discrete complexes of which two are in the intermediate-exchange region on the NMR time scale at 293 K. This is in accordance with the three sets of resonance signals observed in the ¹³C{¹H} NMR at 263 K. Variation of the halide changes the ratio between the sets of isomers; the amount of complex in the intermediate exchange, at room temperature, increases as the ion radius increases: 4 (56:44%), 5 (49:51%), 6 (45:55%).

Cationic Complexes. [Pd(Me)(L)′(th-metMe)](O₂SCF₃) (L′ = CD₂Cl₂, MeCN, Pyridine, 2-Picoline, 2,6-Lutidine). In solution, the ¹H downfield shifts of the C¹H₁ (Δδ = 0.05–0.53 ppm) and the C⁴H resonances (Δδ = 0.39–0.56 ppm) (Table 3) indicate NS¹ coordination for all the cationic complexes, while a ¹⁹F singlet at −78.66 ppm, indicates that the triflate anion is not coordinated to the palladium atom. The thienyl, i.e., C⁹H, C¹⁰H, and C¹¹H, and the methyl ester resonance signals show no shift as compared to those of the neutral complexes, indicating that S² or carboxylic oxygen coordination does not occur.

The cationic complex 7 (L′′ = CD₂Cl₂), prepared in situ, shows one set of resonance signals with pronounced couplings for the methionine backbone (Table 4), pointing to a rigid C¹H–C¹¹H–C⁴H–C⁹H moiety. Irradiation and COSY experiments clearly showed a specific coupling between C⁴H and C⁹H (J₄H₄a = 11.4 Hz) and the absence of coupling between C⁴H and C⁹H, giving an angle of either 0° or 180° between C⁴H and C⁹H and an angle of 90° between C⁴H and C⁹H. This vicinal coupling constant resembles quite closely the corresponding value found for chelated N,N'-2,Met₇ in which Sadler²⁸ showed that the ring adopts an envelope conformation.

Addition of MeCN (8) enhances the flexibility of the methionine backbone, as can be seen from the existence of two sets of resonance signals in the ¹H NMR, which resembles the spectra observed for the neutral complexes (1–6). Conductivity measurements showed the existence of a cationic complex in solution [MeCN: 46 052 μS (253 K); 103 813 μS (293 K); 119 675 μS (313 K)]. An increase of the steric bulk of the coligand, i.e., going from pyridine to 2,6-lutidine, changes the appearance of the ¹H NMR spectra notably. The pyridine-containing complex (9) shows three sets of resonance signals, in a ratio 4:5:1:4:5, whereas [Pd(Me)(2-picoline)(th-metMe)](O₂SCF₃) (10) shows a doublet and a broad resonance signal, in a 1:1 ratio, for C¹H in the ¹H NMR. Coordination of 2-picoline is indicated by the low-field shifts of the methyl substituent (Δδ = 0.33 ppm), H³pic and H⁴pic (Δδ = 0.76 ppm), H⁵pic (Δδ = 0.94 ppm), and H⁶pic (Δδ = 0.32 ppm) in the ¹H NMR and a low-field shift of the methyl group (Δδ = 7.0 ppm) in the ¹³C{¹H} NMR. The complex with the most bulky coligand, i.e., 11 (L′′′ = 2,6-lutidine) shows the exclusive formation of one isomer, which exhibits only a doublet multiplicity for the C⁴H resonance signal, as has been found for 7 (L′′′ = CD₂Cl₂) (vide supra) indicating an envelope conformation of the six-membered NS chelate ring. Coordination of the 2,6-lutidine moiety is indicated by the low-field shifts of the methyl groups (Δδ = 0.93 ppm), H³⁰H (Δδ = 0.58 ppm), and H⁶⁰H (Δδ = 0.77 ppm).

Reactivity of the Ligand and the Complexes. [PdCl(L)]₂. The reactivity of the th-metMe ligand is highlighted by the acidity of C¹H, leading to racemization of the α-amino acid during isolation of the free amine after esterification. This reactivity was also manifested during recrystallization of 4; air stable orange crystals were obtained consisting of dimeric molecules, of which one is shown in Figure 4. Since this reaction could not be reproduced, a new synthetic route was developed, which involves reaction of the ligand with palladium acetate in a basic medium, leading to a high yield of the dimer (eq 3).

The structure of complex 12 in the solid state shows two monomeric ligands coordinated to one palladium center via S¹ and anionic C⁴, forming a five-membered ring with an envelope conformation, and to another metal nucleus via N,
forming a six-membered ring with a boat conformation (Figure 4). This results in a dihedral angle of 73° between the coordination planes and a nonbonding interaction between the metal centers (Pd(1A)...Pd(2A) = 3.05 Å). The methyl ester moieties are positioned axially in the six-membered ring. The methyl groups on both methinic sulfur donors are again directed away from the thiophene rings, while these potential donors are again positioned above the coordination plane (Pd...S2A = 3.23 Å), similar to the case of 1.

In solution, one set of resonance signals is observed for 12 in both the 1H and 13C{1H} NMR spectra. The low-field shift of the C7H(°) (Δδ = 0.98 ppm) and the high-field shifts of the C7H (Δδ = 0.42 ppm) and the C4 (Δδ = 0.64 ppm) resonance signals point to NC5S coordination. The characteristic multiplicity, in the 1H NMR, of the signals of the methine C7H(°)−C7H backbone (JH=H7° = 13.1 Hz, JH=H7° = 14.3 Hz, JH=H7° = 0 Hz, JH=H7° = 6.2 Hz) indicates rigidity of this part of the ligand. Variable-temperature experiments did not reveal any dynamic behavior of the ligand backbone. The product is very stable, since no reactions were observed with CO, phosphines, alkylzinc, and several alkyl lithium reagents.

**CO Insertion.** Reaction of the methyl complexes 4−11 with CO, either by pressurizing an evacuated reaction flask containing a solution of the methylpalladium complex or by bubbling CO through a solution of the alkyl complex, afforded the corresponding acyl complexes 13−18 (eq 4).

At room temperature, solutions of the neutral (13−15) and the cationic acyl products (16−18) in CH2Cl2, CHCl3, or MeCN are unstable and colloidal palladium was formed immediately. The 1H NMR of 13 (X = Cl, Table 5) and the 13C{1H} NMR of 14 (X = Br, Experimental Section) showed the formation of the acyl product (eq 4) in one isomeric form. A 1H downfield shift of the C7H (Δδ = 0.11−0.52 ppm) and C7H2 resonances (Δδ = 0.16−0.56 ppm) indicates coordination of the imine N and the methionine S1 donors. The formed chelate ring probably has a boat conformation, as indicated by the coupling constants (3JH=H7° = 5.6 Hz and 3JH=H7° = 6.6 Hz) of C4H4 for 13 at 243 K (Table 4).

The reactivity of the neutral and cationic alkylpalladium complexes toward CO insertion was measured by using a low-temperature IR cell30 and gas buret and high-pressure NMR techniques.31 Half-lives were determined by pressurizing a flask filled with 0.02 mmol of the complex in 5 mL of solvent at room temperature, which was connected to a gas buret, using 5 bar of CO. The results are presented in Table 6.

The CO insertion rate, measured at room temperature (Table 6), increases upon going from chloride to iodide. Abstraction of the halide and replacement with a facile leaving group such as the triflate anion give a more reactive species. The cationic complexes to which a coligand was added, i.e., MeCN (8), pyridine (9), or 2,6-lutidine (11), showed a lower reactivity toward CO than 7, which lacks this coligand.

### Discussion

**Molecular System in the Solid State.** It is clear from the comparison of the N-thienylidene-L-methionyl backbone of the N-[N-(5-methyl-2-thienylidene)-L-methionyl]histamine ligand2 in the solid state with the backbone of the ligand in 1 that rotations around the C4−C1−C2 axes in the ligand occurred. The dihedral angles within the C7−N1−C4−C3−C2−S1−C1 chain are rotated 126, 138, 92, and 86°, respectively, compared to those of the free ligand. Since the use of excess ligand in the complexation reaction does not change the bidentate coordination mode of the ligand, the geometry of the ligand is dominated by the preferences of the metal and the chelating effect of the ligand. Otherwise, polymers would be formed by monodentate-bonded ligands, completely stretched out, coordinating to two palladium centers, as has been found for the

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**Table 5. 1H NMR Data for the Reaction Products, All Recorded at 293 K**

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<thead>
<tr>
<th>Entry (solvent)</th>
<th>C6H6</th>
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<th>Pd−COOME6</th>
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<tbody>
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<td>*</td>
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</tbody>
</table>

*a* m = multiplet, ′′JH=H7°′′ = see Table 6; ′d′′ = doublet, 3.4 Hz < ′′JH=H7°′′ < 4.0 Hz; ′d′′ = doublet, 4.8 Hz < ′′JH=H7°′′ < 5.9 Hz; s = singlet; dd = doublet. * = broad resonance; obsc = obscured by solvent or coligand resonance signals.

**Table 6. Half-Lives for the CO Insertion Reaction**

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<th>5</th>
<th>6</th>
<th>7</th>
<th>8</th>
<th>9</th>
<th>11</th>
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<td>τ1/2 (s)</td>
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<td></td>
<td></td>
<td></td>
<td></td>
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</tbody>
</table>

*a* Defined as the time after which the amounts of starting complex and insertion product are equal, measured by gas buret techniques (5 bar of CO, room temperature, in 5 mL of solvent). The neutral complexes were studied in CH2Cl2 and the cationic compounds in MeCN.

---


Table 7. Selected Distances (Å) and Angles (deg) for Pd(II) Complexes Containing the th-metMe Ligand

| Compound |  
| --- | ---  
| Pd–Cl(1) | 2.275(3)  
| Pd–Cl(2) | 2.322(2)  
| Pd–S(1) | 2.283(2)  
| Pd–N(1) | 2.030(7)  
| Pd–S(2) | 3.111  
| Cl(1)–Pd–Cl(2) | 90.1(1)  
| Cl(1)–Pd–S(1) | 92.7(1)  
| Cl(2)–Pd–N(1) | 90.5(2)  
| S(2)–Pd–N(1) | 86.7(2)  

| Compound 5a |  
| --- | ---  
| Pd(1)–Br(1) | 2.4464(6)  
| Pd(1)–Br(2)[C(13)] | 2.3975(13)[2.08(5)]  
| Pd(1)–S(1) | 2.2782(11)  
| Pd(1)–N(1) | 2.043(4)  
| Pd(1)–S(2) | 3.058(5)  
| Br(1)–Pd(1)–Br(2)[C(13)] | 90.56(3)[94.0(13)]  
| S(1)–Pd(1)–Br(2)[C(13)] | 91.38(4)[87.9(13)]  
| N(1)–Pd(1)–Br(1) | 90.50(10)  
| S(1)–Pd(1)–N(1) | 87.66(10)  

| Compound 12 |  
| --- | ---  
| Pd(1A)–Pd(2A) | 3.046(6)  
| Pd(1A)–Cl(1A) | 2.390(2)  
| Pd(1A)–S(1A) | 2.268(2)  
| Pd(1A)–C(4A) | 2.068(6)  
| Pd(1A)–N(1A) | 2.074(5)  
| Pd(1A)–S(2A) | 3.234(2)  
| Pd(2A)–Cl(2A) | 2.414(2)  
| Pd(2A)–S(1B) | 2.276(1)  
| Pd(2A)–C(4B) | 2.060(6)  
| Pd(2A)–N(2A) | 2.087(5)  
| Pd(2A)–S(2B) | 3.082(2)  

| Compound 5a |  
| --- | ---  
| Cl(1A)–Pd(1A)–S(1A) | 87.45(6)  
| Cl(1A)–Pd(1A)–N(1A) | 94.3(1)  
| S(1A)–Pd(1A)–C(4A) | 88.0(2)  
| N(1A)–Pd(1A)–Cl(4A) | 90.0(2)  
| Cl(2A)–Pd(2A)–S(1B) | 88.74(5)  
| Cl(2A)–Pd(2A)–N(2A) | 94.5(1)  
| S(1B)–Pd(2A)–C(4B) | 87.6(2)  
| N(2A)–Pd(2A)–Cl(4B) | 89.1(2)  

The most intriguing feature in complexes 1 and 5 is the configuration of the six-membered ring which is formed upon coordination. This ring has a twisted-boat geometry, which is in contrast to the perturbed chair conformation found in the corresponding [PdCl₂(Met₅-S-N₅)] complex.⁶ Both the relatively long Pd–S¹ distances (2.283(2) and 2.2782(11) Å) and the relative small N–Pd–S¹ angles (i.e., 86.9 and 87.6°) cannot be explained by imine coordination compared to amine coordination and will therefore be caused by the rigidity of the backbone of the methionine moiety imposed by the position of the thiophene carbaldimine unit (vide infra), similar to the case of [PtCl₂(Gly-MetH-N₅,S₅)].⁵ The methyl ester moiety is placed equatorially (C⁴ has an R configuration), which is probably induced by the position of the thiopeine ring of a neighboring molecule, because the groups are positioned parallel to each other with an average distance of 4 Å, thus forming a layer of alternating thienyl and ester groups. In Figure 2 the RR-1 complex is shown, whereas the SS-1 complex, also present in the unit cell, is omitted for clarity.

The thienylmethylidene moiety, in 1, 5, and 12, is close to planar due to π-conjugation between the imine, which has the E configuration, and the thiopeine ring system. As predicted by MNDO and AM1 calculations, the s-cis configuration of the S²–C₅–C₇–N moiety is energetically favored over the s-trans form, which is confirmed by the crystal structures. The geometry of the methionine backbone in the solid state is fixed, because of the chelating effect, resulting in a fixed C₇–N–C₅–C₃ dihedral angle. Therefore, the thienyl sulfur atom is in the proximity of the metal center, having the ring almost perpendicular (1, 77.8°; 5, 79.4°; 12, 81.8 and 84.4°) to the coordination plane. The long Pd–S distances (1, 3.111 Å; 5, 3.107 Å; 12, 3.234 and 3.082 Å) indicate a weak interaction with the central palladium ion.³³

**Molecular System in Solution.** PdX₂(th-metMe) (X = Cl, Br, I), PdX(Me)(th-metMe) (X = Cl, Br, I), [Pd(Me)(L′)(th-metMe)](O₂SCF₃) [(L′ = CH₂Cl₂, MeCN, Pyridine, Picoline, Lutidine)]. The structure of the complexes in solution can be resolved by looking at the geometry of the methionine backbone, which can be elucidated by looking at the multiplicity of the C¹H resonance in the ¹H NMR. The coupling constants (Table 4) of the double doublet multiplicity observed for complex 1 (X = Cl) at room temperature, using the Karplus relation,³⁴ give dihedral angles of 38° and 160°, respectively. These angles are also found between C¹H–C¹H² and C¹H–C¹H³ in the crystal structure. Therefore, the sharp set of resonance signals (approximately 25%) belongs to a structure in which the chelate backbone has a boat geometry, as was found in the solid state. Unfortunately the structures of the isomers, which are in the intermediate-exchange region at room temperature, could not be elucidated. However the solubility of 4 in CDCl₃ enabled us to study all isomers.

Again, the multiplicity of C¹H offered the opportunity of elucidating the structures of the isomers. In Scheme 1 the two possible diastereomers for the SS(RR) and SR(RR) complexes are depicted schematically. Complex 4A is the isomer which is observed in the solid state (SS- or RR-4A) in which the six-membered ring has a twisted-boat geometry, similar to that of 1. Puckering of the ring would place the ester as well as the methyl group in an axial position, which enhances steric hindrance between both groups (Scheme 1, 4B). Inversion at the sulfur center,²⁵ i.e., placing it axially, leads to the formation of the RS or SR isomer (Scheme 1, 4C). The trend in the free energy associated with this inversion process, i.e., ∆G°<sub>‡</sub> < ∆G°<sub>‡</sub>′′, cannot be explained by the trans influence of the halide, which would predict the opposite trend.²⁶ Since the differences are small and fall within the experimental error, no conclusions can be drawn. However the ∆G° values measured are lower than those (approximately 72 kJ·mol⁻¹) found for the platinum methionine complexes investigated by Sadler,³¹ which can be explained by the stronger bonding of the ligand to platinum compared to palladium.

When the mixture was heated to 363 K, the resonance signals belonging to the chair conformers were sharpened. However conversion of 4C to 4D could not be accomplished. After the mixture was cooled to room temperature, two sets of resonance signals were obtained in the same ratio as found in the spectrum after going from 243 to 293 K (vide supra).

A change in the polarity of the solvent shows the existence

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of the same isomers as were found in CDCl$_3$. In acetone, two sets of resonance signals are observed of which the C$^3$H resonance ($\Delta \delta = 0.46$ and 0.34 ppm), the C$^4$H resonance ($\Delta \delta = 0.47$ and 0.34 ppm), and one of the C$^3$H$_2$ signals ($\Delta \delta = 0.05$ ppm) are shifted to low field and the other C$^3$H$_2$ signal ($\Delta \delta = 0.19$ ppm) and the Pd–Me resonance signal are shifted to high field ($\Delta \delta = 0.16$ and 0.13 ppm) when compared to the spectrum of 4 in CDCl$_3$. Conductivity experiments showed the existence of neutral monomeric species in solution. [CH$_2$Cl$_2$: 629 $\mu$S (253 K); 368 $\mu$S (293 K); 450 $\mu$S (313 K). Acetone: 2360 $\mu$S (253 K); 2050 $\mu$S (293 K); 2073 $\mu$S (313 K)]. The ratio of isomers of 4 in 293 K in acetone, i.e., 1:0.5 between the boat and chair conformers, respectively, is different from the ratio found in CDCl$_3$. Heating of the sample to 348 K causes a conversion of the boat into the chair form, indicated by the ratio of 1:1 boat:chair ratio (at 348 K). Dissolving 4 in CD$_2$OD results, at room temperature, in three sets of signals having a ratio of approximately 1:0.2:0.1. The major component shows shifts to lower field compared to the case of 4 in CDCl$_3$. The imine proton signal is shifted to 9.01 ppm, and the C$^4$H signal of the C$^4$H resonance is due to coupling with C$^3$H$_a$ and the position of the thienyl ring. It is obvious that, upon addition of a coligand, the Pd–N and Pd–S$_1$ bonds are influenced as well as the position of the thienyl ring, resulting in the formation of several isomers in solution, which unfortunately could not be elucidated properly. However, it is clear that, upon addition of 2,6-lutidine, only the envelope conformation of the six-membered ring is formed, which is probably caused by steric interactions of the methyl substituents on the coligand and the thienyl ring.

$[\text{PdCl(th-metMe)}]_2$. The formation of 12 was followed by NMR spectroscopy. No preconditioning of one of the donor atoms was observed, because all the resonance signals belong to the dimeric product appeared simultaneously. In the presence of Et$_3$N base, an equilibrium between the O- and C-enolate anion occurs in which the C-enolate form binds to the palladium nucleus. This means that the reaction in which C$^4$ coordinates to the palladium center, via the preformed enolate structure, is fast (eq 5).

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\text{[PdCl(th-metMe)]}_2 \xrightarrow{\text{Et}_3\text{N}} [\text{PdCl(th-enolate)}]_2
\]

Osmometry experiments clearly proved the existence of dimeric molecules in solution. The $^1$H NMR resonances of C$^3$H$^+$, C$^3$H$^3$, C$^3$H$^3$, and C$^3$H$^+$ are a double triplet at 3.69 ppm, a double triplet at 3.50 ppm, a double doublet at 2.62 ppm, and a double doublet at 1.78 ppm. The coupling constants are $J_{\text{H}^1}$ = 13.1 Hz, $J_{\text{H}^1\text{H}^1} = 14.3$ Hz, $J_{\text{H}^1\text{H}^1} = 0$ Hz, and $J_{\text{H}^1\text{H}^1} = 6.2$ Hz, respectively, resulting in dihedral angles which correspond to the angles found in the crystal structure.

**CO Insertion Reactions.** The $^1$H shifts of the C$^3$H and C$^3$H$_3$ and the multiplicity of C$^3$H of the acyl product indicate that the ligand is chelating and that the six-membered ring has a chair conformation. The puckering of the ring upon substitution of a methyl group with an acyl group is probably determined by the position of the thiophene unit determined by a steric interaction of the acyl group with the ring. This interaction is also highlighted by the observation of a hydrolysis of the imine

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**Scheme 1. Dynamic Behavior of Complex 4 in Solution**

![Diagram](image.png)

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bond of the acyl complex, similar to the hydrolysis of peptides in \([\text{Pd(H}_2\text{O})(\text{OH})(\text{AcMet-Gly})]^{+}\) reported by Kostic.\(^{37}\) The hydrolysis product is the stable complex \(\text{PdCl(C(O)Me)-(HmetMe-N,S)}\), whereas the fate of the thienyl moiety could not be determined.\(^{38}\)

The half-lives measured for this reaction (Table 6) show the following trend: \(7 > 6 > 8 \simeq 5 \simeq 4 \simeq 11 > 9\). The cationic complex is the most reactive, while the chloride is slower than the corresponding bromide, which in turn is slower than the iodide complex. This trend can be explained by the existence of open sites during the insertion process,\(^{39}\) formed by dissociation of the halide or one of the ligand donors. It is evident that addition of coligand (MeCN, pyridine, or 2,6-lutidine) reduces the reaction rate by blocking the open site. It is striking, however, that the 2,6-lutidine complex reacts faster than the pyridine-containing complex. This can be explained by the less strongly bonded 2,6-lutidine on the palladium center, because of steric interactions, when compared to the MeCN or pyridine ligand, which enhances dissociation of the bulky coligand.

The instability of the acyl product obtained after the reaction of CO with the palladium methyl species can be explained by assuming the formation of palladium carbonyl complexes, which are unstable and will give dissociation of the CO ligand and colloidal palladium.

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**Supporting Information Available:** Tables giving further details of the structure determinations for \(5a\text{--}c\) and atomic coordinates, bond lengths and angles, and thermal parameters for \(1, 5a\text{--}c,\) and \(12\) (45 pages). Ordering information is given on any current masthead page.