Pyridine-thiolate Titanocene Metalloligands and their Self-Assembly Reactions to Yield Early-Late Metallomacrocycles

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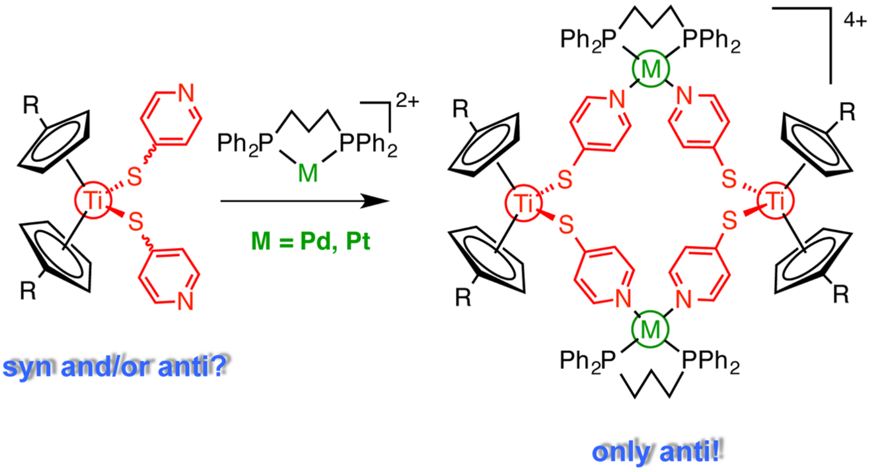
Graphic for Table of Contents



Abstract

New titanocene pyridine-thiolate compounds [(RCp)$_2$Ti(4-Spy)$_2$] (R = H, **1**; Me, **2**) (Cp = cyclopentadienyl; 4-Spy = pyridine-4-thiolate) and [Cp$_2$Ti(2-Spy)$_2$] (**3**) (2-Spy = pyridine-2-thiolate) have been prepared by reaction of the corresponding Li(Spy) salt with the appropriate compound [(RCp)$_2$TiCl$_2$]. Compounds **1-2** have been used as metalloligands in self-assembly reactions with the acceptor late transition metal compounds [M(H$_2$O)$_2$(dppp)](OTf)$_2$ (M = Pd, **a**; Pt, **b**) (dppp = 1, 3-bis(diphenylphosphino)propane) and a series of early-late tetranuclear metallomacrocycles [{(RCp)$_2$Ti(4-Spy)$_2$}{M(dppp)}]$_2$(OTf)$_4$ (R = H, M = Pd (**1$_2$a$_2$**); R = H, M = Pt (**1$_2$b$_2$**); R = Me, M = Pd (**2$_2$a$_2$**); R = Me, M = Pt (**2$_2$b$_2$**)) arising from the anti isomer of the titanocene metalloligands have been obtained. Only ligand transfer reactions from Ti to either Pd or Pt atoms have been observed when the pyridine-2-thiolate derivative **3** has been assayed in self-assembly processes. The obtained species have been characterized by NMR spectroscopy and ESI(+) mass spectrometry. The supramolecular assemblies have shown to be non-rigid in solution and their fluxional behavior has been

studied by VT ^{1}H NMR spectroscopy. A DFT study including *ab initio* molecular dynamics in order to elucidate the structures and the relative stability of the isomers has been performed.

Introduction

The design and synthesis of multi-nuclear discrete coordination architectures and polymeric coordination networks has been a major focus of coordination and metallosupramolecular chemistry over the past decades.[1] The most interesting multimetallic coordination architectures are to be found in closed, geometrically-shaped 2D and 3D architectures including triangles, squares, rectangles, trigonal prisms, boxes, tetrahedra, polyhedral cages, and so forth. [2]

The synthesis of heterometallic supramolecular assemblies is of great interest because the coexistence of different metal atoms into the complexes may provide singular topologies or create unusual metal coordination environments that may influence the properties of the assemblies, such as catalysis,[3] electrochemistry,[4] luminescence,[4c, d, 5] or magnetic behaviour.[6] In this context, early-late heterobimetallic assemblies have the potential to act as multifunctional catalysts for mechanistically different chemical reactions owing to the interplay of widely electronically divergent transition metals. The combination of a Lewis-acidic early transition metal and an electron-rich late transition metal is expected to promote unusual reactivity patterns due to possible synergistic effects and cooperativity arising from the simultaneous or consecutive action of different metal centers.[7] Although fragmentation has been considered a major drawback of the multimetallic catalysts, heterometallic supramolecular assemblies can also behave as a reservoir of unsaturated highly reactive species otherwise not accessible with single catalysts.[8]

Comparison of the well-established supramolecular chemistry of late transition metals such as palladium or platinum with that of early transition metals (mainly titanium or zirconium) reveals that only a limited number of attempts have been made to incorporate in the metallomacrocyclic core metal fragments containing early transition metals.[9]

In particular, to connect different early- and late transition–metal fragments in a single molecule in order to form a heteromulti-metallic assembly is from the synthetic viewpoint, a challenge because the formation of well-shaped metallomacrocyclic compounds usually requires the design of ligands able to accommodate the different electronic and coordination environments of both dissimilar metals. Remarkably, the incorporation of flexible mixed-donor ligands having ambivalent hard-soft character that selectively binds to distinct metals allows for the successful synthesis of d^0-d^8 early-late metallomacrocycles circumventing the geometrical and electronic requirements. Thus, some examples of early-late metallomacrocycles have been assembled using the hard/soft acid–base rule (HSAB) as a design principle.

For example, $[Ti_2Pt_2]$ tetranuclear metallomacrocycles have been successfully assembled using a ditopic bis(pyridine-carboxylate) moiety (Chart 1a),[10] and $[(Ti\text{ or }Zr)_2\text{-}(Rh\text{ or }Ir)_2]$ tetrametallic species have been prepared by using either titanocene or zirconocene moieties containing flexible alkoxyphosphino ligands in which the pendant phosphines are bound to the late metals after the self-assembly process (Chart 1b).[11] The amidophosphine $[(Bu^t_2CH)N(C_6H_4)PPh_2]^-$ has been successfully used as linker in the synthesis of binuclear [Ti(Ni, Pd or Pt)] and tetranuclear $[Ti_2Rh_2]$ heterometallomacrocycles[3a] (Chart 1c) and a bimetallic [TiPt] cage have been obtained with the analogous ambidentate ligand $(SiMe_3)HN(C_6H_4)PPh_2$.[12] Noteworthy, a cyclopentadienyl Ti(IV) complex with a pincer dicarboxylate ligand has been used as a building block for the preparation of tetranuclear $[Ti_2(Rh\text{ or }Ir)_2]$ metallomacrocycles (Chart 1d).[13]

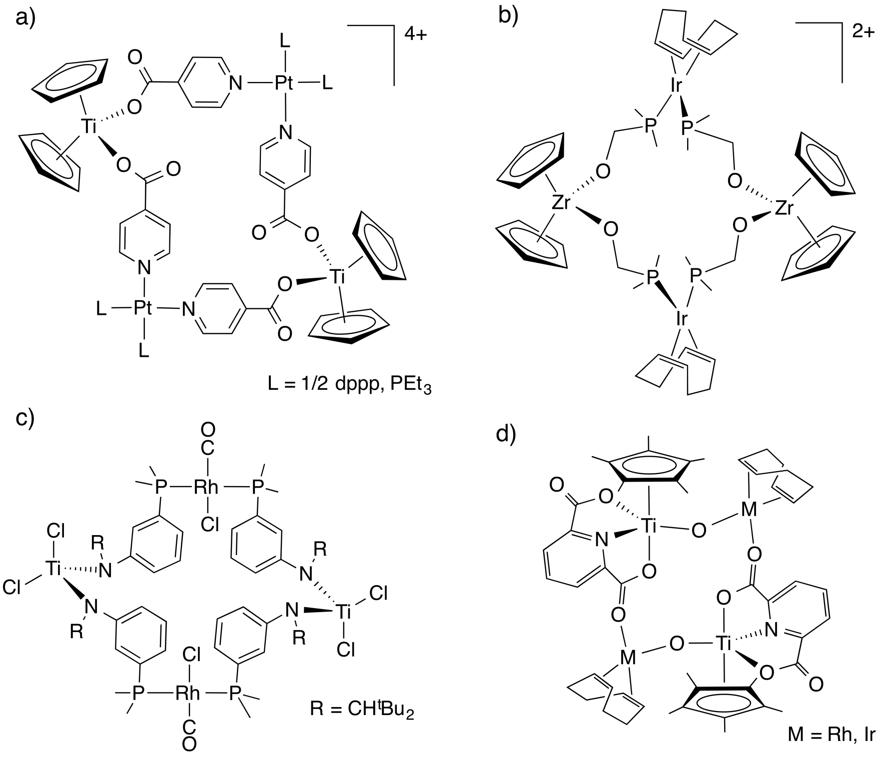


Chart 1. Schematic representation of reported early-late metallomacrocycles.

The use of octahedral complexes constitutes an alternative strategy to introduce early transition metal building blocks with 90° angles in the metallomacrocyclic architectures. In this line, octahedral “TiO_6” synthons containing appended pyridine groups have been reported by Hiraoka and Shionoya.[14] This method has allowed the formation of a [Ti_2Pd_2] ring and tetra- [Ti_2Pd_2], penta- [Ti_2Pd_3] and octanuclear [Ti_4Pd_4] metallocages containing O-donor catechol and acetylacetonate ligands.

We have recently described the self-assembly of [Rh_4(Pd or Pt)$_2$] and [Ir_4(Pd or Pt)$_2$] hexanuclear heterometallomacrocycles from dinuclear rhodium or iridium organometallic ditopic metalloligands bridged by the ambidentate pyridine-4-thiolato ligand.[15] It is important to remark the versatility of the pyridine-4-thiolato ligand, since it contains two different basic atoms and therefore is a good candidate for establishing a stable connection between early and late transition metal building blocks. Thus, we envisage the potential of titanocene thiolato complexes[16] having dangling pyridine groups as metalloligands for late transition metal fragments. Furthermore, the rotation freedom around the central Ti-S-C single bond gives a remarkable flexibility to the ligand that can easily adapt to different coordination environments.

In spite of its coordination possibilities, to our knowledge, a limited number of late-transition metal based assemblies containing this ligand have been described so far, which include the trinuclear $[Cp^*MCl(\mu\text{-}4\text{-}Spy)]_3$ (M = Ir,[17] Rh[17b]) and $[PdCl(PPh_3)(\mu\text{-}4\text{-}Spy)]_3$,[18] the tetranuclear $[Cp^*Ir(4\text{-}Spy)(\mu\text{-}4\text{-}pyS)]_4$,[17a] and the heterotetranuclear $[Pt(4,4'\text{-}dtbpy)(\mu\text{-}4\text{-}Spy)(ZnCl_2)]_2$ (dtbpy= 4,4'-di-tert-butyl-2,2'-bipyridine) complexes.[5b]

From all this, it seemed reasonable to us that the introduction of this ligand in Ti(IV) bis(cyclopentadienyl) complexes could provide flexible ditopic metalloligands suitable for constructing the targeted early-late supramolecules by combination with Group 9 or 10 square-planar acceptor complexes.

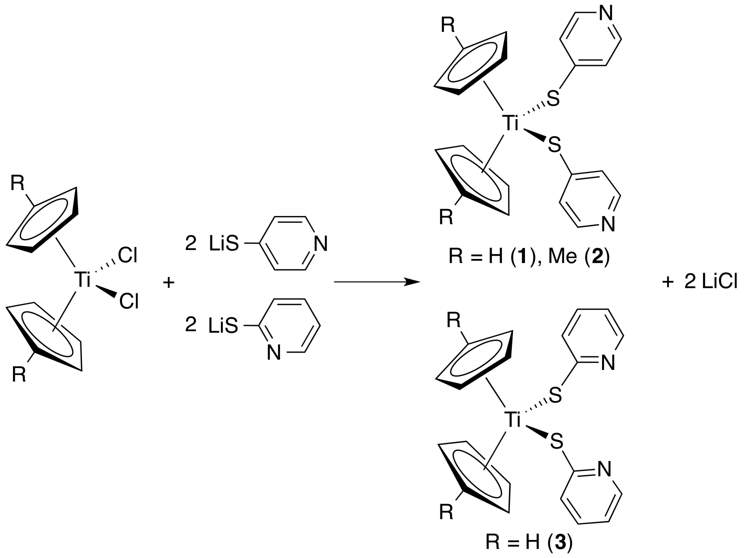
Herein we report on the synthesis of titanocene ditopic metalloligands having the pyridine-4-thiolate moiety and their participation in self-assembly reactions to yield early-late $[Ti_2Pd_2]$ and $[Ti_2Pt_2]$ square-like species. Due to the high flexibility of the pyridine-thiolato ligand DFT calculations have been carried out in order to analyze the stability of the titanium metalloligands and the possible stereoisomers of the metallomacrocycles obtained from the self-assembly process.

Results and Discussion

Synthesis of Titanocene bis(Pyridine-thiolate) [$(RCp)_2Ti(Spy)_2$] (R = H, Me) Metalloligands. Mononuclear titanium complexes having pyridine-thiolato ligands have been prepared from the appropriate metallocene dichloride compound and the corresponding lithium salt of the pyridine-thiol derivative. The lithium salt Li(4-Spy) was prepared in situ by reaction of 4-pySH with n-BuLi in THF at 195 K. Thus, reaction of Li(4-Spy) with [$(RCp)_2TiCl_2$] (R = H, Me) in a 2:1 molar ratio for 2 hours at room temperature gave dark violet suspensions from which the complexes [$(RCp)_2Ti(4\text{-}Spy)_2$] (R = H, **1**; Me, **2**) were isolated as red purple microcrystalline solids in 68% and 80 % yield, respectively, after the appropriate work-up. In fact, efficient removal of the LiCl by-product from the complexes required Soxhlet extraction with dichloromethane due to their similar solubility in THF. Compounds **1** and **2** were fully characterized by elemental analysis, mass spectrometry and NMR spectroscopy. The mass spectra (EI+ for **1** and ESI+ for **2**) showed the molecular ion with the correct isotopic distribution at *m/z* 398.0 [M^+] and 427.08 $[M+H]^+$, respectively, which support the mononuclear formulation of the complexes.

The spectroscopic NMR data for both complexes are in agreement with the proposed structures shown in Scheme 1. The ^1H NMR spectra of **1** ($CDCl_3$) and **2** (C_6D_6) (Figures S1 and S2 in Supporting Information) showed two doublets between δ 8.6-7.4 ppm ($J_{H\text{-}H} \approx$ 4-6 Hz) for the α and β protons of the pyridine rings of the equivalent pyridine-4-thiolato ligands. The equivalent cyclopentadienyl ligands in **1** were observed at δ 6.09 and 113.2 ppm in the ^1H and $^{13}C\{^1H\}$ NMR spectrum, respectively. However, the equivalent methylcyclopentadienyl ligands of **2** give rise to two virtual triplets at δ 5.74 and 5.59 ppm for the cyclopentadienyl protons and a singlet a δ 1.79 ppm for the methyl substituent in the ^1H NMR spectrum. Moreover, the $^{13}C\{^1H\}$ NMR spectrum also shows two resonances (δ 115.1 and 113.4 ppm) for the *C*H of the MeCp rings, which suggests both free rotation of the pyridine-4-thiolato ligands about the Ti-S bond and the MeCp ligands and, thus resulting in a effective C_{2v} symmetry.

In the same way, compound [$Cp_2Ti(2-Spy)_2$] (**3**) featuring pyridine-2-thiolato ligands was prepared from the salt Li(2-Spy) and [Cp_2TiCl_2] following the procedure described above. However, compound **3** was isolated directly from the reaction media due to its low solubility in THF and obtained as a red microcrystalline solid in 59 % yield. The MS (EI+) spectrum of **3** showed the most intense peak at *m*/*z* 333, which correspond to the loss of a Cp ring from the molecular ion. In addition· ^{1}H NMR (Figure S3 in Supporting Information) and ^{13}C NMR spectra show equivalent Cp and 2-Spy ligands, which is in full agreement with the proposed structure (Scheme 1). In contrast to **1** and **2** that are moderately stable on air in the solid state, compound **3** is extremely air and water sensitive both in the solid state and in solution. The compounds are soluble in dichloromethane, partially soluble in tetrahydrofuran, and insoluble in diethyl ether and n-hexane.



Scheme 1. Titanocene Metalloligands Containing Pyridine-thiolato Ligands.

The κ*S* coordination of the 4-Spy ligands in **1** and **2** is supported by the $^{13}C\{^{1}H\}$ NMR spectra that show three resonances at δ 158 (*C*S), 149 and 127 (*C*H) ppm, which compare well with those observed for the dinuclear rhodium $[Rh(\mu\text{-4-Spy})(cod)]_2$ complex having thiolato-bridging ligands (1:2-κ^2*S*).[15] Analogously, κ*S* coordination of 2-Spy ligand is proposed for compound **3**. Although the reported structures of mononuclear titanium complexes featuring pyridine-2-thiolato ligands reveal a κ^2*S,N* coordination mode,[19] the presence of two cyclopentadienyl ligands precludes the formation of a crowded octahedral complex arising from a bidentate coordination of both the 2-Spy. On the other hand, a different coordination mode for each pyridine-2-thiolato ligand cannot be considered because the ^{1}H NMR spectrum of the compound (Figure S3 in Supporting Information) shows their chemical equivalence.

In fact, DFT calculations on the stability of complexes **1** and **3** (Scheme 1) have shown that both complexes are 33.1 and 27.4 kcal/mol more stable respectively, than the corresponding isomers featuring k*S* coordinated pyridine-thiolato ligands (Table S1 in Supporting Information). In this context, it is worth mentioning that a number of tetrahedral metallocene thiolate-titanium $[Cp_2Ti(SR)_2]$ (R = Me, Ph, …)[20] complexes have been structurally characterized.

Self-Assembly Reactions: Topological Considerations. The titanocene complexes **1-3** having pyridine-thiolato ligands feature two peripheral pyridine nitrogen-donor atoms and consequently could be utilized as ditopic building blocks in the preparation of early-late coordination-based supramolecular assemblies. Due to the high flexibility of the ligand an analysis of the possible conformations of the titanocene complexes is required to assess about the possibility of achieving the synthesis of the targeted metallomacrocycles by combination with *cis*-blocked square-planar late metal complexes.

Assuming an *anti* disposition orientation of the terminal 4-pyridyl groups in the metallocene complexes **1** and **2**, the non-bonding sp^2 orbitals of the N atoms are oriented in a divergent fashion, thus allowing the formation of discrete supramolecular assemblies by combination with 90° acidic metal fragments (Figure 1a). In the case of a *syn* orientation of the pyridyl groups (Figure 1b), the parallel disposition of the nitrogen sp^2 orbitals makes possible (by reaction with 90º metal acceptor fragments) the formation of well-defined tetranuclear species. In contrast, the location of the nitrogen-donor atoms in metallocene complex **3**, adjacent to the S-donor atoms, only can produce the assembly of discrete tetranuclear architectures when both terminal 2-pyridyl groups are *anti*-oriented (Figure 1c). However, free rotation about the S-C results in a *syn* positioning of both groups allowing the chelation to only one *cis*-blocked square-planar acceptor fragment. In this case, the formation of dinuclear early-late heterobimetallic species could be envisaged (Figure 1d).

Moreover, it is important to note that the orientation of the donor moieties in all the conformations adopted by these metalloligands along with their conformational flexibility makes also possible the formation of self-assembled polymeric species such as infinite chains or networks by combination with the indicated acceptor units.

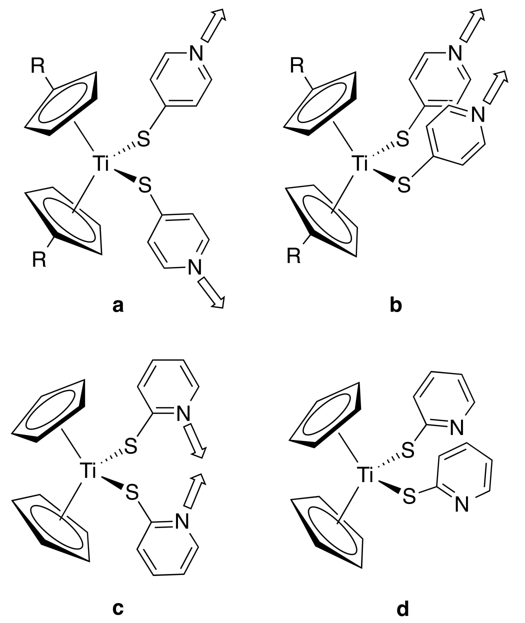
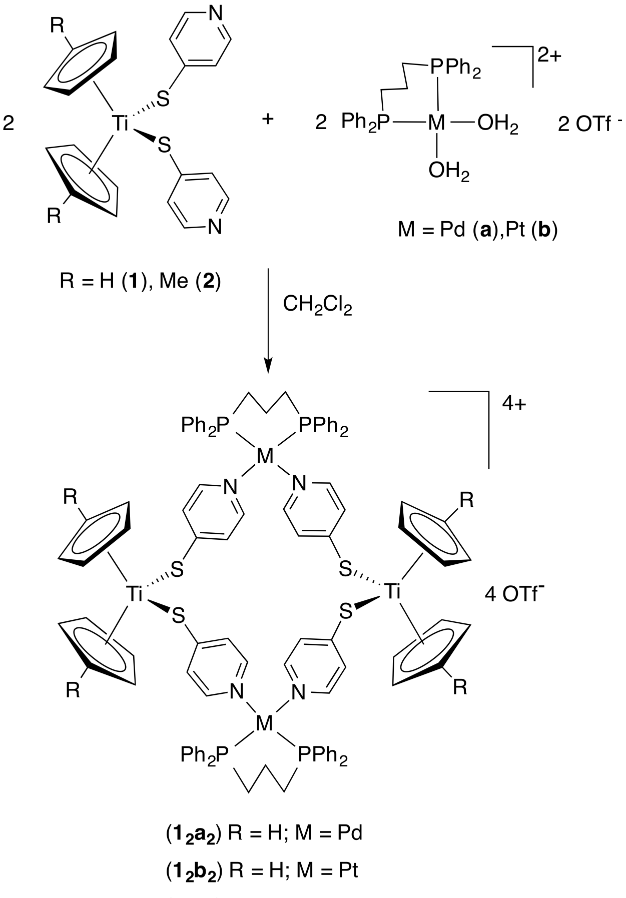


Figure 1. Coordination ability of titanocene metalloligands having pyridine-4-thiolato (**1**, **2**) and pyridine-2-thiolato ligands (**3**).

In order to explore the potential of these metalloligands for the preparation of early-late heterobimetallic assemblies we have chosen the late transition metal mononuclear complexes $[M(H_2O)_2(dppp)]^{2+}$ (M = Pd, Pt) and $[M(cod)(CH_3CN)_2]^+$ (M = Rh, Ir) as acceptor building blocks. Both square-planar species have two available coordination sites protected by poor coordinating ligands at approximately 90° due to the presence of strong coordinating bidentate ligands.

Self-Assembly of Early-Late Tetranuclear Metallomacrocycles. The self-assembly reaction between the pyridine-4-thiolato metalloligand $[Cp_2Ti(4\text{-}Spy)_2]$ (**1**) and the *cis*-chelated square-planar compounds $[M(H_2O)_2(dppp)](OTf)_2$ (M = Pd, **a**; Pt, **b**) in a 1:1 molar ratio in dichloromethane at room temperature allowed the preparation of the heterometallic early-late assemblies $[\{Cp_2Ti(4\text{-}Spy)_2\}\{Pd(dppp)\}]_2(OTf)_4$ ($\mathbf{1_2a_2}$) and $[\{Cp_2Ti(4\text{-}Spy)_2\}\{Pt(dppp)\}]_2(OTf)_4$ ($\mathbf{1_2b_2}$) (Scheme 2). The desired metallomacrocycles precipitated directly from the dichloromethane reaction solution as red and violet solids and were isolated in 73% and 66% yield, respectively. The related metallomacrocycles featuring methylcyclopentadienyl ligands $[\{(MeCp)_2Ti(4\text{-}Spy)_2\}\{Pd(dppp)\}]_2(OTf)_4$ (**2_2a_2**) and $[\{(MeCp)_2Ti(4\text{-}Spy)_2\}\{Pt(dppp)\}]_2(OTf)_4$ (**2_2b_2**) were prepared by reaction of $[(MeCp)_2Ti(4\text{-}Spy)_2]$ (**2**) with the appropriate $[M(H_2O)_2(dppp)](OTf)_2$ (M = Pd, **a**; Pt, **b**) compound following the same procedure and were obtained as orange and violet solids in 75% and 68% yield, respectively (Scheme 2). The obtained compounds are insoluble in most of the common organic solvents except nitromethane, and are very air and water sensitive both in solid state and in solution.



Scheme 2. Self-Assembly of Tetranuclear Heterometallomacrocycles $[Ti_2M_2]$ (M = Pd, Pt).

The formation of the metallomacrocycles was strongly supported by the high-resolution ESI+ mass spectra in acetone solutions, which showed peaks due to successive loss of triflate anions, the doubly charged ion [M-2OTf]$^{2+}$ giving the most intense signal in all cases (Figures S4-S6 in Supporting Information). For example, the ESI+ mass spectrum of $\mathbf{2_2a_2}$ (Figure 2) showed peaks at *m/z* 2337.119, 1094.077, 679.734 and 472.563 with the expected isotope pattern (Figures S4-S6 in Supporting Information) for the ions [($\mathbf{2_2a_2}$) – OTf]$^{+}$, [($\mathbf{2_2a_2}$) – 2OTf]$^{2+}$, [($\mathbf{2_2a_2}$) – 3OTf]$^{3+}$ and [($\mathbf{2_2a_2}$) – 4OTf]$^{4+}$, respectively.

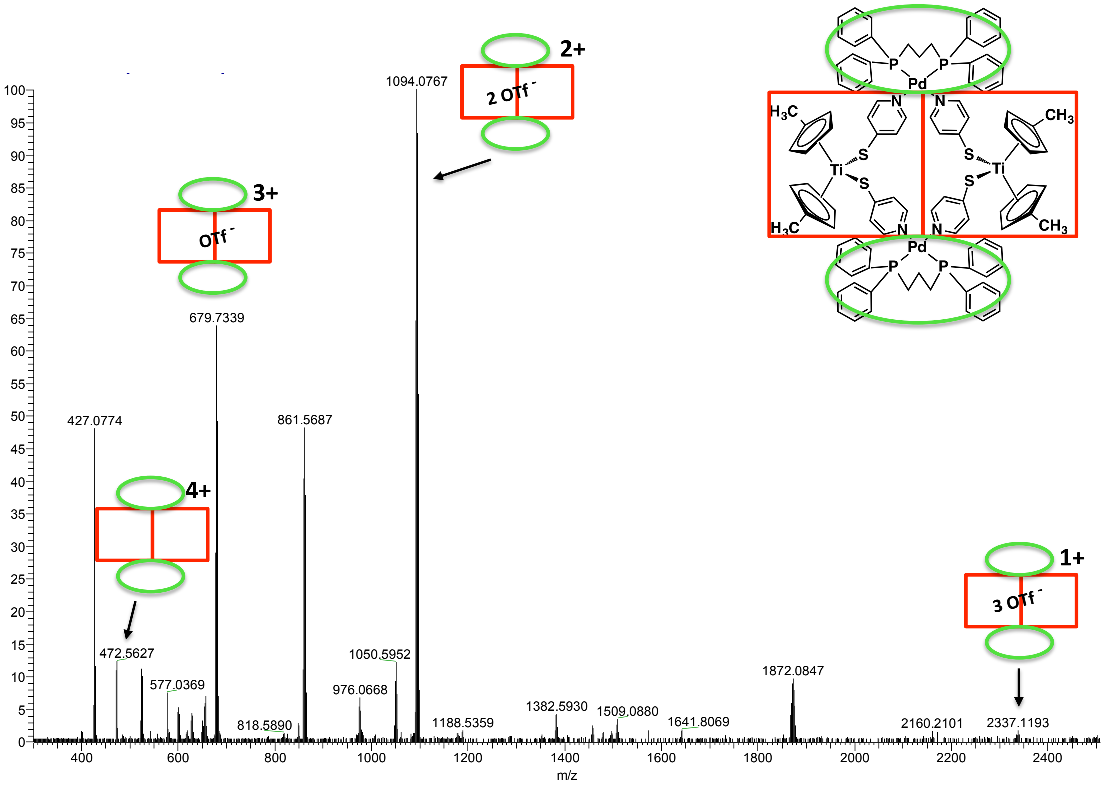


Figure 2. ESI-MS of $[\{(MeCp)_2Ti(4\text{-}Spy)_2\}\{Pd(dppp)\}]_2(OTf)_4$ ($\mathbf{2_2a_2}$) in acetone. (Expansions of relevant peaks showing the experimental and calculated isotopic distribution can be found in Figure S7 in Supporting Information).

The $^{31}P\{^1H\}$ NMR spectrum in nitromethane-d_3 displayed a singlet at $\delta \approx 4.9$ ppm for the palladium macrocycles $\mathbf{1_2a_2}$ and $\mathbf{2_2a_2}$ (Figures S8 and S9 in Supporting Information) and a singlet at $\delta \approx -16.9$ ppm flanked by platinum satellites ($^1J_{Pt-P} \approx 2990$ Hz) for the platinum species **1_2b_2** and **2_2b_2** (Figures S10 and S11 in Supporting Information). The upfield shift of the ^{31}P NMR signals together with the significant decrease in the value of the $^1J_{Pt-P}$ coupling constant evidenced the coordination of the pyridine rings to either the palladium or platinum centers.[21] On the other hand, the chemical equivalence of both the dppp ligands and the phosphorus atoms within the bidentate ligands is indicative of a highly symmetrical structure. The ^1H NMR spectrum of the macrocycles $[\{Cp_2Ti(4\text{-}Spy)_2\}\{M(dppp)\}]_2(OTf)_4$ (M = Pd, **1_2a_2**; Pt, **1_2b_2**) in nitromethane-d_3 at RT showed featureless resonances for the aromatic and $>CH_2$ protons of the dppp ligands evidencing a fluxional behavior (Figures S12 and S13 in Supporting Information). In addition, whereas one rather broad signal appeared for the α and β protons of the 4-pyridyl groups a sharp resonance at $\delta \approx 6$ ppm could be assigned to the protons of the four cyclopentadienyl ligands.

The assemblies $[\{(MeCp)_2Ti(4\text{-}Spy)_2\}\{M(dppp)\}]_2(OTf)_4$ (M = Pd, **2_2a_2**; Pt, **2_2b_2**) also exhibited broad resonances in their ^1H NMR spectra (nitromethane-d_3, RT) although it is remarkable that four broad resonances in the range δ 6.3-5.6 ppm were observed for the unequivalent CH protons of the methylcyclopentadienyl ligands but only a singlet a $\delta \approx 2$ ppm appears for the methyl substituent (Figures S14 and S15 in Supporting Information). As can be seen in Figure 3 for compound **2_2b_2** as a representative example, these resonances became sharper at 253 K. Interestingly, the broad resonances for the α and β protons of the 4-pyridyl groups at 298 K split in two doublet resonances at δ 8.39, 8.29 (H_α), 7.24 and 6.99 (H_β) ppm with a $J_{H\text{-}H} \approx 5$ Hz at 253 K.

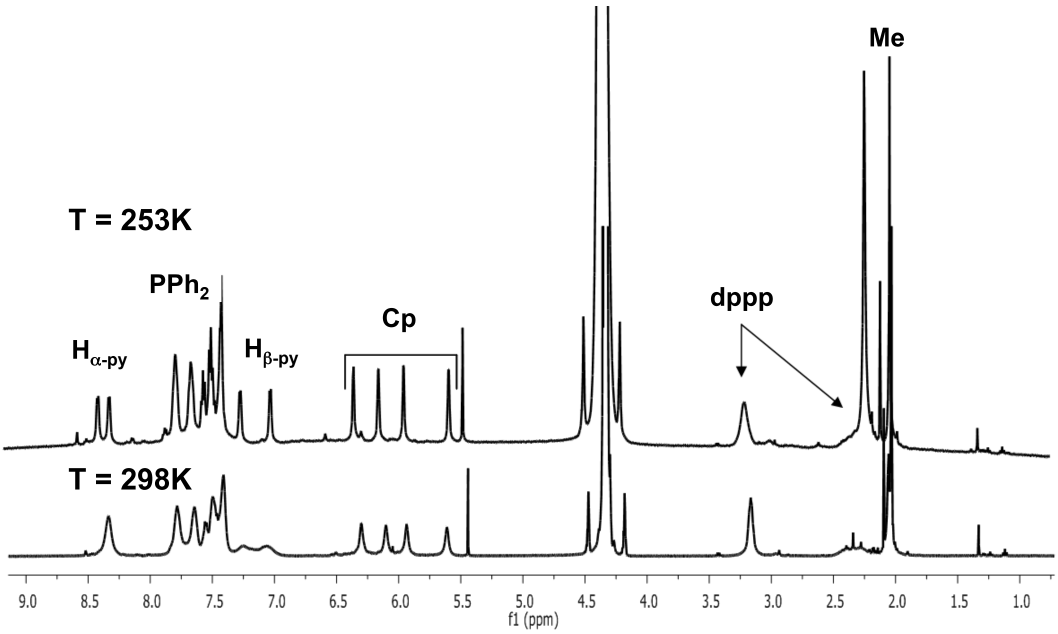


Figure 3. ^{1}H NMR spectrum (nitromethane-d_3) of the metallomacrocycle [{(MeCp)$_2$Ti(4-Spy)$_2$}{Pt(dppp)}]$_2$(OTf)$_4$ (2_2b_2) at 298 K (bottom) and 253 K (top).

The ^{1}H-^{1}H COSY NMR spectrum (nitromethane-d_3) of $\mathbf{2_2b_2}$ at 253 K (Figure 4) shows cross-peaks between the four the CH resonances of the methylcyclopentadienyl ligands thus indicating that the CH protons in the same MeCp ligand are not symmetry-related and, as a consequence, pointing to the chemical equivalence of the four MeCp ligands. In addition, the spectrum also shows two couple of H$_\alpha$ and H$_\beta$ resonances with the expected cross-peaks. The observation of a small coupling between both H$_\beta$ resonances in both 2D COSY and NOESY ^{1}H NMR spectra (Figures S16 and S17 in Supporting information) strongly suggests that the CH protons in the four equivalent pyridine-4-thiolato ligands are symmetry-related. Although the observed fluxional behavior could be explained by the high flexibility of the metallomacrocycle, slow rotation of the 4-pyridyl groups along the S-Ti axis also accounts for the coalescence of the resonances for the pyridine-4-thiolato ligands. Moreover, a coordination-decoordination process involving either Pd or Pt-N$_{py}$ bonds, with the palladium derivatives showing a faster exchange process than platinum (compare H$_\beta$ resonances in

Figures S14 and S15 in Supporting Information), can not be ruled out accordingly with our previous observations in closely related systems.[15, 22]

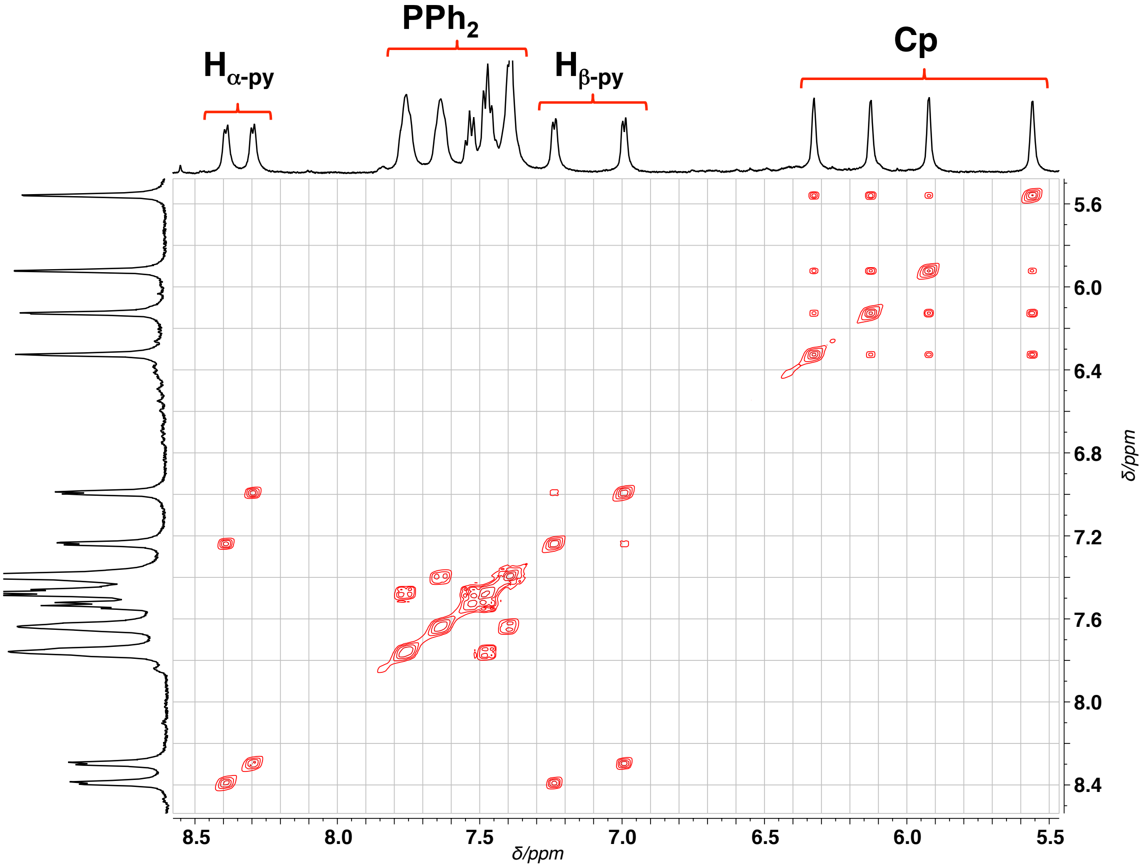


Figure 4. Low-field region of the ^{1}H-^{1}H COSY NMR spectrum (nitromethane-d_3) of the metallomacrocycle $[\{(MeCp)_2Ti(4\text{-}Spy)_2\}\{Pt(dppp)\}]_2(OTf)_4$ (**2_2b_2**) at 253 K.

The spectroscopic data for the obtained early-late tetranuclear metallomacrocycles strongly support a high-symmetry structure having equivalent pyridine-4-thiolato, cyclopentadienyl and phosphine ligands. Having in mind the assembly process leading to the macrocyclic species and considering the possible combinations originated from the conformations showed in Figure 1 for the metalloligands containing pyridine-4-thiolate moieties, the self-assembly process can result in three structures of different symmetry (Figure 5). Considering an *anti* orientation (Figure 1a), the coordination of the $[M(H_2O)_2(dppp)]^{2+}$ fragments to 4-pyridyl groups on the same side of both titanocene metalloligands results in the assembly of a metallomacrocycle of C_{2h} symmetry. Alternatively, the coordination of these metal fragments to alternate 4-pyridyl groups gives rise to an ideally D_2 metallomacrocycle. On the other hand, a *syn* position of the 4-pyridyl groups (Figure 1b) only allows the formation of C_{2v} species as can be seen in Figure 5. Since both structures (C_{2h} and D_2) arising from the *anti* arrrangement of the terminal 4-pyridyl groups in the titanocene metalloligands are compatible with the spectroscopic data, further studies had to be carried out in order to try to establish the actual structure of the obtained assemblies.

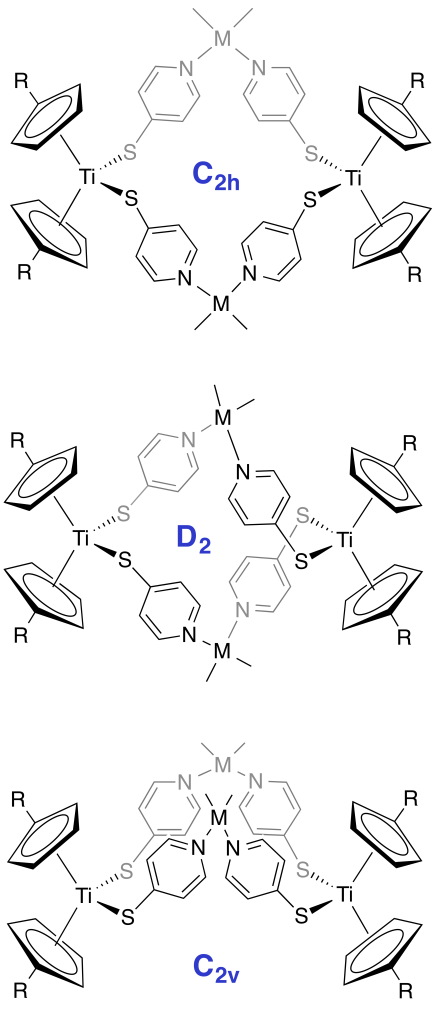


Figure 5. Possible stereoisomers resulting from the self-assembly of [{(RCp)$_2$Ti(4-Spy)$_2$}{M(dppp)}]$_2^{4+}$ metallomacrocycles.

Structure of Heterobimetallic Tetranuclear Metallomacrocycles. Unfortunately, all the efforts to grow good quality single crystals suitable for X-ray analysis proved to be unsuccessful. Alternatively, we have performed DFT calculations in order to determine the relative stability of the possible stereoisomers of the metallomacrocycles.

The structure of the early-late tetranuclear [Ti_2M_2] [M = Pd (**1_2a_2**), Pt (**1_2b_2**)] metallomacrocycles have been established by DFT calculations with the Siesta code using numerical basis sets and pseudopotentials with an exchange-correlation functional including dispersion terms (see Computational details section). The energy values for the optimized structures indicate a preference for the C_{2h} structure but very close in energy to the systems with D_2 symmetry (2.7 and 0.7 kcal/mol, respectively for the platinum and palladium complexes). It is worth noting that both structures are in agreement with the spectroscopic data (^{1}H NMR spectra show the equivalence of cyclopentadienyl ligands) and the theoretical calculations cannot really establish their respective stability taking into account the small energy difference between them. The other isomer with C_{2v} structure shows higher energy (10.9 and 10.0 kcal/mol, respectively for the platinum and palladium complexes). These results show that the C_{2h} *and* D_2 structures are very close in energy, however, the *syn* positioning of the terminal 4-pyridyl groups of the {$Cp_2Ti(4\text{-}Spy)_2$} moiety required for the C_{2v} structure seems to be responsible for the considerable high energy of such structures. In order to check such assumption, we also performed the geometry optimization of the two conformations of the [$Cp_2Ti(4\text{-}Spy)_2$] complex (Figures 1a and 1b and Supporting Information) and the energy difference obtained was 5.8 kcal/mol (Table S1 in Supporting Information). Taking into account the presence of two {$Cp_2Ti(4\text{-}Spy)_2$} fragments in the metallomacrocycle most of the destabilization of the C_{2v} structures is caused by the *syn* conformation of the terminal 4-pyridyl groups. On the other hand, it is remarkable that the C_{2h} isomer of the metallomacrocycle **1_2b_2** has been calculated to be 50.6 kcal/mol more stable than the corresponding isomer resulting from the coordination of the pyridine-4-thiolato ligands to the titanium and platinum centers through the N and S donor atoms, respectively, which is in full agreement with the marked stability of the metalloligand having kS coordinated ligands.

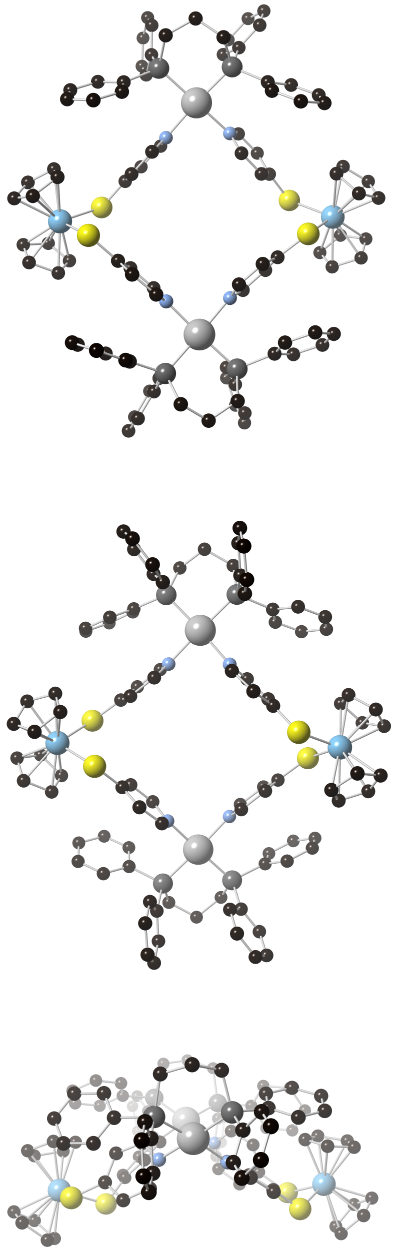


Figure 6. Representation of the DFT optimized structures of the three isomers of the [{Cp$_2$Ti(4-Spy)$_2$}{Pt(dppp)}]$_2^{4+}$ metallomacrocycle (**1$_2$b$_2$**) (see Figure 5, above C_{2h}, middle D_2

and below C_{2v}), see equivalent figure for the Pd^{II} compound ($\mathbf{1_2a_2}$) in Figure S20. Also cartesian coordinates and energies are provided as Supporting Information). Large grey, large blue, yellow, gray, blue and black spheres correspond to platinum, titanium, sulfur, phosphorus, nitrogen, carbon atoms, respectively.

In order to study the aforementioned fluxional behavior displayed by the metallomacrocyclic species, we performed molecular dynamic simulations at 300 K (see Computational details section). The variation of the metal-ligand bond distances during the simulation is depicted in Figure S21. At first glance, the changes in the bond distances are slightly larger for the Pd^{II} compound than for the Pt^{II} system (see the movie of the simulations as Supporting Information) in agreement with the larger fluxionality found experimentally in the Pd^{II} metallomacrocycles in comparison with those holding a Pt^{II} metal center. After the initial thermalization process, the analysis of the metal-ligand bond distances of the 4-Spy ligand shows a broad variation range for the Ti-S bond distances, from 2.3 to 2.8 Å for the Pt^{II} systems and even wider for the Pd^{II} case, *i. e.* from 2.1 to 3.0 Å (Figure S21 in Supporting Information). The results of the simulation should indicate a larger tendency of the Ti-S bond to undergo coordination-decoordination processes than the Pt(Pd)-N_{py} bonds. Such tendency would also facilitate the interconversion between the two more stable isomers, namely the C_{2h} and D_2 structures, because this corresponds to the interchange of positions of the two sulfur atoms coordinated to one Ti center. This may be a consequence of the hard-soft mismatch between the hard early transition metal and the soft sulfur donor atom, which most likely is the driven force for the ligand transfer reactions (see below) and could be also responsible for the high air and water sensitivity of the metallomacrocycles.

Ligand Transfer Reactions. The synthesis of analogous early-late [Ti_2Rh_2] or [Ti_2Ir_2] metallomacrocycles following a similar strategy has proven to be unsuccessful due to ligand redistribution reactions that involve the thiolato transfer to the d^8 late transition metal. For example, reaction of [$Cp_2Ti(4\text{-}Spy)_2$] (**1**) with the cationic species [$Rh(cod)(CH_3CN)_2$]$^+$ in dichloromethane gave an orange solution that contained the dinuclear compound [Rh(μ-4-Spy)(cod)]$_2$.[15] These ligand transfer reactions are believed to proceed through an associative pathway involving a heterobimetallic intermediate where the ligand redistribution takes place.[23] However, monitoring of the reaction by NMR evidenced that the formation of the rhodium dinuclear complex is very fast even at low temperature and the formation of heterobimetallic species was never observed.

Contrasting with the ability of compounds [$(RCp)_2Ti(4\text{-}Spy)_2$] (**1**, **2**) to act as metalloligands in self-assembly processes the reactivity observed for the related [$Cp_2Ti(2\text{-}Spy)_2$] (**3**) is dominated by thiolate ligand transfer processes. The reaction of [$Cp_2Ti(2\text{-}Spy)_2$] (**3**) with the acceptor [$M(H_2O)_2(dppp)$]$(OTf)_2$ (M = Pd, **a**; Pt, **b**) gave a mixture of compounds containing [$M(2\text{-}Spy)_2(dppp)$] (M = Pd, Pt)[24] and unidentified titanium species. Analogously, the reaction of [$Cp_2Ti(2\text{-}Spy)_2$] (**3**) with the cationic [$Rh(cod)(CH_3CN)_2$]$^+$ produced the dinuclear rhodium compound [Rh(μ-2-Spy)(cod)]$_2$[25] together with unidentified titanium species.

Conclusions

A series of mononuclear titanium complexes having pyridine-thiolato ligands have been prepared by reaction of metallocene dichloride compounds with lithium salts of pyridine-thiol derivatives. These titanocene complexes are potential metalloligands for the preparation of early-late coordination-based supramolecular assemblies due to the presence of two peripheral pyridine nitrogen-donor atoms. In fact, the pyridine-4-thiolate complexes $[(RCp)_2Ti(4\text{-}Spy)_2]$ (R = Me, H) behave as efficient ditopic building blocks for the synthesis of tetranuclear heterometallomacrocycles $[\{(RCp)_2Ti(4\text{-}Spy)_2\}\{M(dppp)\}]_2(OTf)_4$ by reaction with *cis*-chelated square-planar compounds of type $[M(H_2O)_2(dppp)](OTf)_2$ (M = Pd, Pt). Conversely, the same reactions with the pyridine-2-thiolato metalloligand $[Cp_2Ti(2\text{-}Spy)_2]$ resulted in the formation of the mononuclear $[M(2\text{-}Spy)_2(dppp)]$ (M = Pd, Pt) thiolate complexes as a consequence of the thiolato transfer to the d^8 late transition metal fragment. In the same way, attempts to synthesize related early-late $[Ti_2M_2]$ (M = Rh, Ir) metallomacrocycles following a similar strategy also resulted in thiolato ligand transfer processes.

NMR data in combination with DFT calculations evidence the coordination of the $[M(H_2O)_2(dppp)]^{2+}$ fragments to 4-pyridyl groups in an *anti* arrangement that results in the assembly of metallomacrocycles of either C_{2h} or D_2 symmetry.

The supramolecular assemblies are non-rigid in solution, which is compatible both with the high flexibility of the metallomacrocycles or/and a coordination-decoordination process involving metal-ligand bonds. In this context, molecular dynamic simulations have revealed that the Ti-S bonds exhibit a larger tendency than the $M\text{-}N_{py}$ (M = Pd, Pt) bonds to undergo coordination-decoordination processes, which may be a consequence of the hard-soft mismatch between the hard early transition metal and the soft sulfur-donor atom.

Further work on the catalytic applications of these tetranuclear heterometallomacrocycles is currently underway.

Experimental Section

General Methods. All manipulations were performed under a dry argon or nitrogen atmosphere using Schlenck-tube techniques. Liquid or solution transfers between reaction vessels were done via cannula. Solvents were dried by standard methods and distilled under argon or nitrogen immediately prior to use, or alternatively from a Solvent Purification System (Innovative Technologies). NMR spectra were recorded at 250, 300, 400 or 500 MHz with Varian and Bruker spectrometers. Chemical shifts are reported in parts per million and referenced to $SiMe_4$ using the signal of the deuterated solvent (^1H) and 85% H_3PO_4 (^{31}P) as external reference, respectively. Elemental C, H and N analysis were performed in a Perkin-Elmer 2400 CHNS/O microanalyzer. Electrospray mass spectra (ESI-MS) were recorded on a Bruker MicroTof-Q using sodium formiate as reference and LTQ-FT Ultra (thermo Scientific) spectrometer. The compounds $[(MeCp)_2TiCl_2]$,[26] $[Pd(H_2O)_2(dppp)](OTf)_2$ (**a**)[27] and $[Pt(H_2O)_2(dppp)](OTf)_2$ (**b**)[27] were prepared as described previously. $[Cp_2TiCl_2]$, 2-pySH and 4-pySH were obtained from Aldrich. 4-pySH was recrystallized from methanol/diethyl ether and stored under argon.

Synthesis of $[Cp_2Ti(4\text{-}Spy)_2]$ (1). A solution of n-BuLi (1.1 ml, 1.76 mmol, 1.6 M) in hexanes was slowly added to a yellow suspension of 4-pySH (0.179 g, 1.610 mmol) in THF (10 mL) at 195 K to give a white suspension of Li(4-Spy) after stirring for 1 hour. Solid $[Cp_2TiCl_2]$ (0.200 g, 0.803 mmol) was added and the suspension stirred for 30 min at 195 K and 2 hours at room temperature to give a dark violet suspension. The solvent was removed under vacuum and the residue stirred with diethyl ether (10 mL). The addition of n-hexane (20 mL) and concentration under reduced pressure while stirring to approximately 10 mL resulted in the formation of a violet solid that was isolated by filtration, washed with n-hexane and dried under vacuum. The solid was extracted with dichloromethane (100 mL) for 12 h in a Soxhlet apparatus under argon to give a dark violet solution. The solution was concentrated under vacuum and then n-hexane was added. Further concentration and addition of n-hexane gave the compound as a red purple microcrystalline solid that was filtered, washed with n-hexane and dried under vacuum. Yield: 0.218 g (68 %). Anal. Calcd for $C_{20}H_{18}N_2S_2Ti$: C, 60.29; H, 4.55; N, 7.03; S, 16.09. Found: C, 60.12; H, 4.42; N, 7.00; S, 16.01. ^{1}H NMR ($CDCl_3$, 298 K, 400.16 MHz) δ: 8.46 (d, 4H, J_{H-H} = 4.8 Hz, H_α), 7.44 (d, 4H, J_{H-H} = 4.4 Hz, H_β) (4-Spy), 6.09 (s, 10H, Cp). ^{13}C{^{1}H} NMR ($CDCl_3$, 298 K, 75.46 MHz) δ: 158.7 (*C*S), 149.2, 126.9 (4-Spy), 113.2 (Cp). MS (EI+, CH_2Cl_2) *m/z*: 398 ([**1**]$^+$ 16%, 398 calcd for $[C_{20}H_{18}N_2S_2Ti]^+$), 288 ([**1**$^+$ - Spy]$^+$ 36%, 288 calcd for $[C_{15}H_{14}NSTi]^+$), 178 ([**1**$^+$-2Spy]$^+$ 36%, 178 calcd for $[C_{10}H_{10}Ti]^+$).

Synthesis of [(MeCp)$_2$Ti(4-Spy)$_2$] (2). [(MeCp)$_2$TiCl$_2$] (0.200 g, 0.722 mmol) and Li(4-Spy), formed in situ by reaction of 4-pySH (0.160 g, 1.44 mmol) with n-BuLi (1 ml, 1.6 mmol, 1.6 M in hexanes), were reacted in THF (8 mL) for 30 min at 195 K and 2 hours at room temperature to give a red purple suspension. The suspension was concentrated under reduced pressure to about one-half of the volume and then n-hexane (12 mL) was added. The solid was isolated by filtration, washed with n-hexane, dried under vacuum and then extracted with dichloromethane (80 mL) for 10 h in a Soxhlet apparatus to give a purple solution. The compound was isolated as a red purple microcrystalline solid following the same procedure described before. Yield: 0.247 g (80 %). Anal. Calcd for $C_{22}H_{22}N_2S_2Ti$: C, 61.97; H, 5.20; N, 6.57; S, 15.04. Found: C, 61.81; H, 5.15; N, 6.51; S, 15.12. ^{1}H NMR (C_6D_6, 298 K, 300.13 MHz) δ: 8.61 (d, 4H, J_{H-H} = 6.0 Hz, H_α), 7.65 (d, 4H, J_{H-H} = 6.0 Hz, H_β) (4-Spy), 5.74 (t, 4H, J_{H-H} = 2.6 Hz, $H_{3,4}$), 5.59 (t, 4H, J_{H-H} = 2.6 Hz, $H_{2,5}$), 1.79 (s, 6H, CH_3) (MeCp). ^{13}C{^{1}H} NMR (C_6D_6, 298 K, 74.47 MHz) δ: 158.5 ($\underline{C}$S), 149.7, 126.9 (4-Spy), 125.3 ($\underline{C}$-Me), 115.1, 113.4 (CH), 15.6 (Me) (MeCp). MS (ESI+, acetone) *m/z*: 427.077 ([**2**+H]$^+$ 100%, 427.078 calcd for $[C_{22}H_{23}N_2S_2Ti]^+$).

Synthesis of [Cp$_2$Ti(2-Spy)$_2$] (3). A solution of n-BuLi (1.0 ml, 1.6 mmol, 1.6 M in hexanes) was slowly added to a solution of 2-pySH (0.179 g, 1.610 mmol) in THF (10 mL) at 195 K to give a pale solution of Li(2-Spy) that was stirred for 15 min. Further reaction with solid [Cp$_2$TiCl$_2$] (0.200 g, 0.803 mmol) gave a fuchsia solution that was stirred for 5 min at

195 K and allowed to warm up at room temperature. Stirring for 10 min at RT resulted in the crystallization of the compound as a red microcrystalline solid that was isolated by filtration, washed with cold THF and diethyl ether and dried under vacuum. Yield: 0.188 g (59 %). Anal. Calcd for $C_{20}H_{18}N_2S_2Ti$: C, 60.29; H, 4.55; N, 7.03; S, 16.09. Found: C, 59.99; H, 4.71; N, 6.95; S, 16.05. ^1H NMR ($CDCl_3$, 298K, 300.08 MHz) δ: 8.54 (d, 2H, $J_{H\text{-}H}$ = 4.0 Hz), 7.65 (d, 2H, $J_{H\text{-}H}$ = 7.0 Hz), 7.55 (td, 2H, $J_{H\text{-}H}$ = 7.0 Hz, $J_{H\text{-}H}$ = 4.0 Hz), 7.03 (t, 2H, $J_{H\text{-}H}$ = 7.0 Hz) (2-Spy), 6.07 (s, 10H, Cp). $^{13}C\{^1H\}$ NMR ($CDCl_3$, 298 K, 75.46 MHz) δ: 169.7 ($\underline{C}$S), 149.2, 136.3, 128.8, 120.2 (2-Spy), 113.3 (s, Cp). MS (EI+, CH_2Cl_2) *m/z*: 333 ([**3**-Cp]$^+$ 78%, calcd 333 for $[C_{15}H_{13}N_2S_2Ti]^+$), 288 ([**3**-Spy]$^+$ 65%, calcd 288 for $[C_{15}H_{14}NSTi]^+$), 268 ([**3**-2Cp]$^+$ 59%, calcd 268 for $[C_{20}H_{18}N_2S_2Ti]^+$), 223 ([**3**-Cp-Spy]$^+$ 100%, calcd 223 for $[C_{10}H_9NSTi]^+$), 158 ([**3**-2Cp-Spy]$^+$ 10%, calcd 158 for $[C_5H_4NSTi]^+$).

Synthesis of [{Cp$_2$Ti(4-Spy)$_2$}{Pd(dppp)}]$_2$(OTf)$_4$ (1$_2$a$_2$). Solid $[Cp_2Ti(4\text{-}Spy)_2]$ (**1**) (0.023 g, 0.058 mmol) was added to a dichloromethane solution (7 ml) of $[Pd(H_2O)_2(dppp)](OTf)_2$ (**a**) (0.050 g, 0.058 mmol) at room temperature. After 15 min of stirring, a red solid precipitated that was isolated by filtration, washed with dichloromethane and dried under vacuum. Yield: 0.053 g (73 %). Anal. Calcd for $C_{98}H_{88}F_{12}N_4O_{12}P_4Pd_2S_8Ti_2$: C, 48.42; H, 3.65; N, 2.30; S, 10.55. Found: C, 47.97; H, 3.75; N, 2.15; S, 10.37.[28] $^{31}P\{^1H\}$ NMR (nitromethane-d_3, 298 K, 101.21 MHz) δ: 4.9 (s, dppp). ^1H NMR (nitromethane-d_3, 298 K, 250.1 MHz): δ 8.35 (d, 8H, $J_{H\text{-}H}$ = 5.4 Hz, H_α) (4-Spy), 7.78-7.37 (m, 40H, Ph), 7.11 (br, 8H, H_β) (4-Spy), 6.08 (s, 20H, Cp), 3.10 (m, 8H, P-CH_2), 2.37 (m, 4H, >CH_2) (dppp). MS (ESI+, acetone) *m/z*: 2281.066 ([(**1$_2$a$_2$**)-OTf]$^+$ 5%, 2281.047 calcd for $[C_{97}H_{88}F_9N_4O_9P_4Pd_2S_7Ti_2]^+$); 1066.046 ([(**1$_2a_2$**)-2OTf]$^{2+}$ 100%, 1066.045 calcd for $[C_{96}H_{88}F_6N_4O_6P_4Pd_2S_6Ti_2]^{2+}$); 661.048 ([(**1$_2a_2$**)-3OTf]$^{3+}$ 32%, 661.048 calcd for $[C_{95}H_{88}F_3N_4O_3P_4Pd_2S_5Ti_2]^{3+}$).

Synthesis of [{Cp_2Ti(4-Spy)$_2$}{Pt(dppp)}]$_2$(OTf)$_4$ (1_2b_2). Solid [Cp_2Ti(4-Spy)$_2$] (**1**) (0.023 g, 0.058 mmol) was added to a dichloromethane solution (7 ml) of [Pt(H_2O)$_2$(dppp)](OTf)$_2$ (**b**) (0.055 g, 0.058 mmol) at room temperature. After 15 min of stirring, a violet solid precipitated that was isolated by filtration, washed with dichloromethane and dried under vacuum. Yield: 0.050 g (66 %). Anal. Calcd for $C_{98}H_{88}F_{12}N_4O_{12}P_4Pt_2S_8Ti_2$: C, 45.13; H, 3.40; N, 2.15; S, 9.84. Found: C, 44.83; H, 3.55; N, 2.11; S, 9.72.[28] $^{31}P\{^1H\}$ NMR (nitromethane-d_3, 298K, 101.21 MHz) δ: -16.9 (s, $^1J_{P\text{-}Pt}$ = 2990 Hz, dppp). ^1H NMR (nitromethane-d_3, 298 K, 250.13 MHz) δ: 8.36 (br, 8H, H_α) (4-Spy), 7.81-7.37 (m, 40H, Ph), 7.13 (br, 8H, H_β) (4-Spy), 6.08 (s, 20H, Cp), 3.16 (br, 8H, P-CH_2), 2.34 (br, 4H, >CH_2) (dppp). ^1H NMR (nitromethane-d_3, 253 K, 500 MHz) δ: 8.44 (d, 4H, $J_{H\text{-}H}$ = 3.8 Hz, H_α), 8.33 (d, 4H, $J_{H\text{-}H}$ = 3.8 Hz, H_α) (4-Spy), 7.91-7.37 (m, 40H, Ph), 7.21 (d, 4H, $J_{H\text{-}H}$ = 3.8 Hz, H_β), 6.99 (d, 4H, $J_{H\text{-}H}$ = 4.0 Hz, H_β) (4-Spy), 6.07 (s, 20H, Cp), 3.17 (br, 8H, P-CH_2), 2.39 (br, 4H, >CH_2) (dppp). MS (ESI+, acetone) *m/z*: 1154.608 ([(1_2b_2)-2OTf]$^{2+}$ 100%, 1154.608 calcd for [$C_{96}H_{88}F_6N_4O_6P_4Pt_2S_6Ti_2$]$^{2+}$); 720.088 ([($1_2b_2$)-3OTf]$^{3+}$ 10%, 720.088 calcd for [$C_{95}H_{88}F_3N_4O_3P_4Pt_2S_5Ti_2$]$^{3+}$); 502.577 ([($1_2b_2$)-4OTf]$^{4+}$ 2%, 502.828 calcd for [$C_{94}H_{88}N_4P_4Pt_2S_4Ti_2$]$^{4+}$).

Synthesis of [{(MeCp)$_2$Ti(4-Spy)$_2$}{Pd(dppp)}]$_2$(OTf)$_4$ (2_2a_2). Solid [(MeCp)$_2$Ti(4-Spy)$_2$] (**2**) (0.019 g, 0.045 mmol) was added to a dichloromethane solution (7 ml) of [Pd(H_2O)$_2$(dppp)](OTf)$_2$ (0.038 g, 0.045 mmol) at room temperature. After 15 min of stirring, an orange solid precipitated that was isolated by filtration, washed with dichloromethane and dried under vacuum. Yield: 0.042 g (75 %). Anal. Calcd for $C_{102}H_{96}F_{12}N_4O_{12}P_4Pd_2S_8Ti_2$: C, 49.26; H, 3.89; N, 2.25; S, 10.32. Found: C, 49.75; H, 3.79; N, 2.43; S, 10.37.[28] $^{31}P\{^1H\}$ NMR (nitromethane-d_3, 298K, 101.21 MHz) δ: 4.8 (s, dppp). ^1H NMR (nitromethane-d_3, 298 K, 250.13 MHz) δ: 8.34 (d, 8H, $J_{H\text{-}H}$ = 6.0 Hz, H_α) (4-Spy), 7.74-7.43 (m, 40H, Ph), 7.12 (br, 8H,

H_β) (4-Spy), 6.28 (br, 4H), 6.09 (br, 4H), 5.93 (br, 4H), 5.62 (br, 4H) (MeCp), 3.11 (m, 8H, P-CH_2), 2.37 (m, 4H, >CH_2), 2.04 (s, Me, overlapped with H_2O resonance) (MeCp). MS (ESI+, acetone) *m/z*: 2337.119 ([(**2_2a_2**)-OTf]$^+$ < 1%, 2337.110 calcd for [$C_{101}H_{96}F_9N_4O_9P_4Pd_2S_7Ti_2$]$^+$); 1094.077 ([(**$2_2a_2$**)-2OTf]$^{2+}$ 100%, 1094.079 calcd for [$C_{100}H_{96}F_6N_4O_6P_4Pd_2S_6Ti_2$]$^{2+}$); 679.734 ([(**$2_2a_2$**)-3OTf]$^{3+}$ 65%, 679.735 calcd for [$C_{99}H_{96}F_3N_4O_3P_4Pd_2S_5Ti_2$]$^{3+}$); 472.563 ([(**$2_2a_2$**)-4OTf]$^{4+}$ 13%, 472.564 calcd for [$C_{98}H_{96}N_4P_4Pd_2S_4Ti_2$]$^{4+}$).

Synthesis of [{(MeCp)$_2$Ti(4-Spy)$_2$}$_2${Pt(dppp)}]$_2$(OTf)$_4$ (2_2b_2). Solid [$(MeCp)_2Ti(4\text{-}Spy)_2$] (0.019 g, 0.045 mmol) was added to a dichloromethane solution (7 ml) of [$Pt(H_2O)_2$(dppp)](OTf)$_2$ (0.042 g, 0.045 mmol) at room temperature. After 15 min of stirring, a violet solid precipitated that was isolated by filtration, washed with dichloromethane and dried under vacuum. Yield: 0.040 g (68 %). Anal. Calcd for $C_{102}H_{96}F_{12}N_4O_{12}P_4Pt_2S_8Ti_2$: C, 45.98; H, 3.63; N, 2.10; S, 9.63. Found: C, 45.64; H, 3.69; N, 2.06; S, 9.57.[28] $^{31}P\{^1H\}$ NMR (nitromethane-*d_3*, 298K, 101.21 MHz) δ: -16.9 (s, $J_{P\text{-}Pt}$ = 2991 Hz, dppp). ^1H NMR (nitromethane-*d_3*, 298 K, 500 MHz) δ: 8.33 (br, 8H, H_α) (4-Spy), 7.78-7.45 (m, 40H, Ph), 7.26 (br, 4H, H_β), 7.05 (br, 4H, H_β) (4-Spy), 6.30 (br, 4H), 6.10 (br, 4H), 5.94 (br, 4H), 5.61 (br, 4H) (MeCp), 3.17 (br, 8H, P-CH_2), 2.29 (m, 4H, >CH_2) (dppp), 2.09 (s, 12H, Me) (MeCp). ^1H NMR (nitromethane-*d_3*, 253 K, 500 MHz) δ: 8.39 (d, 4H, $J_{H\text{-}H}$ = 5.5 Hz, H_α), 8.29 (d, 4H, $J_{H\text{-}H}$ = 5.5 Hz, H_α) (4-Spy), 7.76-7.39 (m, 40H, Ph), 7.24 (d, 4H, $J_{H\text{-}H}$ = 5.0 Hz, H_β), 6.99 (d, 4H, $J_{H\text{-}H}$ = 5.0 Hz, H_β) (4-Spy), 6.33 (s, 4H), 6.13 (s, 4H), 5.92 (s, 4H), 5.56 (s, 4H) (MeCp), 3.18 (br, 8H, P-CH_2), (>CH_2, overlapped with solvent resonance) (dppp), 2.01 (s, 12H, Me) (MeCp). ESI(+) *m/z*: 2514.238 ([(**2_2b_2**)-OTf]$^+$ <1%, 2514.230 calcd for [$C_{101}H_{96}F_9N_4O_9P_4Pt_2S_7Ti_2$]$^+$); 1182.636 ([(**$2_2b_2$**)-2OTf]$^{2+}$ 100%, 1182.639 calcd for [$C_{100}H_{96}F_6N_4O_6P_4Pt_2S_6Ti_2$]$^{2+}$); 738.440 ([(**$2_2b_2$**)-3OTf]$^{3+}$ 82%, 738.775 calcd for [$C_{99}H_{96}F_3N_4O_3P_4Pt_2S_5Ti_2$]$^{3+}$), 516.842 ([(**$2_2b_2$**)-4OTf]$^{4+}$ 37%, 516.844 calcd for [$C_{98}H_{96}N_4P_4Pt_2S_4Ti_2$]$^{4+}$).

Computational details

Electronic structure calculations were carried out using the SIESTA (Spanish Initiative for Electronic Simulations with Thousands of Atoms) code.[29] This numerical computer code is highly efficient when dealing with systems that contain a large number of atoms and therefore for those studied here. Full optimizations of the six studied complexes were performed (see cartesian coordinates as SI). For such calculations, the DRSLL functional (also often called vdW-DF),[30] that was especially designed for weak interactions, was employed. In previous studies, we have checked that it provides a better agreement with the available experimental crystal structure for similar metallomacrocycles than other GGA functionals,[31] such as the commonly employed PBE one.[32] Pseudopotentials were generated according to the method suggested by Trouiller and Martins._ENREF_69[33] Using the following cutoff radii for the s, p, d and f shells: Ti, Pt ($6s^1$ r=2.35 $6p^0$ r=2.50 $5d^9$ r=1.24 $5f^0$ r=2.35), Pd ($5s^1$ r=2.30 $5p^0$ r=2.60 $4d^9$ r=1.20 $4f^0$ r=2.25), Ti ($3s^2$ r=1.50 $3p^6$ r=1.40 $3d^4$ r=2.00 $4f^0$ r=2.00), S ($3s^2$ r=1.70 $3p^4$ r=1.70 $3d^0$ r=1.70 $4f^0$ r=1.7'), P ($3s^2$ r=1.85 $3p^4$ r=1.85 $3d^0$ r=1.85 $4f^0$ r=1.85), N ($2s^2$ r=1.14 $2p^3$ r=1.14 $3d^0$ r=1.14 $4f^0$ r=1.14), C($2s^2$ r=1.25 $2p^2$ r=1.25 $3d^0$ r=1.25 $4f^0$ r=1.25) and H ($1s^1$ r=1.14 $2p^0$ r=1.14 $3d^0$ r=1.14 $4f^0$ r=1.14). As basis set for Pt and Pd atoms a double-ζ for the *n*s and *(n-1)*d orbitals and single-ζ for the *n*p ones, and for the titanium atoms single-ζ quality for the 3s, 3p and 4p orbitals and double-ζ quality for the 3d and 4s ones, while a double-ζ basis with polarization functions was used for the other elements. Values of 50 meV for the energy shift and 250 Ry for the mesh cutoff provide a good compromise between accuracy and the computational cost. Born-Oppenheimer molecular dynamics simulations[34] in the canonical ensemble (NVT) for the two most stable isomers were carried out also with the Siesta code. We employed a Nosé thermostat_ENREF_69[35] at 300 K with a time step of

0.5 fs to perform a simulation of 2 ps (4000 steps) with less accurate values (100 meV for the energy shift and 100 Ry for the mesh cutoff) than those employed in the geometry optimizations.

Supporting Information Available: Figures giving ^1H and $^{31}P\{^1H\}$ NMR spectra and ESI-MS spectra for metalloligands and metallomacrocycles. Representations of $\mathbf{1_2a_2}$ assemblies and cartesian coordinates and energies of DFT optimized structures. Representations of the time evolution of the metal-ligand bond distances and the movie of the molecular dynamic simulations. This material is available free of charge via the Internet at http://pubs.acs.org.

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Note

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