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Dinuclear Complexes

P-N Bridged Dinuclear Rh-METAMORPhos Complexes: NMR and Computational Studies

Frederic W. Patureau,^{[a,b][‡]} Jessica Groß,^[b] Jan Meine Ernsting,^[a] Christoph van Wüllen,^{*,[b]} and Joost N. H. Reek^{*,[a]}

Abstract: Sulfonamido-phosphoramidites are known to form six-membered ring Rh-P-N-Rh-P-N- dinuclear complexes. Apart from a single X-ray structure, little is known about their three dimensional structure in solution. This study proposes a ³¹P, ¹⁵N

and ¹⁰³Rh NMR investigation of the question, as a well as a DFT study. The AA'MM'XX' 6 spin system of the corresponding ¹⁵N-enriched dinuclear complex is notably described.

Introduction

Since the ground-breaking 1865 proposition of Kekulé,^[1,2] the atomic six-membered ring structure has been found to be one of the most dominant cyclic arrangements in Nature. This arises from the relative stability of the six-membered ring vs. other ring sizes. In this study, we propose to prove: 1) that sulfonamido-phosphoramidite (METAMORPhos) ligands^[3] promote a characteristic Rh-P-N-Rh-P-N- six-membered ring organometallic dinuclear structure,^[4] 2) that a strong Rh-N bond exists in solution, 3) that ¹⁵N enrichment of this characteristic dinuclear complex leads to a rare AA'MM'XX' 6-spin system including ³¹P, ¹⁰³Rh, and ¹⁵N nuclei, in which we propose to solve the spin-spin couplings.^[5] Moreover, we propose to investigate the 3D-geometries of those complexes through computational studies, and thereby investigate the possibility of several conformers/twistamers in solution.

Joining anionic phosphoramidite METAMORPhos ligand (HNEt₃)(L¹) together with cationic Rh^I precursor Rh(nbd)₂BF₄ leads to dinuclear complex Rh₂(nbd)₂(L¹)₂ (Scheme 1, Figure 1), releasing one equivalent of (HNEt₃)(BF₄) salt and one nbd (norbornadiene) per Rh center. This dinuclear complex yields a characteristic AA'XX' 4-spin system in the ³¹P NMR profile, which we originally reported in 2009.^[4a] The 4-spin coupling system can be easily solved with Günther's equations.^[6] In the case of L¹ (R = *para-n*-butyl-phenyl), J = 261 Hz, J' = -3 Hz, J_A = 29 Hz and J_X is negligible. Because J_{PP'} was expected to be signifi-

cantly superior to J_{RhRh'}, we originally assigned A-spins to ³¹P and X-spins to ¹⁰³Rh, thus yielding the following coupling attributions: J_{RhP} = 261 Hz, J_{RhP'} = -3 Hz, J_{PP'} = 29 Hz and J_{RhRh'} ca. 0 Hz.^[7]

Scheme 1. Preparation of Rh₂(nbd)₂(L)₂.

In the case of L² (R = CF₃), which we will utilize as second METAMORPhos ligand in this study, J_{RhP} = 265 Hz, J_{RhP'} = -3 Hz, J_{PP'} = 21 Hz. These NMR coupling constants confirm the symmetrical dinuclear disposition of Rh₂(nbd)₂(L¹ or ²)₂, but say little about the coordination mode of the dinuclear core in the organometallic complex. In particular, at this point, neither NMR nor HRMS distinguishes μ-P,N bridging (**Structure I**) vs. P,O bridging mode (**Structure II**). In 2009, early DFT calculations indicated that the μ-P,N bridging mode should be favored by approximately 6 kcal/mol.^[4a] This was confirmed in 2013 when the racemic CF₃- analogue of this complex based on (HNEt₃)(±L²) was successfully crystallized and characterized by X-ray, thus demonstrating the P,N character of the ligand in a

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Figure 1. Real and simulated $^{31}\text{P}\{^1\text{H}\}$ NMR (CD_2Cl_2 , 202.3 MHz), of $\text{Rh}_2(\text{nbd})_2(\text{R-L}^1)_2$ (AA' part), $J_{\text{RhP}} = 261$ Hz, $J_{\text{RhP}'} = -3$ Hz, $J_{\text{PP}'} = 29$ Hz and $J_{\text{RhRh}'} \approx 0$ Hz, top, and of $\text{Rh}_2(\text{nbd})_2(\text{R-L}^2)_2$, $J_{\text{PRh}} = 265$ Hz; $J_{\text{PRh}'} = -3.0$ Hz; $J_{\text{PP}'} = 21$ Hz; $J_{\text{RhRh}'} \approx 0$ Hz, beneath, (the CF_3 gives a singlet in ^{19}F NMR: no significant interference with the AA'XX' 4-spin system).

cyclic six membered ring Rh-P-N-Rh-P-N- structure.^[8] This was the first direct experimental evidence for the $\mu\text{-P,N}$ bridging mode in the solid state. However, in other organometallic complexes based on METAMORPhos ligands, including Rh complexes, the P,O coordination mode was found to take place as well.^[3b–3c] These dinuclear complexes are not always easy to crystallize however, and in addition, solid and solutions states could greatly differ in the assembly of dinuclear complexes. Moreover, the diastereomeric effects arising from the C_2 -chiral binol backbones may have unexpected influence on the dinuclear complexation mode (i.e., dinuclear **structure I or II**). We therefore propose here an NMR method in order to characterize those organometallic systems in solution, as well as a computational investigation.

Results and Discussion

When we first discovered the dinuclear complex $\text{Rh}_2(\text{nbd})_2(\text{L}^1)_2$ in 2009,^[4a] we originally imagined it as a single most stable regioisomer. The first X-ray structure of such a dinuclear system, published in 2013,^[8] comforted this idea. However, when we started to look deeper into the ^{103}Rh NMR of those species in solution, it became clear that this notion needed further investigations. An initial ^{103}Rh NMR study of dinuclear complex $\text{Rh}_2(\text{nbd})_2(\text{L}^1)_2$ was performed, in which we were hoping to find the XX' half spin system corresponding to the AA' part of the ^{31}P NMR (Figure 1). However, the ^1H - ^{103}Rh HMQC spectra of $\text{Rh}_2(\text{nbd})_2(\text{L}^1)_2$ revealed a more complex situation than anticipated (Figure 2).^[4a,9] In particular, it is unclear whether the

projection along the ^{103}Rh axis belongs solely to a second order XX' half spin system (Figure 2), or if some additional lines are present as well.

Figure 2. ^1H - ^{103}Rh HMQC NMR experiment of $\text{Rh}_2(\text{nbd})_2(\text{L}^1)_2$ (121.5 and 9.4 MHz respectively, top), and projection along ^{103}Rh axis.

Because parts of the characterization difficulties in those systems arise from the second order symmetry, we had originally decided that a convenient solution could be to simplify the spin system by performing a scrambling experiment.^[4a] One of the aims was to suppress the second ordered AA'XX' 4-spin system. Thus, $[\text{HNET}_3][(\text{R})\text{-L}^1]$ can be united with inequivalent $[\text{HNET}_3][(\text{R})\text{-L}^2]$ and $\text{Rh}(\text{nbd})_2\text{BF}_4$ in a 1:1:1 ratio. Under those conditions, one obtains an approximately statistical mixture (ca. 25:50:25) of *homo*1-, *hetero*-, and *homo*2- complexes: $\text{Rh}_2(\text{nbd})_2(\text{L}^1)_2$, $\text{Rh}_2(\text{nbd})_2(\text{L}^1)(\text{L}^2)$, and $\text{Rh}_2(\text{nbd})_2(\text{L}^2)_2$ respectively.^[4a] Therefore, in the case of the combination of $(\text{R})\text{-L}^1$ and $(\text{R})\text{-L}^2$, the statistical distribution indicates that no significant sorting occurs (Figure 3). As expected, in the *hetero* combination: $\text{Rh}_2(\text{nbd})_2(\text{L}^1)(\text{L}^2)$, the second order has completely disappeared and each phosphorus signal now displays a simple first order doublet of doublet ($^1J_{\text{P-Rh}}$ and $^3J_{\text{P1-P2}}$, Figure 3). This interpretation is confirmed by a special $^{31}\text{P}\{^{103}\text{Rh}\}$ NMR experiment of this mixture, in which the latter signals become simple dou-

blets ($^3J_{P1-P2}$), while previously second ordered *homo1* and *homo2* complexes $Rh_2(nbd)_2(L^1)_2$ and $Rh_2(nbd)_2(L^2)_2$ become, as expected, singlets. In this particular system, $^1J_{P1or2-Rh1or2} = 268$ Hz, $^1J_{P2or1-Rh2or1} = 258$ Hz, and finally $^3J_{P1-P2} = 25$ Hz. We then performed a ^{31}P - ^{103}Rh HMQC experiment of the mixture. Strikingly, the first order $Rh_2(nbd)_2(L^1)(L^2)$ complex does *not* display as originally anticipated a single line per Rh atom along the ^{103}Rh axis (Figure 4). Indeed, each of the two inequivalent Rh atoms in $Rh_2(nbd)_2(L^1)(L^2)$ is in fact split in a least 6 individual lines, lacking any obvious symmetry. Moreover, the most outer lines are distant by at least 119 Hz, which arguably excludes any unexpected NMR coupling. This is supported by the fact that large $^3J_{Rh-Rh}$ couplings do not fit in our simulation models.^[7] Moreover, 1H - ^{103}Rh NMR couplings arising from the nbd unit are known not to exceed 4 Hz.^[9] This is in good accordance with the 1H NMR profiles of our $Rh_2(nbd)_2(L)_2$ complexes, for which the largest vinylic signals do not exceed 3 to 4 Hz NMR couplings.^[7]

Figure 3. Scrambling experiment (top), $^{31}P\{^1H\}$ NMR (CD_2Cl_2 , 121.5 MHz, middle, see SI for the 202 MHz spectrum), and $^{31}P\{^{103}Rh\}$ NMR (CD_2Cl_2 , 121.5 MHz, beneath).

It thus seems that the $^{31}P\{^1H\}$ NMR profile of $Rh_2(nbd)_2(L^1)(L^2)$, displaying one dd for each ligand, could be

Figure 4. Scrambling experiment, ^{31}P - ^{103}Rh HMQC NMR experiment (121.5 and 9.4 MHz respectively, top), and zoom in on the top left pattern (beneath).

in fact an average/overlap of several species. In contrast to ^{31}P , ^{103}Rh NMR benefits from a considerably larger span of chemical shifts, and is thus more sensitive to minor geometry changes. Likewise, ^{195}Pt NMR has also been found in previous studies to be very sensitive to minor geometrical changes in the coordination sphere of the metal center.^[10] In the present case, several *chair*, *boat* and *twist* configurations may be envisaged, each potential configuration further sub-divided in twistameric and diastereomeric isomerism. A great number of those configurations might thus potentially co-exist in solution at room temperature. This intriguing possibility, which is reminiscent of the various possible conformers of cyclohexane and its organic derivatives,

called for a detailed DFT investigation. The full model minus the butyl chain of complexes $\text{Rh}_2(\text{nbd})_2(\text{L}^1)_2$, $\text{Rh}_2(\text{nbd})_2(\text{L}^1)(\text{L}^2)$, and $\text{Rh}_2(\text{nbd})_2(\text{L}^2)_2$ were thus respectively considered, under all imaginable conformer possibility. Only *homo*-chiral (*R*)-binaphthol derived dinuclear complexes were investigated. The mixed chiral (*R*)/(*S*) case was not considered because of the self-sorting effect (Scheme 1).

All DFT calculations were originally performed in the gas-phase. It was found that the six-membered Rh-P-N-Rh-P-N- has at least seven optimizable conformers of various energies for each dinuclear complex. Two *boat* conformers were notably found, in which the P-N lines are quasi parallel, and which differ "only" by the arrangement of the binaphthol and sulfone units (**B1** and **B2**). A *chair* configuration (**S**) was also identified, as well as four twistamers (**Twist a-d**, Figure 5). Importantly, in

all cases, **Twist b** dominates all other conformers. For $\text{Rh}_2(\text{nbd})_2(\text{L}^2)_2$, **Twist b** dominates the next most stable conformer (**Twist a**) by 25 kJ/mol. In $\text{Rh}_2(\text{nbd})_2(\text{L}^1)_2$, the next most stable conformer is the *boat* **B2**, by 44 kJ/mol, and in the *hetero* complex $\text{Rh}_2(\text{nbd})_2(\text{L}^1)_2$ the next most stable conformers is the *chair* **S** by 49 kJ/mol. All energies and structures are provided in the SI. Clearly, at room temperature, the equilibrium co-existence of several regio-isomers seems excluded by these gas-phase DFT calculations. We then also quantified solvent effects by a series of COSMO calculations (supporting Information, Tables S13–S15). While there is some effect on relative conformer stability, the overall picture remains unchanged, especially that **Twist b** is by far the most stable conformer. Noteworthy to mention, in all three complexes, the most stable **Twist b** displays a similar Rh–Rh distance, of 3.34 Å for $\text{Rh}_2(\text{nbd})_2(\text{L}^1)_2$,

Figure 5. The seven conformers: *Boat B1*, *B2*, *Chair S*, Twistamers **a**, **b**, **c**, and **d**, all represented for $\text{Rh}_2(\text{nbd})_2(\text{R-L}^1)_2$, in the gas phase.

Figure 6. ORTEP representation (30 % probability) of the known X-ray structure of $\text{Rh}_2(\text{nbd})_2(\text{R-L}^2)_2 \cdot \text{Rh}_2(\text{nbd})_2(\text{S-L}^2)_2$, the $\text{Rh}_2(\text{nbd})_2(\text{R-L}^2)_2$ part is represented (CCDC-931393, top),^[8] and corresponding computed optimized geometry of $\text{Rh}_2(\text{nbd})_2(\text{R-L}^2)_2$ in the most stable conformer **Twist b** (gas phase, bottom picture).

Scheme 2. Synthesis of $(\text{HNEt}_3)(^{15}\text{N-L}^3)$ and $\text{Rh}_2(\text{nbd})_2(^{15}\text{N-L}^3)_2$.

3.32 Å for $\text{Rh}_2(\text{nbd})_2(\text{L}^2)_2$, and of 3.31 Å for the mixed complex $\text{Rh}_2(\text{nbd})_2(\text{L}^1)(\text{L}^2)$. In the solid state X-ray structure of $\text{Rh}_2(\text{nbd})_2(\text{L}^2)_2$, the Rh–Rh distance is 3.1460(4) Å. Again, the apparent deviation may come from comparing gas-phase (DFT) and solid state. In general, surprisingly, the contrasting electronic and steric parameters of L^1 (NTs) vs. L^2 (NTf) do not seem to impact much the Rh–Rh distance nor the relative energies and structures of the various conformers (Figure 5). Likewise, the N–Rh bond, which is strategic to maintain the six-membered ring dinuclear structure of the complex, is remarkably consistent in the most stable **Twist b** isomer of $\text{Rh}_2(\text{nbd})_2(\text{L}^1)_2$ (2.189 Å), of $\text{Rh}_2(\text{nbd})_2(\text{L}^2)_2$ (2.206 Å), and the X-ray structure of the latter [2.185(3) Å]. For a visual comparison, we have reproduced the known X-ray structure of $\text{Rh}_2(\text{nbd})_2(\text{R-L}^2)_2$, $\text{Rh}_2(\text{nbd})_2(\text{S-L}^2)_2$ and the computed most stable **Twist b** conformer of $\text{Rh}_2(\text{nbd})_2(\text{R-L}^2)_2$ in Figure 6.

The reality and strength of the N–Rh bond in solution was then looked at with ^{15}N enrichment. In order to do so, a 99 % ^{15}N -enriched METAMORPhos analogue of L^1 was prepared in two simple steps: $(\text{HNET}_3)(^{15}\text{N-L}^3)$. The latter displays a characteristic $^1J_{31\text{P}-15\text{N}} = 70$ Hz (Scheme 2). It should be noted that while the $^1J_{\text{H}-15\text{N}}$ NMR coupling in $^{15}\text{N-TsNH}_2$ is quite large, at 80 Hz, no NMR coupling could be detected between the ^{15}N of $(\text{HNET}_3)(^{15}\text{N-L}^3)$, and the proton of the HNET₃ cation. This is in good agreement with the ionic character of the phosphoramidite. $(\text{HNET}_3)(^{15}\text{N-L}^3)$ was then united with $\text{Rh}(\text{nbd})_2\text{BF}_4$ to produce the characteristic dinuclear complex $\text{Rh}_2(\text{nbd})_2(^{15}\text{N-L}^3)_2$. The resulting $^{31}\text{P}\{^1\text{H}\}$ NMR profile is presented in Figure 7, together with its corresponding simulation. By analogy with $\text{Rh}_2(\text{nbd})_2(\text{L}^1)_2$, which is electronically and sterically most similar, the following NMR coupling constants: $J_{\text{RhP}} = 261$ Hz, $J_{\text{RhP}'} = -3$ Hz, $J_{\text{PP}'} = 29$ Hz and $J_{\text{RhRh}'} = 0$ Hz can be considered unchanged. Unfortunately, the strategic $^1J_{15\text{N-Rh}}$ does not impact the $^{31}\text{P}\{^1\text{H}\}$ NMR simulation of $\text{Rh}_2(\text{nbd})_2(^{15}\text{N-L}^3)_2$. Indeed, a small (2 Hz) or large value (50 Hz) yields the same profile. In other words, one cannot utilize the $^{31}\text{P}\{^1\text{H}\}$ simulation to iteratively determine $^1J_{15\text{N-Rh}}$. On the other hand, $^1J_{15\text{N-P}}$ could be approached by iterative $^{31}\text{P}\{^1\text{H}\}$ simulations and found to be 88 Hz.

In order to determine the strategic $^1J_{15\text{N-Rh}}$ coupling, another $^{31}\text{P}-^{103}\text{Rh}$ HMQC experiment was conducted on $\text{Rh}_2(\text{nbd})_2(^{15}\text{N-L}^3)_2$. The resulting 2D profile is presented in Figure 7. Four large doublets are clearly visible along the ^{103}Rh axis, each corresponding to one of the four great line packages along the ^{31}P axis. Each ^{103}Rh -directed doublet displays the same large coupling: $^1J_{15\text{N-Rh}} = 30 \pm 1$ Hz. Importantly, the projection along the ^{103}Rh axis gives approximately the same pattern which had been observed for $\text{Rh}_2(\text{nbd})_2(\text{L}^1)_2$ and $\text{Rh}_2(\text{nbd})_2(\text{L}^1)(\text{L}^2)$, only each line doubled by a 30 Hz coupling ($^1J_{15\text{N-Rh}}$). The full spin system is represented in Scheme 3.

Conversely, it is mildly surprising that the $^2J_{15\text{N-P}}$ across the Rh atom was found to be very small, less than 1 Hz. It is well known however that small coordination angles (*cis* coordination) can dramatically decrease the NMR coupling between two inequivalent ^{31}P spins at a metal center. By extension, the rather short N–Rh–P angle [93.22(7)° in the crystal structure of $\text{Rh}_2(\text{nbd})_2(\text{R-L}^2)_2$, $\text{Rh}_2(\text{nbd})_2(\text{S-L}^2)_2$],^[8] may account for a similar

Figure 7. AA' part of AA'MM'XX' 6-spin system of $\text{Rh}_2(\text{nbd})_2(^{15}\text{N-L}^3)_2$ in $^{31}\text{P}\{^1\text{H}\}$ NMR (CD_2Cl_2 , 202.3 MHz) and corresponding simulation (top), corresponding $^{31}\text{P}-^{103}\text{Rh}$ HMQC NMR experiment (121.5 and 9.4 MHz respectively, middle down), and zoom in of the latter spectrum.

Scheme 3. AA'MM'XX' 6 spin system based on ^{31}P , ^{15}N and ^{103}Rh , all none displayed NMR couplings are approximately 0 Hz.

effect. It should be noted that the $^{31}\text{P}\{^1\text{H}\}$ NMR simulation does not accommodate a $^2J_{15\text{N-P}}$ larger than 1 Hz, above which the simulated $^{31}\text{P}\{^1\text{H}\}$ profile becomes significantly more complex (more lines) than reality. In order to illustrate this point, simulations at $^2J_{15\text{N-P}} = 0, 1, 2$, and 5 Hz are provided in supplementary information.^[7] Finally, it should be noted that $^2J_{\text{Rh-}^{15}\text{N}}$ is probably small, certainly much smaller than the $^1J_{15\text{N-Rh}} = 30 \pm 1$ Hz. However, its value does not affect the $^{31}\text{P}\{^1\text{H}\}$ NMR simulation, rendering iterative estimation impossible. The ^{103}Rh axis projections are moreover too broad for direct determination. In contrast, we can however safely say that $^3J_{15\text{N-Rh}} \approx 0$ Hz, as any other value significantly alters the $^{31}\text{P}\{^1\text{H}\}$ NMR simulation compared to reality.

Conclusions

In conclusion, we reported here the first AA'MM'XX' 6-spin system based on ^{31}P , ^{15}N and ^{103}Rh . It is as far as we know also the first such AA'MM'XX' 6-spin system to involve a transition metal. ^{15}N -enrichment of METAMORPhos has allowed the NMR characterization of the Rh–N bond in the six-membered ring $\text{Rh}_2(\text{nbd})_2(\text{L})_2$ complex, in solution. The $^1J_{15\text{N-Rh}}$ was found to be 30 Hz, which is for the best of our knowledge also one of the largest ever reported NMR coupling between ^{15}N and ^{103}Rh .^[11] This relatively high value suggests the existence of a strong N–Rh bond in the dinuclear complex in solution. Moreover, ^{103}Rh NMR characterization and computational studies revealed that several conformers/twistamers are conceivable, even if Twistamer **b** seems to have a significant advantage over the other conformers according to those DFT studies. The interpretation of the multiple ^{103}Rh NMR lines observed for these complexes remains therefore open. In general, the characteristic dinuclear disposition of these complexes could have an impact on the development of future cooperative catalysis applications, such as asymmetric hydrogenation reactions. We hope that this study will also inspire characterization and computational solutions for other organometallic coordination problems, particularly those based on cooperative dinuclear complexes.

Experimental Section

Synthetic Procedures and Selected Characterization (for Spectra, See SI): All reactions were carried out in dry glassware under argon or nitrogen atmosphere. Every solution addition or transfer was performed with syringes. All solvents were dried and distilled with standard procedures. Chromatographic purifications were performed by flash chromatography on silica gel 60–200 μm , 60 $\text{\AA}$. Nuclear Magnetic Resonance experiments were performed either on a Varian Inova500 spectrometer (^1H : 500 MHz, ^{31}P : 202.3 MHz, ^{13}C : 125.7 MHz), Varian Mercury300 (^1H : 300.1 MHz, ^{19}F : 282.4 MHz, ^{31}P : 121.5 MHz), or Bruker DRX300 (^1H : 300 MHz, ^{31}P : 121.5 MHz, ^{103}Rh : 9.4 MHz). All available spectra can be found in the SI.

$\text{Rh}_2(\text{nbd})_2(\text{R-L}^1)_2$: The synthesis was partly described in a previous publication.^[4a] $^{31}\text{P}\{^1\text{H}\}$ NMR (202.3 MHz, CDCl_3 , room temp.): $\delta = 95.869$ (AA'XX' half spin system, $^1J_{\text{P-Rh}} = 260.7$, $^2J_{\text{P-Rh}} = -2.6$ Hz, $^3J_{\text{P-P}} = 28.7$ Hz, $^3J_{\text{Rh-Rh}} \approx 0$ Hz) ppm. MS (FAB⁺): m/z calcd. for

$\text{C}_{74}\text{H}_{66}\text{N}_2\text{O}_8\text{P}_2\text{Rh}_2\text{S}_2$ ($[\text{M}]^+$): 1442.18; obsd.: 1442.2. ^{31}P – ^{103}Rh HMQC (121.5 and 9.4 MHz, CD_2Cl_2):

$\text{Rh}_2(\text{nbd})_2(\text{R-L}^2)_2$: The synthesis was partly described in a previous publication.^[4a] ^1H NMR (500 MHz, CDCl_3 , room temp.): $\delta = ^{31}\text{P}\{^1\text{H}\}$ NMR (202.3 MHz, CD_2Cl_2 , room temp.): $\delta = 103.487$ (AA'XX' half spin system: $^1J_{\text{P-Rh}} = 264.8$ Hz; $^2J_{\text{P-Rh}} = -3.0$ Hz; $^3J_{\text{P-P}} = 21.2$ Hz; $^3J_{\text{Rh-Rh}} \approx 0$ Hz) ppm. ^{19}F NMR (282.4 MHz, CD_2Cl_2 , room temp.): $\delta = -75.969$ (s, CF_3), -148.734 (s, Et_3NHBf_4) ppm. MS (FAB⁺): m/z calcd. for $\text{C}_{56}\text{H}_{40}\text{F}_6\text{N}_2\text{O}_8\text{P}_2\text{Rh}_2\text{S}_2$ ($[\text{M}]^+$): 1313.97; obsd.: 1313.9. ^{31}P – ^{103}Rh HMQC (121.5 and 9.4 MHz, CD_2Cl_2):

$\text{Rh}_2(\text{nbd})_2(\text{R-L}^2)_2 \cdot \text{Rh}_2(\text{nbd})_2(\text{S-L}^2)_2$: The synthesis was described in a previous publication.^[8]

$\text{Rh}_2(\text{nbd})_2(\text{R-L}^1)(\text{R-L}^2)$: The synthesis was partly described in a previous publication.^[4a] ligand (**R**)-[Et₃NH][1] (0.013 mmol, 1 equiv.) and (**R**)-[Et₃NH][2] (0.013 mmol, 1 equiv.) were united with $\text{Rh}(\text{nbd})_2\text{BF}_4$ (0.026 mmol, 2 equiv.) and dissolved in 0.6 mL of CD_2Cl_2 , resulting in a very dark purple solution. ^{31}P NMR yield: quantitative, as a statistical mixture: **$\text{Rh}_2(\text{nbd})_2(\text{R-L}^1)(\text{R-L}^2)/\text{Rh}_2(\text{cod})_2(\text{R-L}^1)_2/\text{Rh}_2(\text{nbd})_2(\text{R-L}^2)_2$** (50:25:25). $^{31}\text{P}\{^1\text{H}\}$ NMR (202.3 MHz, 107 mm in CD_2Cl_2 , room temp.): $\delta = \text{Rh}_2(\text{nbd})_2(\text{R-L}^1)(\text{R-L}^2)$: 103.78 (dd, $^1J_{\text{P2-Rh2}} = 268$ Hz, $^3J_{\text{P2-P1}} = 25$ Hz, P^2 of **L**²); 93.65 (dd, $^1J_{\text{P1-Rh1}} = 258$ Hz, $^3J_{\text{P1-P2}} = 25$ Hz, P^1 of **L**¹). $^{31}\text{P}\{^1\text{H}, ^{103}\text{Rh}\}$ NMR (121.5 MHz, CD_2Cl_2 , room temp.): $\delta =$ (ppm): **$\text{Rh}_2(\text{nbd})_2(\text{R-L}^1)(\text{R-L}^2)$** : 103.78 (d, $^3J_{\text{P2-P1}} = 25$ Hz), 93.65 (d, $^3J_{\text{P1-P1}} = 25$ Hz), the following data had not been reported before: ^{31}P – ^{103}Rh HMQC (121.5 and 9.4 MHz, CD_2Cl_2): main ^{103}Rh lines (9.4 MHz) of **$\text{Rh}_2(\text{nbd})_2(\text{R-L}^1)(\text{R-L}^2)$** : δ [ppm/(%)]: 432.25 (0.4), 433.64 (0.35), 435.23 (0.57), 438.01 (0.72), 441.72 (0.25), 444.9 (0.12), 473.16 (0.37), 474.36 (0.32), 476.18 (0.52), 478.99 (0.76), 482.71 (0.30), 485.59 (0.14), see also Figure 4. MS (FAB⁺): m/z calcd. for $\text{C}_{65}\text{H}_{53}\text{F}_3\text{N}_2\text{O}_8\text{P}_2\text{Rh}_2\text{S}_2$ ($[\text{M}]^+$): 1378.08; obsd.: 1378.1.

Ligand (HNEt₃)(¹⁵N-L³): Commercially available $^{15}\text{NH}_4\text{Cl}$ (>98 %, 9.2 mmol) was exposed to 200 mL of CH_2Cl_2 together with Ts-Cl

(9.2 mmol). Et₃N (23 mmol) was added to it under strong magnetic stirring. The suspension was stirred at room temp. for 1 h. The solvent was evaporated. The product was dissolved in THF, filtered and the solvents evaporated. Finally the product was crystallized from CH₂Cl₂/Hexanes (2:3). Isolated yield: 17.5 %, white crystals: Ts-¹⁵NH₂. ¹H NMR (500 MHz, CD₂Cl₂, 298 K): δ = (ppm): 7.823 (broad d ≈ small second order, ³J = 8 Hz, 2 aromatic H), 7.375 (broad d ≈ small second order, ³J = 8 Hz, 2 aromatic H), 4.933 (d, ¹J_{H-15N} = 80 Hz, Ts-¹⁵NH₂), 2.469 (s, CH₃ of Ts moiety). ¹³C{¹H} NMR (125.7 MHz, CD₂Cl₂, 298 K): δ = (ppm): 144.301 (s, C_{quat}, CH₃-C), 139.885 (d, ²J_{C-15N} = 4 Hz, C_{quat}, C-SO₂-¹⁵NH₂), 130.262 (s, CH), 126.832 (s, CH), 21.798 (s, CH₃ of Ts-¹⁵NH₂). 1.6 mmol of this compound was then dissolved in 12 mL of THF and Et₃N (4 mmol). A 5 mL of THF solution of R-(+)-1,1'-Bi-2-naphthol-PCl (7.0 mmol, 1 equiv.) was added dropwise under strong magnetic stirring, leading to a suspension, which was stirred at room temp. overnight. The solution was then filtered and the solvents evaporated. The product was submitted to 10 mL of Et₂O and subsequently evaporated. The process was repeated twice. The product was then washed with 10 mL of Et₂O. The product was obtained as a white powder with a close to quantitative yield. ³¹P{¹H} NMR (202.3 MHz, CD₂Cl₂, 298 K): δ = (ppm): +171.9 (very broad m). ³¹P{¹H} NMR (121.5 MHz, THF unlocked, room temp.) approx. 174 ppm [sharp d., ¹J_{31P-15N} = 70 Hz]. ¹H NMR (500 MHz, CD₂Cl₂, 298 K): δ = (ppm): 10.2 (broad s, NH), 8.017–6.925 (aromatic area), 2.788 (dq, q: ³J_{H_a-CH₃} = 7 Hz, d: ²J_{H_a-H_b} = 14 Hz, H^a of CH₃-CH^aH^b-N), 2.498 (s, CH₃-Ar), 2.482 (broad m, H^b of CH₃-CH^aH^b-N), 0.827 (t, ³J = 7 Hz, CH₃-CH^aH^b-N). ¹³C{¹H} NMR (125.7 MHz, CD₂Cl₂, 298 K): δ = (ppm): note: some lines are missing or overlapped, main lines: 133.37 (C_{quat}), 131.89 (C_{quat}), 131.19 (C_{quat}), 130.58 (CH), 129.53 (2CH), 129.41 (CH), 129.23 (CH), 128.90 (CH), 128.69 (CH), 127.15 (CH), 126.75 (CH), 126.59 (CH), 126.47 (2CH), 125.20 (CH), 124.97 (CH), 124.57 (CH), 122.80 (CH), 45.52 (CH₂ of Et₃NH⁺), 21.70 (CH₃), 8.46 (CH₃ of Et₃NH⁺).

Rh₂(nbd)₂(¹⁵N-L³)₂: Ligand (HNEt₃)(¹⁵N-L³) (0.10 mmol, 1 equiv.) was united with Rh(nbd)₂BF₄ (0.10 mmol, 1 equiv.) and dissolved in 0.6 mL of CD₂Cl₂, resulting in a very dark blue solution. ³¹P NMR yield: quantitative. ³¹P NMR characterization: see Scheme 3 and Figure 7. MS (FAB⁺): *m/z* calcd. for C₆₈H₅₄¹⁵N₂O₈P₂Rh₂S₂: [M]⁺: 1360.08; obsd.: 1360.1007. ¹H NMR (500 MHz, CD₂Cl₂, 298 K): δ = (ppm): 8.22 (d, *J* = 8.8 Hz, 1 H), 8.10 (d, *J* = 8.3 Hz, 1 H), 8.01 (d, *J* = 8.3 Hz, 1 H), 7.96 (d, *J* = 8.8 Hz, 1 H), 7.91 (d, *J* = 8.5 Hz, 1 H), 7.8–7.1 (aromatic area), 6.78 (broad s, ca. 4 H, free nbd), 6.74 (d, *J* = 8.1 Hz, 2 H), 6.30 (~q, *J* ≈ 3.7 Hz, 1 H), 5.95 (~q, *J* ≈ 3.7 Hz, 1 H), 4.66 (s, 1 H), 4.02 (s, 1 H), 3.61 (s, 2 H, free nbd), 3.43 (s, 1 H), 3.17 (dq, ³J = 7.4 Hz, ³J = 5.2 Hz, 6 H, CH₃-CH₂-NH⁺), 2.58 (s, 1 H), 2.20 (s, 3 H, CH₃-Ar), 2.00 (s, ≈ 2 H, ≈ free nbd), 1.50–1.30 (aliphatic area), 1.36 (t, ³J = 7.5 Hz, ≈ 9 H, CH₃-CH₂-NH⁺). ¹³C{¹H} NMR (125.7 MHz, CD₂Cl₂, 298 K): δ = (ppm): note: due to the large number of lines, NMR couplings were not systematically solved, only the visible lines are given: 150.45 (C_{quat}), 150.33 (C_{quat}), 148.95 (C_{quat}), 142.46 (C_{quat}), 142.23 (C_{quat}), 132.87 (C_{quat}), 132.76 (C_{quat}), 132.34 (C_{quat}), 131.51 (C_{quat}), 130.79 (CH), 130.08 (CH), 129.70 (CH), 129.52 (CH), 129.11 (2CH), 128.74 (CH), 127.42 (2CH), 127.23 (CH), 126.68 (CH), 126.53 (CH), 126.13 (CH), 125.89 (CH), 125.47 (CH), 124.19 (CH), 123.85 (C_{quat}), 123.42 (CH), 121.83 (C_{quat}), 97.44 (d, ¹J_{13C-103Rh} = 11.0 Hz, CH), 92.14 (d, ¹J_{13C-103Rh} = 14.8 Hz, CH), 65.36 (CH₂, free nbd), 60.21 (d, ¹J_{13C-103Rh} = 9.3 Hz, CH), 57.65 (d, ¹J_{13C-103Rh} = 8.4 Hz, CH), 52.61 (CH), 52.35 (CH), 47.65 (CH₂ of Et₃NH⁺), 46–8 (aliphatic area), including: 21.6 (CH₃-Ar), 9.07 (CH₃ of Et₃NH⁺).

Quantum Chemical Calculations: All DFT calculations were performed in the gas-phase using the B3LYP functional^[12] and the def2-TZVP^[13] basis for all atoms. The rhodium atom carries a quasirelativistic effective core potential (def2-ecp)^[14] replacing 28 core

electrons. The D3 correction by Stefan Grimme^[15] was used to account for dispersion interaction. For the sake of completeness, the dispersion contribution to relative conformer energies is documented in the supporting Information, Tables S7–S9. All calculations were performed with TURBOMOLE.^[16] For geometry optimization steps the Berny algorithm^[17] as implemented in Gaussian 09^[18] was used, using the “external” interface of that program. This means, all energies, gradients, and force constants are calculated with TURBOMOLE, and the Gaussian program decides on which steps to take on the potential energy surface. Except in a single case (see supporting Information, Table S6), all minima were characterised by frequency calculations having no negative Hessian eigenvalue. To assess the importance of solvent effects on relative conformer energies, geometry optimizations have also been performed with the COSMO model^[19] (see supporting Information, Tables S13–S15). While solvation somewhat affects the relative stability, it does not change the overall trend.

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- [1] A. Kekulé, *Ber. Dtsch. Chem. Ges.* **1890**, 23, 1302.
- [2] A. Kekulé, *Bull. Soc. Chim.* **1865**, 3, 98–110.
- [3] For an early mention of sulfonamido-phosphorus compounds, see: a) A. Schmidpeter, H. Rosknecht, *Z. Naturforsch. B* **1971**, 26, 81. For the first mention of an anionic sulfonamido-phosphoramidite, see: b) F. W. Patureau, M. Kuil, A. J. Sandee, J. N. H. Reek, *Angew. Chem. Int. Ed.* **2008**, 47, 3180; *Angew. Chem.* **2008**, 120, 3224. See also: c) F. W. Patureau, C. Worch, M. A. Siegler, A. L. Spek, C. Bolm, J. N. H. Reek, *Adv. Synth. Catal.* **2012**, 354, 59. For structurally related ligands, see: d) P. Braunschtein, *Chem. Rev.* **2006**, 106, 134; e) O. Köhl, *Coord. Chem. Rev.* **2006**, 250, 2867.
- [4] Selection: a) F. W. Patureau, S. de Boer, M. Kuil, J. Meeuwissen, P.-A. R. Breuil, M. A. Siegler, A. L. Spek, A. J. Sandee, B. de Bruin, J. N. H. Reek, *J. Am. Chem. Soc.* **2009**, 131, 6683; b) S. Oldenhof, M. Lutz, J. I. van der Vlugt, J. N. H. Reek, *Chem. Commun.* **2015**, 51, 15200; c) F. G. Terrade, A. M. Kluwer, R. J. Detz, Z. Abiri, A. M. van der Burg, J. N. H. Reek, *ChemCatChem* **2015**, 7, 3368; d) S. Oldenhof, F. G. Terrade, M. Lutz, J. I. van der Vlugt, J. N. H. Reek, *Organometallics* **2015**, 34, 3209; e) P. Boulens, E. Pellier, E. Jeanneau, J. N. H. Reek, H. Olivier-Bourbigou, P.-A. R. Breuil, *Organometallics* **2015**, 34, 1139; f) S. Oldenhof, M. Lutz, B. de Bruin, J. I. van der Vlugt, J. N. H. Reek, *Chem. Sci.* **2015**, 6, 1027; g) S. Oldenhof, M. Lutz, B. de Bruin, J. I. van der Vlugt, J. N. H. Reek, *Organometallics* **2014**, 33, 7293; h) T. León, M. Parera, A. Roglans, A. Riera, X. Verdager, *Angew. Chem. Int. Ed.* **2012**, 51, 6951; *Angew. Chem.* **2012**, 124, 7057.
- [5] PhD thesis of FWP (2009, HIMS, University of Amsterdam).
- [6] a) H. Günther, *Angew. Chem. Int. Ed. Engl.* **1972**, 11, 861; *Angew. Chem.* **1972**, 84, 907; b) H. Günther, *NMR Spectroscopy Second Edition. Basic Principles, Concepts and Applications in Chemistry* **1995**, publisher, Wiley.
- [7] See experimental section.

- [8] F. G. Terrade, M. Lutz, J. N. H. Reek, *Chem. Eur. J.* **2013**, *19*, 10458, the X-ray structure of $\text{Rh}_2(\text{nbd})_2(\text{R-L}^2)_2\text{-Rh}_2(\text{nbd})_2(\text{S-L}^2)_2$: CCDC-931393. CCDC 931393 (for $\text{Rh}_2(\text{nbd})_2(\text{R-L}^2)_2\text{-Rh}_2(\text{nbd})_2(\text{S-L}^2)_2$) contains the supplementary crystallographic data for this paper. These data can be obtained free of charge from The Cambridge Crystallographic Data Centre.
- [9] ^1H - ^{103}Rh HMQC NMR, selected references: a) J. M. Ernsting, S. Gaemers, C. J. Elsevier, *Magn. Reson. Chem.* **2004**, *42*, 721; b) R. Fornika, H. Goerls, B. Seemann, W. Leitner, *J. Chem. Soc., Chem. Commun.* **1995**, *14*, 1479; c) W. Leitner, M. Buehl, R. Fornika, C. Six, W. Baumann, E. Dinjus, M. Kessler, C. Krueger, A. Rufinska, *Organometallics* **1999**, *18*, 1196; d) C. J. Elsevier, B. Kowall, H. Kragten, *Inorg. Chem.* **1995**, *34*, 4836; e) J. G. Donkervoort, M. Buehl, J. M. Ernsting, C. J. Elsevier, *Eur. J. Inorg. Chem.* **1999**, *27*; f) L. Orian, A. Bisello, S. Santi, A. Ceccon, G. Saielli, *Chem. Eur. J.* **2004**, *10*, 4029; g) M. Bühl, W. Baumann, R. Kadyrov, A. Borner, *Helv. Chim. Acta* **1999**, *82*, 811.
- [10] For ^{195}Pt NMR, see: a) B. M. Still, P. G. A. Kumar, J. R. Aldrich-Wright, W. S. Price, *Chem. Soc. Rev.* **2007**, *36*, 665; b) E. Gabano, E. Marengo, M. Bobba, E. Robotti, C. Cassino, M. Botta, D. Osella, *Coord. Chem. Rev.* **2006**, *250*, 2158; c) K. R. Koch, M. R. Burger, J. Kramer, A. N. Westra, *Dalton Trans.* **2006**, 3277; d) J. R. L. Priqueler, I. S. Butler, F. D. Rochon, *Appl. Spect. Rev.* **2006**, *41*, 185.
- [11] G. H. Rentsch, W. Kozminski, W. von Philipsborn, F. Asaro, G. Pellizer, *Magn. Reson. Chem.* **1997**, *35*, 904.
- [12] a) P. J. Stephens, F. J. Devlin, C. F. Chabalowski, M. J. Frisch, *J. Phys. Chem.* **1994**, *98*, 11623–11627; b) A. D. Becke, *J. Chem. Phys.* **1993**, *98*, 5648–5652; c) A. D. Becke, *Phys. Rev. A* **1988**, *38*, 3098–3100; d) C. Lee, W. Yang, R. G. Parr, *Phys. Rev. B* **1988**, *37*, 785–789; e) S. H. Vosko, L. Wilk, M. Nusair, *Can. J. Phys.* **1980**, *58*, 1200–1211.
- [13] a) F. Weigend, R. Ahlrichs, *Phys. Chem. Chem. Phys.* **2005**, *7*, 3297–3305; b) F. Weigend, *Phys. Chem. Chem. Phys.* **2006**, *8*, 1057–1065.
- [14] D. Andrae, U. Häußermann, M. Dolg, H. Stoll, H. Preuß, *Theor. Chim. Acta* **1990**, *77*, 123–141.
- [15] S. Grimme, J. Antony, S. Ehrlich, H. Krieg, *J. Chem. Phys.* **2010**, *132*, 154104.
- [16] TURBOMOLE V7.2 2017, a development of University of Karlsruhe and Forschungszentrum Karlsruhe GmbH, 1989–2007, TURBOMOLE GmbH, since 2007; available from <http://www.turbomole.com>.
- [17] H. B. Schlegel, *J. Comput. Chem.* **1982**, *3*, 214–218.
- [18] M. J. Frisch, G. W. Trucks, H. B. Schlegel, G. E. Scuseria, M. A. Robb, J. R. Cheeseman, G. Scalmani, V. Barone, B. Mennucci, G. A. Petersson, H. Nakatsuji, M. Caricato, X. Li, H. P. Hratchian, A. F. Izmaylov, J. Bloino, G. Zheng, J. L. Sonnenberg, M. Hada, M. Ehara, K. Toyota, R. Fukuda, J. Hasegawa, M. Ishida, T. Nakajima, Y. Honda, O. Kitao, H. Nakai, T. Vreven, J. A. Montgomery Jr., J. E. Peralta, F. Ogliaro, M. Bearpark, J. J. Heyd, E. Brothers, K. N. Kudin, V. N. Staroverov, R. Kobayashi, J. Normand, K. Raghavachari, A. Rendell, J. C. Burant, S. S. Iyengar, J. Tomasi, M. Cossi, N. Rega, J. M. Millam, M. Klene, J. E. Knox, J. B. Cross, V. Bakken, C. Adamo, J. Jaramillo, R. Gomperts, R. E. Stratmann, O. Yazyev, A. J. Austin, R. Cammi, C. Pomelli, J. W. Ochterski, R. L. Martin, K. Morokuma, V. G. Zakrzewski, G. A. Voth, P. Salvador, J. J. Dannenberg, S. Dapprich, A. D. Daniels, Ö. Farkas, J. B. Foresman, J. V. Ortiz, J. Cioslowski, D. J. Fox, *Gaussian 09, Revision D.01*, Gaussian, Inc., Wallingford CT, **2016**.
- [19] A. Klamt, G. Schüürmann, *J. Chem. Soc. Perkin Trans. 2* **1993**, 799–805.

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