Skeletal change in the PNP pincer ligand leads to a highly regioselective alkyne dimerization catalyst†

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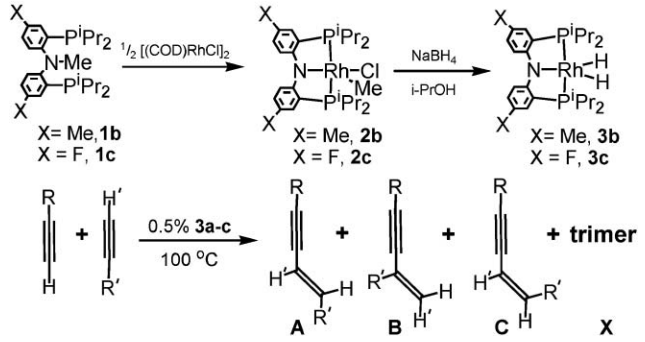
A Rh complex of a bulky diarylamino-based PNP pincer ligand is a robust catalyst for the dimerization of terminal alkynes and highly selective for the *trans*-enyne product.

Alkyne dimerization is an attractive, atom-economical method of synthesizing conjugated enynes.[1] Conjugated enynes are attractive as building blocks in organic synthesis and components of biologically active molecules.[2] The challenge is tuning the selectivity to the desired enyne isomer (**A**, **B** or **C**, Scheme 1).[3–7] Additionally, dimerization to butatrienes, alkyne cyclotrimerization, oligo-, and polymerization are often viable competing processes. Few examples of highly selective catalysis have been reported.[3–7] Lanthanide catalysts are capable of producing head-to-head *cis*-enynes (**C**, Scheme 1) with high selectivity.[5] Methly alumoxane has been shown to catalyze selective alkyne dimerization to the *gem*-enynes **B**.[6] Pd and Ni catalysts have been shown to produce the *trans*-enynes **A**,[7] but the chemo- and the regioselectivity, as well as the breadth of their scope, are not ideal.

We have been engaged in the transition metal chemistry of the diarylamido-based PNP pincer ligands (such as those in **2** and **3**, Scheme 1).[8] Related ligands have been used by other groups as well.[9] We have recently described that N–C oxidative addition (to give **2a–c**) provides a way to introduce anionic diarylamido-PNP ligands into the coordination sphere of Rh.[8] Compounds **2a–c** can be efficiently converted to the dihydrides (PNP)RhH_2 (**3a–c**) by action of $NaBH_4$ in ^{i}PrOH.



Scheme 1

We have previously discussed that the "tied" ^{T}PNP ligand, such as in **3a**, exerts a greater degree of steric pressure than the "untied" ^{Me}PNP ligand, such as in **3b** (or ^{F}PNP in **3c**).[8] Here this disparity leads to a qualitative difference in the solid state structures of **3a** and **3b**.‡ **3a** is a monomer in the solid state, but **3b** is a dimer, loosely bound by bridging hydrides (Fig. 1). The nature of the bridge-bonding is outside the scope of this report, but the resistance to dimerization by ^{T}PNP is in accord with its greater steric bulk. Notably, the P–Rh–P angle in **3b** (156.58(16)°) is much smaller than that in **3a** (169.11(6)°). This contraction in **3b** is in part necessary to accommodate the dimeric solid state structure. The smaller P–Rh–P angle corresponds to a greater twist of the PNP backbone resulting in a larger angle between the two aromatic rings. Such a distortion is barred in **3a** by the CH_2CH_2 linker connecting the two aromatic rings in ^{T}PNP.

In solution, the hydrides of each of **3a–c** give rise to a single resonance, split into a doublet of triplets ($J_{Rh-H} \approx 21$ Hz, $J_{H-P} \approx 9$ Hz) at similar chemical shifts in their ^{1}H NMR spectra. The ^{31}P NMR resonances of **3a–c** possess similar chemical shifts as well. The unsymmetric dimer was not observed upon co-dissolution of **3b** and **3c**. All of this is indicative of a monomeric structure for **3a–c** in solution. Presumably, **3a–c** in solution adopt the Y-shaped 5-coordinate geometry that is also observed for $Cl(P^iPr_3)_2RhH_2$.[10] Pertinent analysis of the structural preferences of 5-coordinate d^6 complexes can be found elsewhere.[11]

All three compounds **3a–c** are active as alkyne dimerization catalysts (Scheme 1, Table 1). None of the catalysts give rise to isomer **C**. **3a** is both more active and more selective for the formation of **A** than **3b** or **3c**. **3a** is capable of the essentially regiospecific production of **A** for a variety of different 1-alkynes. Dimerization of $HC{\equiv}CCH_2NMe_2$ is an exception, perhaps owing to the possibility of coordination of the amino group.[12] While a few other catalysts have been reported to display selectivity for **A**,[7] none match **3a** in both scope and selectivity. Moreover, few

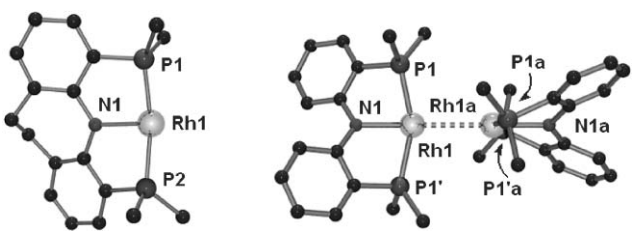


Fig. 1 POV-Ray renditions§[1] of the X-ray solid state structures of **3a** (left) and **3b** (right). The Me groups of the ^{i}Pr groups and those on the aromatic ring in **3a**, as well as all H atoms, are omitted for clarity.

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Table 1 Alkyne dimerization with catalysts **3a–c**[a]

#	R	Catalyst	Time/h	**A** : **B** : **X**[b]	% Conversion[c]
1	Ph	**3a**	8	99 : 1 : 0	98
2	4-MeC_6H_4	**3a**	7	98 : 2 : 0	98 (98)[e]
3	4-FC_6H_4	**3a**	7	99 : 1 : 0	99
4	^{n}Bu	**3a**	7	99 : <1 : 0	97
5	^{n}Pr	**3a**	3	99 : 1 : 0	100
6	Me_2NCH_2	**3a**	120	90 : 10 : 0	63
7	^{t}Bu	**3a**	120	58 : 0 : 35[d]	89
8	Me_3Si	**3a**	13	90 : <1 : 10	92
9	Me_3SiOCH_2	**3a**	13	98 : 2 : 0	90
10	$HOCH_2$	**3a**	3	97 : 3 : 0	98 (96)[e]
11	Ph	**3b**	120	99 : 1 : 0	57
12	4-MeC_6H_4	**3b**	120	98 : 2 : 0	85
13	4-FC_6H_4	**3b**	120	98 : 2 : 0	60
14	^{n}Bu	**3b**	120	68 : 32 : 0	73
15	^{n}Pr	**3b**	120	66 : 34 : 0	62
16	Me_2NCH_2	**3b**	120	74 : 26 : 0	40
17	^{t}Bu	**3b**	120	78 : 0 : 22	14
18	Me_3Si	**3b**	120	83 : 2 : 11[d]	87
19	Me_3SiOCH_2	**3b**	120	50 : 50 : 0	16
20	$HOCH_2$	**3b**	120	70 : 30 : 0	65
21	Ph	**3c**	120	99 : 1 : 0	64
22	^{n}Pr	**3c**	120	60 : 40 : 0	44

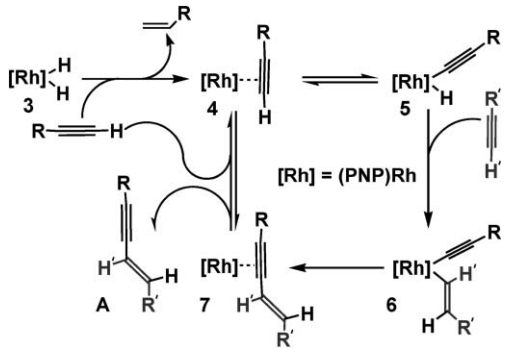
[a] Reactions performed at 100 °C in 0.5 mL of C_6D_6, 3.29 mmol alkyne and 0.5 mol% catalyst. [b] By ^{1}H NMR integration, ±2%; GC-MS was used to verify the identity of each. [c] Fraction of consumed alkyne by ^{1}H NMR integration *vs.* an internal integration standard (1,4-dioxane), ±2%. [d] Balance tetramer. [e] Isolated yield in parentheses.

catalysts are this selective for *any* enyne isomer. In contrast to many other examples,[3–7] catalysis by **3a–c** does not require additives (*e.g.*, donor solvents or bases) and is also not plagued by cyclotrimerization and oligomerization. Small amounts of tri- and tetramers were observed only for the bulkiest (and slowest to react) alkynes. Products of cyclotrimerization were not detected for any of the substrates in Table 1, although the electron-deficient alkyne $HC{\equiv}CCO_2Et$ gave primarily cyclotrimerization products (see ESI†).

The catalysts employed in this study operate at a relatively high temperature, however, this corresponds to a low (0.5%) catalyst loading. With 1-pentyne as substrate, the catalyst (from **3a**) was active at the end of a standard reaction and continued functioning upon addition of further substrate with the same high regioselectivity (>600 turnovers were achieved). Catalysis by **3a–c** is not sensitive to hydroxyl groups in the substrate, is tolerant of water and, to some degree, also to air.† Such tolerance by **3a–c** is in contrast with the lanthanide catalysts which, albeit more active, are notoriously air and moisture sensitive.[5]

We tentatively propose the mechanism outlined in Scheme 2 to account for our observations. One equivalent of alkyne serves to strip the Rh center of two hydrogens *via* hydrogenation of the triple bond, producing an alkene by-product (observed by NMR in the reaction mixtures). The Rh^I alkyne complex **4** may undergo C–H oxidative addition to give the Rh^{III} hydrido–alkynyl complex **5**. Insertion of the second equivalent of alkyne is then possible into the Rh–H bond. C–C reductive coupling from **6** gives the enyne complex **7**. Displacement of the enyne by alkyne closes the catalytic loop. Werner *et al.* recently demonstrated the relevance of similar steps to alkyne dimerization.[13]

The proposed mechanism is consistent with the observed relative selectivity. The *cis*-isomer **C** is not observed with **3a–c**. **C**



Scheme 2 Proposed mechanism of alkyne dimerization.

cannot be produced when insertion of an alkyne into a Rh–H bond is involved (**5** → **6**). The choice between **A** and **B** is made at the same insertion step (**5** → **6**). Positioning of the non-H substituent away from Rh should be preferred for steric reasons. The more sterically imposing ^{T}PNP should therefore lead to higher preference for **A**, as is the case.

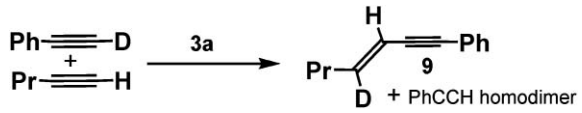
A closely related mechanistic proposal has been put forth recently by Ogoshi and Kurosawa for the Ni^0/P^tBu_3 system to account for a preference for **A**.[7] Goldman *et al.* and Ishikawa *et al.* proposed a similar mechanism for alkyne dimerization by the $[(Me_3P)_2RhCl]_2$ and the $(Ph_3P)_3RhCl$ fragment, respectively.[4d,14] The selectivity in the catalysis provided by $(Ph_3P)_3RhCl$ and $[(Me_3P)_2RhCl]_2$ varied greatly depending on the alkyne, presumably because of the lack of steric enforcement of **A** over **B** (but **C** was not observed).[4d,14] Our PNP ligand family was designed, among other reasons, to serve as a chelate analogue of the ubiquitous *mer*-$Cl(R_3P)_2$ motif.[8] Other Rh compounds have been shown to catalyze alkyne dimerization, but with inferior selectivities, requiring additives such as MeI or bases, and often by mechanisms other than the one proposed here.[3,4,14]

Preparation of three carbonyl derivatives (**8a–c**, Table 2) allowed us to assess the electronic properties of the three PNP ligands. Based on this analysis, **3b** is closer to **3a** electronically, while nearly identical to **3c** sterically. Since the selectivity of **3b** as a catalyst differs greatly from that of **3a** but is almost identical to that of **3c**, the selectivity most likely arises from their steric differences.¶

We were able to isolate the enyne complex **7a-Ph** (R = Ph, ^{T}PNP ligand). It is the terminal organometallic product of the reaction of **3a** with PhC≡CH. Solution NMR studies indicate coordination of Rh to the triple bond, which acts as a 2-electron donor[15] ($^{13}C\{^1H\}$ NMR: δ 93.9 (dt, J_{C-Rh} = 7 Hz, J_{C-P} = 4 Hz), 86.8 (br d, J_{C-Rh} = 12 Hz); ^{1}H NMR: δ 7.74 and 6.96 (both: d, 16 Hz, olefinic CH)). **7a-Ph** catalyzes the dimerization of PhC≡CH with the same selectivity (and very similar activity) as **3a**.† Addition of excess enyne **A-Ph** (R = Ph, Scheme 2) had no discernible effect on the rate of dimerization of PhC≡CH.

Table 2 Comparative electronic and catalytic properties of PNP complexes

$(PNP)Rh_2$ catalyst	**3a**	**3b**	**3c**
PrCCH dimer, selectivity **A** : **B**	99 : 1	66 : 34	60 : 40
ν_{CO} of (PNP)Rh(CO) (**8**)/cm^{-1}	1943	1945	1950



Scheme 3

We also designed an experiment (inspired by a literature example)[14] to test for the intermediacy of a vinylidene complex. Cross-dimerization of PhC≡CH and ^{n}PrC≡CH produced only one isomer of the cross-dimer and the homodimer of PhC≡CH. The analogous reaction between PhC≡CD and ^{n}PrC≡CH has led only to a single isotopomer of **9**, shown in Scheme 3. Had a vinylidene formed from either of the alkynes, the two substituents on the triple bond (Ph and D or Pr and H) would have been found on the same carbon in the product. As this was not the case, a vinylidene can be ruled out as an intermediate.

In summary, we are reporting a regiospecific, moisture- and somewhat air-tolerant alkyne dimerization catalyst, as well as the mechanistic proposals. The increased selectivity of the ^{T}PNP-based catalyst is believed to arise from skeletal adjustment in the pincer ligand that does not affect the substitution on the atoms directly bound to the metal. The robustness of the PNP catalysts presumably originates from the insensitivity of a late metal, such as Rh, to O-based functionalities and impurities, as well as the rigid and strong binding of Rh by the PNP ligand. The latter factor defines the coordination sphere and restricts the reactivity of the remaining coordination sites.

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Notes and references

‡ Crystal data **3a**: $C_{26}H_{40}NP_2Rh$, M = 531.46, orthorhombic, space group: $P2_12_12_1$, a = 10.3888(4), b = 12.6906(13), c = 20.1427(8) Å, U = 2655.6(3) Å^3, Z = 4, ρ_{calc} = 1.329 g cm^{-3}, T = 294 K, μ(Mo-Kα) = 0.779 mm^{-1}, plate-like habit, red-orange, 0.29 × 0.36 × 0.50 mm. Data collected on an Enraf-Nonius CAD-4U diffractometer, 4468 unique data, 2818 [$I > 1.96\sigma(I)$], 271 parameters, R = 0.0489, R_w = 0.0505, Flack X = 0.37(6), CCDC 281662. Crystal data for **3b**: $C_{26}H_{42}NP_2Rh$, M = 533.48, tetragonal, space group: $I4_1/a$, a = 18.053(14), b = 18.053(14), c = 16.603(5) Å, U = 5411(6) Å^3, Z = 8, ρ_{calc} = 1.310 g cm^{-3}, T = 294 K, μ(Mo-Kα) = 0.765 mm^{-1}, diamond-like habit, red-orange, 0.14 × 0.29 × 0.29 mm. Data collected on an Enraf-Nonius CAD-4 Turbo diffractometer, 2050 unique data, 913 [$I > 1.96\sigma(I)$], 137 parameters, R = 0.0578, R_w = 0.0534, CCDC 281663. For both **3a** and **3b** the bridging H atoms (2 per Rh) were not located. For crystallographic data in CIF or other electronic format see DOI: 10.1039/b511148j

§ Created using Persistence of Vision Ray Tracer (POV-Ray, http://www.povray.org/) and Ortep-3 for Windows.[16]

¶ The ^{T}PNP complexes also possess a different twist angle of the amido plane with respect to the coordination square plane of the metal.[8] We cannot exclude the possibility that this contributes to the difference in reactivity.

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