Monoaryloxide Pyrrolide (MAP) Imido Alkylidene Complexes of Molybdenum and Tungsten That Contain 2,6-Bis(2,5-R2-pyrrolyl)phenoxide (R = i-Pr, Ph) Ligands and an Unsubstituted Metallacyclobutane on Its Way to Losing Ethylene

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ABSTRACT: We report the synthesis of Mo and W MAP complexes that contain O-2,6-(2,5-R2-pyrrolyl)2C6H3 (2,6-dipyrrolylphenoxide or ODPPR) ligands in which R = i-Pr, Ph. W(NAr)(CH-t-Bu)(Pyr)-(ODPPPh) (4a; Ar = 2,6-disopropylphenyl, Pyr = pyrrolyl) reacts readily with ethylene to yield a metallacyclobutane complex, W(NAr)(C3H6)(Pyr)-(ODPPPh) (5). The structure of 5 in the solid state shows that it is approximately a square pyramid with the WC4 ring spanning apical and basal positions. This SP′ structure, which has never been observed as an actual intermediate, must now be regarded as an integral feature of the metathesis reaction.

In the last several years sterically demanding phenoxide ligands have been employed to make Mo- and W-based MAP (monoaryloxide pyrrolide) catalysts for stereoselective olefin metathesis reactions. One of the first was OBr2Bitet, an enantiomerically pure monophenoxide ligand that yielded diastereomeric mixtures of MAP catalysts (R′ = H, Me) for enantioselective ring-opening/cross-metathesis reactions. In the process, it was found that the reaction was not only enantioselective but also Z-selective. The search for other suitable sterically demanding phenoxides led to terphenoxides such as O-2,6-(2,4,6-i-Pr3C6H2)2C6H3 (OHIPT)2 and O-2,6-(mesityl)2C6H3 (OHMT),3 which were employed to produce Z-selective catalysts for ROMP4 and homometathesis of terminal olefins.5 Decafluoroterphenoxide (O-2,6-(C6F5)2C6H3 = ODFT) has now been added to the list of 2,6-terphenoxides.6 Recently it also has been possible to make bisaryloxide complexes that are especially efficient in certain stereoselective reactions, one example being Mo(NC6F5)(CHCMe2Ph)(OF2Bitet),7 where OF2Bitet is a fluorinated relative of OBr2Bitet.8 For all of the above reasons we felt it desirable to prepare and use other sterically demanding arylxide complexes in monoaryloxide or bisaryloxide olefin metathesis catalysts. Here we describe the synthesis of complexes that contain O-2,6-(2,5-R2-pyrrolyl)2C6H3 (2,6-dipyrrolylphenoxide or ODPP) ligands in which R = i-Pr, Ph.

2-Methoxy-1,3-diaminobenzene was prepared from 2-bromo-1,3-dinitrobenzene, as shown in eq 1. The pyrrolyl groups were then constructed by employing the desired γ-diketone in a Paal−Knorr condensation followed by deprotection with BBr3.

Both DPPiPrOH and DPPPhOH were purified by employing column chromatography and recrystallized from hexane (DPPiPrOH) or isopropyl alcohol. (See the Supporting Information for full details.)

Addition of 1 equiv of DPPiPrOH or DPPPhOH to Mo(NAd)(CHCMe2Ph)(Pyr)2, Mo(NAd)(CHCMe2Ph)(Me2Pyr)2, Mo(NAr)(CHCMe2Ph)(Pyr)2, and Mo(NAr)-(CHCMe2Ph)(Me2Pyr)2 (Ad = 1-adamantyl, Ar = 2,6-i-
Pr,C6H5, Pyr = pyrrole; Me,Pyr = 2,5-dimethylpyrrole) produced MAP complexes 1a,b, 2a,b, and 3a,b.

The reaction to give 1a required heating the mixture for 1 h at 80 °C, whereas the reaction to give 1b was complete at 22 °C (∼20 mM) within 4 h. For steric reasons, the reactions to give 2a,b are slower than those that yield 1a,b. It should be noted, for comparison, that both Mo(NAd)(CHCMe2Ph)(Pyr)-(OH)5 and Mo(NAr)(CHCMe2Ph)(Pyr)-(OH)5 have been prepared (the latter in situ) from Mo(NR)(CHCMe2Ph)-(Pyr)2 (R = Ad, Ar) and 1 equiv of HIPTOH. Therefore, ODPPph and ODPPiPr behave approximately like the HIPT ligand in terms of the synthesis of MAP species through protonation of bipyrrrolides, although apparently small steric differences between ligands can have profound consequences.

Figure 1. Thermal ellipsoid representation of the structure of 2b at the 50% probability level. The solvent molecule and hydrogen atoms are omitted for clarity.

The X-ray structure of Mo(NAr)(CHCMe2Ph)(Me2Pyr)-(ODPPiPr) (3b) is shown in Figure 1. The dihedral angles between the phenyl ring in ODPPiPr and the pyrrolyl rings are 70.3(2)°, consistent with the steric demand of the ODPPiPr ligand system being greater than that of the ODPPPh ligand system.

Reactions of MAP complexes with ethylene are becoming routine means of assessing the stability of metallacyclobutane and methyldiene complexes. For example, compound 4a reacts readily with ethylene to yield a metallacyclobutane complex, W(NAr)(C3H6)(Pyr)(ODPPPh) (5a). According to proton and carbon NMR data, 5 has a TBP geometry. Surprisingly, the structure of 5 in the solid state (Figure 3) is closer to a square pyramid than a TBP, according to the τ value (0.26), which for an SP is 0 and for a perfect TBP is 1.10 The metallacyclobutane carbon atom in approximately the apical position (W−C1 = 2.035(2) Å) is closer to the metal than is the carbon atom in the basal position (W−C2 = 2.083(2) Å) by a statistically significant amount (Figure 4). The C3−C2 bond lengths (1.590(3) and 1.603(3) Å) are statistically essentially the same but vary in the direction which implies that an ethylene that contains C2 and C3 is approaching or leaving the CNO face of W(NAr)(CH2)(Pyr)(ODPPPh) approximately trans to the pyrrolyl (Figure 4). The W−C(2) distance is 2.370(2) Å, which is 0.1−0.2 Å longer than a typical W−C single bond.

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complexes would never approach 1, as a consequence of the constraints inherent in a complex that contains a metallacyclobutane ring in the equatorial position; the maximum τ value is ~0.68. It should be noted that the W−C(2) distance of 2.370(2) Å in 5 is essentially what is found in the TBP structures.

Calculations concerning metallacyclobutanes made from MAP alkylidenes suggest that the SP structure is further than the transition state for olefin loss than a TBP structure, and an SP’ structure is the closest. All three can be interconverted readily through five-coordinate rearrangements. According to calculations the olefin approaches the more “open” CNO (imido/alkylidene/OR) face “trans” to the pyrrolide and forms an SP’ metallacyclobutane structure, without olefin binding to the metal, to give an intermediate alkylidene/olefin complex. The SP’ structure becomes a TBP when the O−M−N angle opens to ~180° and the pyrrolide moves into an equatorial position where the N1−M−C3 and N1−M−C1 angles are equal. A continuation of the movement of N2, N1, and O leads to a second SP’ structure in which the metallacyclobutane again spans apical (now C3) and basal (now C1) sites and the ethylene that is leaving the coordination sphere contains C1 and C2. Both from experiments and in terms of calculations the barrier for interconversion of TBP and SP forms is relatively low. TBP and SP’ metallacyclobutane structures would seem to be even more easily interconverted, since minimal movement of the imido and aryloxide ligands is required. The SP’/TBP/SP’ sequence is proposed to be the intimate mechanism of metathesis by a MAP catalyst, and the SP structure is a relatively low energy sink.

It is somewhat surprising that the SP’ structure, of which 5 is the first example to our knowledge, can be observed, but it is not clear why in this particular case. At this stage we can only offer that the energy difference between the SP’ and TBP structures is so low that intramolecular steric forces and/or packing forces in the crystal tip the balance in favor of SP’. So far there is no evidence for the SP’ structure in solution NMR spectra of 5. Evidence would consist of a loss of mirror symmetry in the metallacylobutane ring at low temperatures.

It should be noted that in NMR studies of Mo and W metallacyclobutane species it was found necessary to invoke a “methylenide/ethylene” intermediate in order that the kinetic scheme be self-consistent. However, no ethylene/methylenide has been found to be an intermediate through calculations.

Therefore, an important question is whether the intermediate observed in the NMR studies is an SP’ metallacycle instead of an “ethylene/methylenide” complex.

The ROMP polymerization of 50 equiv of 5,6-dicarboxymethoxynorbornadiene was chosen as an initial measure of the stereoselectivity of the six MAP catalysts described earlier. All polymers were found to have a >99% cis,syndiotactic structure, the same structure observed when the initiator is Mo(NAr)(CHCMe2Ph)(Pyr)(OHIPT).4a

In contrast, compounds 4a,b show markedly different behavior in the homometathesis of 1-oxene (Table 1). For comparison, W(NAr)(C6H6)(Pyr)(OHIPT)6 was employed under identical conditions. Catalyst 4a initially provides the product at a faster rate than 4b or 6, but selectivity for the Z product erodes over time, with 62% Z product being observed after 400 min. Catalyst 4b is much slower, providing 83% conversion over 400 min, but the Z configuration of the product is maintained, as it is with 6. The difference in performance between ODPP4b and ODPP5b highlights the extreme sensitivity of activity and Z-selectivity of MAP complexes to steric factors associated with the aryloxide.

Now that an SP’ metallacycle has been structurally characterized, a persistent question that remains is the degree
to which the structures and dynamics of unsubstituted metallacyclobutanes differ from the structures and dynamics of substituted metallacyclobutanes. Since substituted metallacyclobutanes are inherently more labile toward loss of olefin than unsubstituted metallacyclobutanes, obtaining answers to this question through experimental studies is likely to remain challenging.

ASSOCIATED CONTENT

Supporting Information
Text, tables, and CIF files giving experimental details for the synthesis of all compounds and details of X-ray structural studies. This material is available free of charge via the Internet at http://pubs.acs.org.

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Notes
The authors declare no competing financial interest.

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Table 1. Homocoupling of 1-Octene with 4a,b**

| catalyst | $t$ (min) | conversion (%) | $Z$ (%) |
|----------|-----------|---------------|----------|
| 4a       | 10        | 62            | >95      |
| 4a       | 40        | 72            | 90       |
| 4a       | 110       | 88            | 84       |
| 4a       | 400       | >95           | 62       |
| 4b       | 10        | 24            | -        |
| 4b       | 40        | 36            | -        |
| 4b       | 110       | 59            | >95      |
| 4b       | 400       | 83            | 94       |
| 6        | 10        | 5             | -        |
| 6        | 40        | 16            | -        |
| 6        | 110       | 46            | >95      |
| 6        | 400       | 93            | >95      |

*Conditions: 25 °C, 4 mol % catalyst loading, 0.3 M in C$_6$H$_6$. See the Supporting Information for details.