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Inversion of Configuration at the Metal in Diastereomeric Imido Alkylidene Monoaryloxide Monopyrrolide Complexes of Molybdenum

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Recently we discovered[1] that 14e Mo(NR)(CHR′)(OR″)(η^1-pyrrolide) (monoalkoxidepyrrolide, MAP) complexes can be prepared through addition of 1 equiv of alcohol to Mo(NR)(CHR′)-(pyrrolide)$_2$ complexes.[2] Of particular interest in terms of enantioselective metatheses are diastereomers that are formed when the alkoxide or aryloxide is enantiomerically pure. A dramatic example is Mo(NAr)(CHCMe$_2$Ph)(Me$_2$Pyr)(**1**) (**2**, where Ar = 2,6-diisopropylphenyl, Me$_2$Pyr = 2,5-dimethylpyrrolide, and **1** is the monophenoxide derived from (*R*)-3,3′-dibromo-5,5′,6,6′,7,7′,8,8′-octahydro-1,1′-bi-2-naphthol that is monoprotected with Si(*t*-Bu)Me$_2$) that serves as an initiator for an asymmetric ring-closing of an intermediate in the enantioselective synthesis of the Aspidosperma alkaloid, quebrachamine,[3] a reaction that yielded no product when several chiral Mo(NR)(CHR′)(diolate) catalysts[4] were employed. Initiator **2** can be prepared *in situ* and is effective (95% ee) at relatively low loadings as a 7:1 mixture of diastereomers. Two issues that arise concern the relative reactivity of diastereomers and their interconversion through inversion of configuration at the metal. Therefore we turned to an exploration of reactions between the diastereomers and 2e donors such as PMe$_3$, which are models[5] for the initial unobserved olefin adduct,[6] and the conditions under which inversion of configuration at Mo might take place.

A 7:1 mixture of the two diastereomers of Mo(NAr)(CHCMe$_2$Ph)-(Me$_2$Pyr)(**1**) ((*S*)-**2** and (*R*)-**2**, respectively[3,7]) is generated upon addition of (*R*)-**1H** to Mo(NAr)(CHCMe$_2$Ph)(Me$_2$Pyr)$_2$.[1] Pure (*S*)-**2**[3] and pure (*R*)-**2**[8] have both been isolated and structurally characterized. Each is unchanged in C$_6$D$_6$ or THF-d_8 after a week at 22 or 40 °C. The alkylidene is in the *syn* orientation in the solid state and in solution judging from the J_{CH} value (118 Hz in (*S*)-**2** and 122 Hz in (*R*)-**2**).

Trimethylphosphine (15 equiv) was added to pure (*S*)-**2** ([Mo] = 0.1 M, pentane). The solution was stored for several hours at 22 °C, and crystals of a phosphine adduct were isolated in good yield (75%). An X-ray structural study revealed that the product is (*R*)-**2**(PMe$_3$), not (*S*)-**2**(PMe$_3$). The overall structure is closest to a square pyramid with the *syn*-alkylidene in the apical position (Figure 1) and PMe$_3$ *trans* to the pyrrolide. The N2−Mo−P1 angle is 165.00(10)°, and the N1−Mo−O1 angle is 158.12(14)°, while the angles between C45 and the four other atoms bound to Mo are 100.31(17)° (to N1), 106.29(15)° (to N2), 100.75(15)° (to O1), and 85.61(12)° (to P1). The Mo−P1 distance (2.5703(11) Å) is relatively long and the Mo−P bond likely to be relatively weak.

When (*R*)-**2**(PMe$_3$) is dissolved in C$_6$D$_6$ or toluene-d_8, largely (*R*)-**2** and free PMe$_3$ are observed at room temperature. At a concentration of initial (*R*)-**2**(PMe$_3$) equal to 10 mM at −30 °C, largely (*R*)-**2**(PMe$_3$) is observed, while at 40 °C only free PMe$_3$ and (*R*)-**2** are observed. Over a period of 8 h at 40 °C, (*R*)-**2** is converted into an equilibrium mixture of (*R*)-**2** and (*S*)-**2** (K_{eq} = [(*S*)-**2**]/[(*R*)-**2**] = 2.0 at 40 °C). The approach to equilibrium at 40 °C depends on PMe$_3$ concentration to the first order (as shown in runs between 10 and 50 mM total PMe$_3$ concentration) and follows classic behavior,[9] with $k_{RS} + k_{SR} = 9.0 \times 10^{-3}$ M^{-1} s^{-1}. In THF-d_8 at 40 °C, $k_{RS} + k_{SR} = 14 \times 10^{-3}$ M^{-1} s^{-1} (K_{eq} = 2.0), and in 1:1 acetonitrile-d_3/C$_6$D$_6$ at 40 °C, $k_{RS} + k_{SR} = 24 \times 10^{-3}$ M^{-1} s^{-1} (K_{eq} = 0.8). (In the absence of PMe$_3$ in the last experiment, ∼5% inversion can be observed after several days at 60 °C; therefore, inversion by acetonitrile is extremely slow compared to inversion by PMe$_3$.) All results are consistent with PMe$_3$-catalyzed interconversion of (*R*)-**2** and (*S*)-**2**.

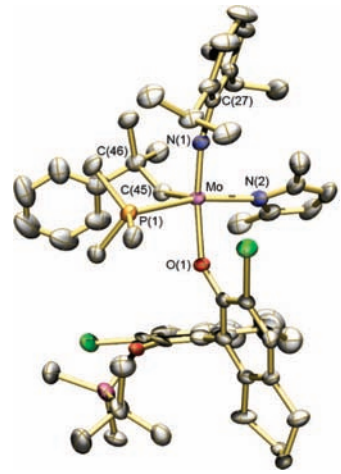

Figure 1. POV-ray drawing of (*R*)-**2**(PMe$_3$). Thermal ellipsoids are displayed at 50% probability level. Hydrogen atoms are omitted.

Inversion at Mo is also catalyzed by PPhMe$_2$ and (neat) pyridine-d_5. For 1 M PPhMe$_2$ in C$_6$D$_6$ at 40 °C, $k_{RS} + k_{SR} = 1.5 \times 10^{-5}$ M^{-1} s^{-1}, 600 times slower than the PMe$_3$-catalyzed reaction. Inversion by pyridine-d_5 and (very slowly) acetonitrile (see above) rules out any required reaction between the 2e donor ligand and some ligand bound to the metal (e.g., between the phosphine and the alkylidene to yield an intermediate and unobservable ylide complex). The lack of any dramatic solvent effect argues against ionization to yield a four-coordinate cation with pyrrolide or aryloxide as the anion.

Mixtures of largely (*S*)-**2**, (*S*)-**2**(PMe$_3$), and PMe$_3$ (2 equiv) in toluene-d_8 between −30 and 22 °C were examined by ^{1}H NMR, and formation of (*R*)-**2** and (*R*)-**2**(PMe$_3$) was monitored. After ∼6 h at 22 °C, *four* phosphine adducts were observed, (*S*)-**2**(PMe$_3$) (δH_α = 15.51 ppm at −30 °C, J_{CH} = 121 Hz, J_{HP} = 5 Hz), (*S*)-**2′**(PMe$_3$) (∼20% of total (*S*) adduct; δH_α = 13.94 ppm, J_{HP} = 6 Hz), (*R*)-**2′**(PMe$_3$) (∼5% of total (*R*) adduct; δH_α = 14.86 ppm, J_{HP} = 8 Hz), and (*R*)-**2**(PMe$_3$) (δH_α = 13.83 ppm, J_{CH} = 122 Hz, J_{HP} = 7 Hz), along with (*S*)-**2** and (*R*)-**2**; the amount of each depends upon time, temperature, concentration, and the amount of PMe$_3$ present. In all four adducts, coupling of the alkylidene H$_\alpha$ proton

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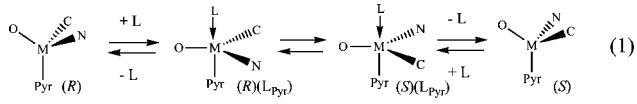
to ^{31}P is lost as the temperature is raised, equilibria shift toward phosphine free species, and (*S*)-**2** and (*R*)-**2** interconvert.

To further identify the adducts, ^{15}N- or ^{13}C-labeled analogues were prepared. In analogues that contain ^{15}N-labeled dimethylpyrrolide, couplings of ^{15}N to ^{31}P are 24.1 Hz in (*S*)-**2**(PMe_3), 26.5 Hz in (*S*)-**2′**(PMe_3), 31.6 Hz in (*R*)-**2′**(PMe_3), and 26.5 Hz in (*R*)-**2**(PMe_3). Since pyrrolide is *trans* to PMe_3 in (*R*)-**2**(PMe_3), we propose that it is *trans* to the pyrrolide in all four adducts. In analogous $^{13}C_\alpha$-labeled neopentylidene complexes, (*R*)-**2′**(PMe_3) (<5% of total adducts) was identified as an *anti* species (J_{CH} = 143 Hz), while (*S*)-**2′**(PMe_3) is *syn* (J_{CH} = 120 Hz); the difference between (*S*)-**2′**(PMe_3) and (*S*)-**2**(PMe_3) is ascribed to different conformations of the aryloxide in the crowded environment. NOESY studies confirm (*R*) and (*S*) assignments.

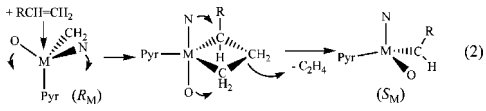
All data are consistent with inversion at Mo in fluxional five-coordinate adducts. In terms of trigonal bipyramidal (TBP) intermediates (as shown in eq 1; SP species analogous to the observed structure of (*R*)-**2**(PMe_3) in the solid state are alternatives), L enters *trans* to the pyrrolide (Pyr) to give (*R*)(L_{Pyr}). A series of Berry pseudorotations or (equivalent) turnstile rearrangements[10] permutes the alkylidene and imido positions to give (*S*)(L_{Pyr}), from which L leaves *trans* to Pyr to give (*S*)-**2**. Entry and exit of L only *trans* to Pyr in the two diastereomers is consistent with the structure of (*R*)-**2**(PMe_3) and is the most unifying proposal in our opinion. Catalyzed inversion at M by PMe_3 is the most efficient, and a PMe_3 adduct is the only one that can be isolated.



(1)

We then turned to an exploration of reactions between (*S*)- or (*R*)-Mo(NAr)($CHCMe_2Ph$)(Me_2Pyr)(**1**) and ethylene, which is often generated in ring-closing reactions of terminal or 1,1-disubstituted olefins. These reactions give rise to observable (*S*)- or (*R*)-Mo(NAr)(CH_2)(Me_2Pyr)(**1**) (67% at 10 °C, δH_α = 12.35, 12.13; 33% at 10 °C, δH_α = 12.94, 12.24) and Mo(NAr)($CH_2CH_2CH_2$)(Me_2Pyr)(**1**) (at −70 °C, δH_α = 6.16, 5.69, 5.24, 5.03; δH_β = 0.74, −0.16). The two interconvert readily on the NMR time scale (at 22 °C) through gain and loss of ethylene, respectively. Although Mo(NAr)($CH_2CH_2CH_2$)(Me_2Pyr)(**1**) loses ethylene readily, and therefore is not likely to be isolable, its NMR parameters are analogous to those of W(NAr)($CH_2CH_2CH_2$)(Me_2Pyr)(**1**), which has been isolated and shown in an X-ray structure to be an essentially undistorted TBP with apical imido and aryloxide ligands and dimethylpyrrolide in the equatorial plane.[11] (Reactions involving ethylene and Mo and W MAP species will be reported in detail separately.) It is clear that inversion at the metal can be fast on the NMR time scale near room temperature.

We propose that an olefin attacks the metal in MAP species *trans* to the pyrrolide ligand to form an intermediate metallacyclobutane that contains the pyrrolide and two carbons of the resulting metallacycle in equatorial positions (e.g., eq 2). The product olefin



(2)

(ethylene in this example) then leaves *trans* to the pyrrolide to generate the new alkylidene (M = CHR in this case) with the opposite configuration at M. In effect, the reactant olefin enters "*trans*" to the pyrrolide and the product olefin leaves "*trans*" to the pyrrolide, all via an intermediate TBP with axial imido and aryloxide ligands, inverting the configuration at M with each metathesis step. This proposal is consistent with recent calculations[6] if it is assumed that pyrrolide is a "donor" relative to the aryloxide (the "acceptor," relatively), and with the preferred approach of PMe_3 described above.

It seems likely that inversion at M by an olefin will be faster than a reaction that involves rearrangement of a five-coordinate olefin adduct, in part because a metallacyclobutane ring forms rapidly. (There is only one reported observation of an olefin adduct of a high oxidation state alkylidene.[12]) That being said, it also should be noted that rearrangement of the five-coordinate metallacyclobutane itself might compete with loss of olefin in circumstances where the metallacyclobutane lifetime is relatively long, i.e., in tungstacyclobutane species. The speed of metathesis/inversion at M is expected to vary widely and exceptionally finely as steric interactions generated in reactions between a given diastereomer and a given olefin become more significant and unavoidable.

To the best of our knowledge, it has not been possible to probe "inversion" at a catalytically competent tetrahedral transition metal center to which four ligands are covalently bound, especially if one of those ligands is exchanged during catalysis/inversion. Inversion at M in imido alkylidene complexes is a central issue in the context of enantioselective metathesis reactions that involve MAP species.[3,8] Lastly, controlling inversion at the metal is key to the long-sought goal of employing "stereogenic-at-metal" complexes for possibly more efficient enantioselective reactions.[13]

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Supporting Information Available: Experimental details and crystallographic data (CIF). This material is available free of charge via the Internet at http://pubs.acs.org.

References

(1) Singh, R.; Schrock, R. R.; Müller, P.; Hoveyda, A. H. *J. Am. Chem. Soc.* **2007**, *129*, 12654.
(2) Hock, A.; Schrock, R. R.; Hoveyda, A. H. *J. Am. Chem. Soc.* **2006**, *128*, 16373.
(3) Malcolmson, S. J.; Meek, S. J.; Sattely, E. S.; Schrock, R. R.; Hoveyda, A. H. *Nature*, published online November 16, 2008, doi: 10.1038/nature07594.
(4) (a) Schrock, R. R.; Hoveyda, A. H. *Angew. Chem., Int. Ed.* **2003**, *42*, 4592. (b) Schrock, R. R.; Czekelius, C. C. *Adv. Synth. Catal.* **2007**, *349*, 55.
(5) (a) Schrock, R. R.; Crowe, W. E.; Bazan, G. C.; DiMare, M.; O'Regan, M. B.; Schofield, M. H. *Organometallics* **1991**, *10*, 1832. (b) Schrock, R. R.; Gabert, A. J.; Singh, R.; Hock, A. S. *Organometallics* **2005**, *24*, 5058. (c) Gabert, A. J.; Schrock, R. R.; Müller, P. *Chem. Asian J.* **2008**, *3*, 1535. (d) Adamchuk, J.; Schrock, R. R.; Tonzetich, Z. J.; Müller, P. *Organometallics* **2006**, *25*, 2364. (e) Feldman, J.; Schrock, R. R. *Prog. Inorg. Chem.* **1991**, *39*, 1.
(6) Poater, A.; Solans-Monfort, X.; Clot, E.; Coperet, C.; Eisenstein, O. *J. Am. Chem. Soc.* **2007**, *129*, 8207.
(7) To be less cumbersome, this notation will substitute for the full description of the diastereomers, i.e., (S_M)(R_1)-**2** and (R_M)(R_1)-**2**.
(8) Meek, S. J.; Malcolmson, S. J.; Li, B.; Schrock, R. R.; Hoveyda, A. H., unpublished results.
(9) Moore, J. W.; Pearson, R. G. *Kinetics and Mechanism*, 3rd ed.; John Wiley & Sons: New York, 1981.
(10) (a) Berry, R. S. *J. Chem. Phys.* **1960**, *32*, 933. (b) Gillespie, P.; Hoffman, P.; Klusacek, H.; Marquarding, D.; Pfohl, S.; Ramirez, R.; Tsolis, E. A.; Ugi, I. *Angew. Chem., Int. Ed.* **1971**, *10*, 687. (c) Westheimer, F. H. *Acc. Chem. Res.* **1968**, *1*, 70. (d) Ramirez, F. *Acc. Chem. Res.* **1968**, *1*, 168. (e) Mislow, K. *Acc. Chem. Res.* **1970**, *3*, 321. (f) Muetterties, E. L. *Acc. Chem. Res.* **1970**, *3*, 266. (g) Muetterties, E. L. *J. Am. Chem. Soc.* **1969**, *91*, 1636. (h) Muetterties, E. L. *J. Am. Chem. Soc.* **1969**, *91*, 4115.
(11) Jiang, A.; Schrock, R. R.; Hoveyda, A. H., unpublished results.
(12) Kress, J.; Osborn, J. A. *Angew. Chem., Int. Ed. Engl.* **1992**, *31*, 1585.
(13) (a) Brunner, H. *Angew. Chem., Int. Ed.* **1999**, *38*, 1194. (b) Fontecave, M.; Hamelin, O.; Ménage, S. *Top. Organomet. Chem.* **2005**, *15*, 271.

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