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Embedding an Allylmetal Dimer in a Chiral Cavity: The Unprecedented Stereoselectivity of a Twofold Wittig [1,2]-Rearrangement

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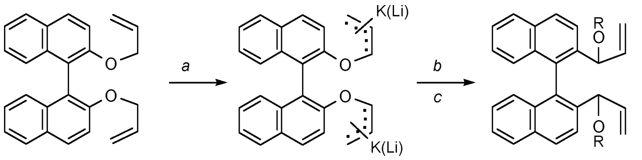
1,1′-Binaphthyl-2,2′-bis(diphenylphosphine) ("BINAP") is arguably the most popular ligand for the catalysis of asymmetric hydrogenation and isomerization reactions. The bisphosphine was originally prepared starting from 1,1′-binaphthalene-2,2′-diol ("BINOL"), a cornerstone of atropisomeric chemistry, through 2,2′-dibromonaphthalene[1] until an improved procedure based on the palladium-mediated condensation of the BINOL-derived 1,1′-binaphth-2,2′-diyl bis(trifluoromethane sulfonate) with diphenylphosphine was disclosed.[2] This triflate was also found to be amenable to a palladium-catalyzed methoxycarbonylation, providing dimethyl 1,1′-binaphthyl-2,2′-dicarboxylate in high yield.[3] This switch from oxygen to carbon functionality intrigued us. We wondered whether it could not be brought about in a different manner featuring a Wittig rearrangement as the key step. In fact, when a solution of 2,2′-di(2-propenoxy)-1,1′-binaphthyl in tetrahydrofuran was treated at −75 °C with the LIC−KOR mixture[4] (butyllithium + potassium *tert*-butoxide) before being neutralized at +25 °C, 1,1-(1,1′-binaphth-2,2′-diyl)bis(2-propen-1-ol) (**1a**; see Scheme 1) was isolated indeed in high yield (72% after recrystallization). The mother liquors contained not even trace amounts of a 3-(1,1′-binaphthyl)-substituted propanal. This would have resulted from a [1,4]- rather than [1,2]-migration, the former process being the predominant mode when alkyl allyl ethers, as opposed to aryl allyl ethers, are subjected to the rearrangement.[5]

The diol **1a** was converted into 1,1-(1,1′-binaphthyl-2,2′-bis(3-chloro-1-propene) (**2**). Consecutive *vic*-dihydroxylation of the olefinic double bonds using sodium periodate and osmium tetroxide-promoted glycol cleavage gave 1,1-dinaphthyl-2,2′-dicarbaldehyde (**3**, 63%; Scheme 2).[6] The dialdehyde **3** could be reduced with sodium borohydride to 1,1′-dinaphthyl-2,2′-bismethanol[7] and was oxidized with sodium chlorite to give 1,1′-dinaphthyl-2,2′-dicarboxylic acid[8] (**4**, 91%; Scheme 2). Repetition of the entire reaction sequence employing optically active BINOL[9] produced of course the enantiomerically pure diacid **4**.[10]

Due to its two exocyclic stereocenters, the diol **1** exhibits both axial and tetrahedral chirality. High crystallinity and a narrow melting range suggested immediately that *a single diastereoisomer was formed* in the course of the Wittig rearrangement. This was confirmed by X-ray crystallography of the 4-bromobenzoate **1b** (see Scheme 1). The axial chirality (*M*)[11] was found to be associated with the (*S*) configuration of the oxygen-bearing side chain and the (*P*)[11] helicity with the (*R*) configuration (see Scheme 3).

In the allyl alcohol family, diastereoselectivity can be readily traded in for enantioselectivity by applying the Sharpless−Katsuki epoxidation protocol[12] for kinetic racemate resolution. In fact, when the racemic mixture of (*M*)-(*S*,*S*)-**1a** and (*P*)-(*R*,*R*)-**1a** was exposed at −25 °C for 20 h to *tert*-butyl hydroperoxide, titanium tetraisopropoxide, and (+)-diisopropyl (*R*,*R*)-tartrate (DIPT) in dichloromethane and in the presence of molecular sieves, the (*P*)-(*R*,*R*)-**1** component was completely consumed, with the supposed (*R*,*R*)-bisepoxide **5** (27%) being isolated as the main product (Scheme 4). Enantiomerically pure (*M*)-(*S*,*S*)-**1a** was recovered almost quantitatively (Scheme 3).

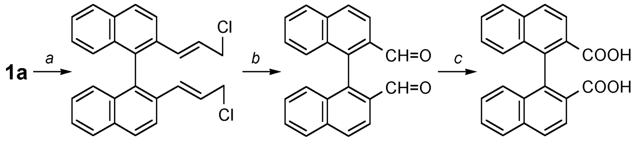
Scheme 1. Witting Rearrangement of 2,2′-Di(2-propenoxy)-1,1′-binaphthyl To Afford 1,1-(1,1′-Binaphth-2,2′-diyl)bis(2-propen-1-ol) (**1**; 72%)[a]



1a: OR = OH
1b: OR = OCO-C_6H_4-*p*-Br

[a] Conditions: (a) LiC_4H_9 + $KOC(CH_3)_3$ in tetrahydrofuran at −75 °C; (b) temperature increased to +25 °C; (c) H_2O.

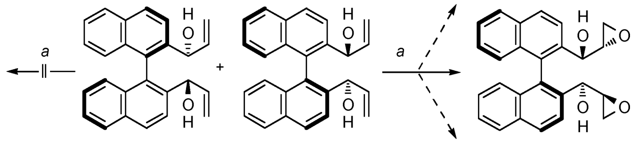
Scheme 2. Transformation of the Diol **1** to the Bis(allyl chloride) **2** (90%) and Oxidation of the Latter to the Dialdehyde **3** (82%) and the Dicarboxylic acid **4** (91%)[a]



2 **3** **4**

[a] Conditions: (a) Ethanolic hydrogen chloride; (b) OsO_4 (1%) + excess $NaIO_4$ in aqueous THF at 25 °C; (c) $NaClO_2$ + H_2O_2 in NaH_2PO_4-buffered aqueous acetonitrile at +40 °C.

Scheme 3. Kinetic Resolution of the Diol Stereoisomers (*M*)-(*S*,*S*)-**1a** and (*P*)-(*R*,*R*)-**1a** by the Sharpless−Katsuki Method[a]



(*M*)-(*S*,*S*)-**1a** : (*P*)-(*R*,*R*)-**1a** : **5**
48 % recov'd (*ee* ⩾ 99 %) consumed

[a] Conditions: (a) $(H_3C)_3COOH$ + $Ti(O^iC_3H_7)_4$ + (+)-DIPT in CH_2Cl_2 at 25 °C.

Irrespective of its practical potential, we need to rationalize the origin of this unprecedented diastereoselectivity. The phenomenon must have to do with intramolecular organometallic aggregation as the monoallyl ether **6** underwent stereochemically random rearrangement giving rise to a 1:1 mixture of (*R*) and (*S*) alcohols **7** (see Scheme 4). In contrast, the Wittig rearrangement of doubly metalated 2,2′-di(2-methyl-2-propenoxy)-1,1′-binaphthyl **8** proved again perfectly diastereoselective, affording the presumed (*M*)-(*S*,*S*)-**9** and (*P*)-(*R*,*R*)-**9** structures (Scheme 4).

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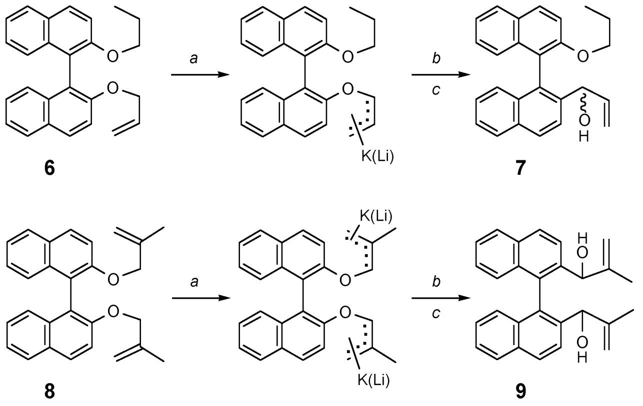
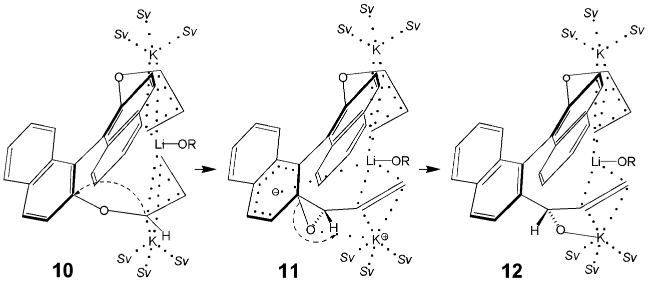
Scheme 4. Diastereochemically Unselective and Selective Rearrangement of Metalated 2-(Propenyloxy)-2′-propyloxy-1,1′-binaphthyl and Dimetalated 2,2′-Bis(2-methyl-2-propenyloxy)-1,1′-binaphthyl To Afford Products **7** (70%) and **9** (82%), Respectively[a]



[a] Conditions: (a) LiC$_4$H$_9$ + KOC(CH$_3$)$_3$ in tetrahydrofuran at −75 °C; (b) temperature increased to +25 °C; (c) H$_2$O.

Scheme 5. Metamorphosis of the Internal Bisallylmetal Aggregate **10** through the Meisenheimer Complex **11** to the Mixed Aggregate **12**, The Intermediate Formed in the First Rearrangement Step



[OR = OC(CH$_3$)$_3$; *Sv* = solvent (*i.e.* THF)]

Our detailed analysis of the rearrangement process relies on plausible assumptions. In view of the immense difference in O−M and C−M bond strength[13] (M = alkali metals), it is safe to surmise that allylpotassium species and lithium *tert*-butoxide prevail as soon as metallomeric equilibrium has been attained. With allyl−allyl distances of approximately 4.5 Å at a 45° aryl−aryl twist, the allyl units can readily assemble one on top of the other (constructing the internal aggregate **10**; see Scheme 5) to accommodate one or two lithium atoms in the pocket thus formed (average C−Li distance 2.3 Å[14]). On the other hand, no potassium atom (average C−K distance 3.2 Å[14]) fits into this gap, not even if the torsion angle were compressed to unrealistically small 25°. Thus, potassium has to occupy the outside allyl faces (Scheme 5, species **10**). In agreement with substituent effects on the rearrangement rates,[15] we believe the aryl [1,2]-migration occurs by intramolecular nucleophilic substitution (passing through a spiro-6-oxa[5,2]octa-3,5-dienide Meisenheimer complex **11**; see Scheme 5) rather than by the radical cleavage/recombination sequence[16] governing the alkyl [1,2]-migration and postulated[17] for the mono-rearrangement of a structurally related allyl naphthyl ether. If the carbon−carbon linking obeys the inversion mode with respect to the location of the potassium atom (and the retention mode with respect to lithium), the first new stereocenter should have the (*S*) configuration when accompanied by (*M*) helicity and the (*R*) configuration when associated with a (*P*) axis. The second rearrangement must follow instantaneously, before any structural reorganization can take place. The conversion of the dimetalated species **10** into the mono-rearranged species **12** (see Scheme 5) should weaken the intra-aggregate stabilization and hence provide an extra driving force for further transformation. Moreover, metal−π interactions[18] may well be operative in the new intermediate **12** (as shown in Scheme 5) and help to prevent a premature structural collapse of this mixed aggregate. Consequently, also the second rearrangement step will proceed under (*M*) → (*S*) and (*P*) → (*R*) stereocontrol.

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Supporting Information Available: Working procedures and complete characterization data for compounds **1a**, **1b**, and **2−9** and full crystallographic details of compound **1b** (including the associated CIF tables) are provided. This material is available free of charge via the Internet at http://pubs.acs.org.

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