Pergamon

Tetrahedron: *Asymmetry* 10 (1999) 2665–2674

TETRAHEDRON: *ASYMMETRY*

Synthesis, properties, and reactions of enantiomerically pure, chiral fluorous phosphines of the formula (menthyl)P($CH_2CH_2(CF_2)_{n-1}CF_3)_2$ (*n*=6, 8)

Alain Klose [a,b] and J. A. Gladysz [a,b,*,†]

[a] *Department of Chemistry, University of Utah, Salt Lake City, Utah 84112, USA*

[b] *Institut für Organische Chemie, Friedrich-Alexander Universität Erlangen–Nürnberg, Henkestrasse 42, D-91054 Erlangen, Germany*

Received 6 May 1999; accepted 24 June 1999

Abstract

Reactions of (menthyl)PH_2 and $H_2C{=}CHR_{f6}$ (menthyl=1*R*,3*R*,4*S*; $R_{fn}=(CF_2)_{n-1}CF_3$) or $H_2C{=}CHR_{f8}$ (AIBN, refluxing THF) give (menthyl)$PH(CH_2CH_2R_{fn})$ and then (menthyl)$P(CH_2CH_2R_{fn})_2$ (*n*=6, **7**; *n*=8, **8**), but with purification or other difficulties at each stage. Reactions of (menthyl)PCl_2 with $IMgCH_2CH_2R_{fn}$ give, under careful conditions, analytically pure **7** or **8** in 28–32% yields after distillation. Some $R_{fn}(CH_2)_4R_{fn}$ also form. These represent the first chiral (and non-racemic) fluorous phosphines. Reactions of **7** or **8** with $[Ir(COD)Cl]_2$ and CO give *trans*-$[(menthyl)P(CH_2CH_2R_{fn})_2]_2Ir(Cl)(CO)$ (*n*=6, 71%; 8, 51%) as analytically pure yellow oils. Their IR ν_{CO} values show the donor/acceptor properties of **7** and **8** to be intermediate between those of $P((CH_2)_3R_{f8})_3$ and $P((CH_2)_4R_{f8})_3$. The $CF_3C_6F_{11}$:toluene partition coefficients of **7** and **8** (27°C, 78.4:21.6 and 93.7:6.3) are distinctly lower than those of $P((CH_2)_2R_{fn})_3$ (*n*=6, 98.8:1.2; *n*=8, >99.7:<0.3), reflecting the replacement of a linear C_8–C_{10} group that is ca. 75–80% fluorinated by a cyclic C_{10} terpenyl group. Reactions of **7** or **8** with $[Rh(COD)Cl]_2$ give $[(menthyl)P(CH_2CH_2R_{fn})_2]Rh(Cl)(COD)$ (*n*=6, 69%; 8, 70%) as orange crystallizable oils.

1. Introduction

One important frontier of enantioselective organic synthesis is the development of easily recyclable chiral catalysts and reagents.[1] Recently, Horváth has popularized a conceptually innovative protocol, 'fluorous biphase chemistry', for catalyst or reagent recovery or immobilization.[2,3] The term fluorous is utilized as an analog to aqueous for highly fluorinated alkane, ether, or tertiary amine solvents. These

* Corresponding author. E-mail: gladysz@organik.uni-erlangen.de

† Address correspondence to the new Universität Erlangen–Nürnberg permanent address.

0957-4166/99/$ - see front matter
PII: S0957-4166(99)00272-4

non-polar media often give bilayers with organic solvents at room temperature. However, many systems become miscible at higher temperatures, allowing the option of homogeneous reaction conditions. Catalysts and reagents with exceptional fluorous phase affinities and recoverabilities can be obtained by appending sufficient numbers of fluoroalkyl groups or 'pony tails' of the formula $(CH_2)_m(CF_2)_{n-1}CF_3$ ($=(CH_2)_mR_{fn}$). The $(CH_2)_m$ spacers constitute tuning elements that can insulate the reaction center from the electron withdrawing fluorines (high *m*), or impart enhanced Lewis acidity (low *m*). Most educts and products encountered in organic synthesis have markedly greater affinities for the non-fluorous phase.[3c]

We recently reported efficient preparations of the aliphatic fluorous phosphines $P(CH_2CH_2(CF_2)_5CF_3)_3$ (**1**=$P(CH_2CH_2R_{f6})_3$) and $P(CH_2CH_2(CF_2)_7CF_3)_3$ (**2**=$P(CH_2CH_2R_{f8})_3$),[4] the corresponding rhodium complexes $ClRh[P(CH_2CH_2R_{fn})_3]_3$,[5] and related phosphines with longer CF_2 or CH_2 segments.[4] These compounds are catalysts for many organic transformations,[5–7] and can be recovered in high yields using fluorous solvents. The thermodynamic distribution between perfluoro(methylcyclohexane) ($CF_3C_6F_{11}$) and toluene phases has been measured, and partition coefficients are ≥98.8:1.2.[4] We sought to extend these studies to chiral phosphines, for which extensive applications in enantioselective synthesis are known. Due to their polarizable electron cloud, aryl groups commonly confer enhanced solubilities in non-fluorous phases.[3c] Hence, for initial testing and calibration, we decided to replace one of the $CH_2CH_2R_{fn}$ pony tails in **1** and **2** by a chiral aliphatic moiety. We selected a menthyl substituent,[8] which: (1) features approximately the same number of carbons; (2) has an extensive history of use in chiral phosphines;[9] and (3) has also been employed in closely related chiral, water soluble phosphines.[10]

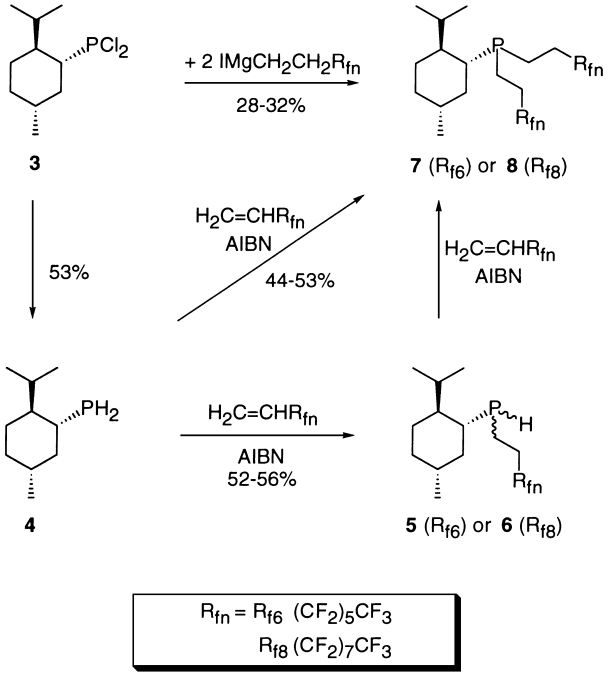
In this paper, we describe: (i) syntheses of the title menthyl phosphines; (ii) partition coefficients that quantify their affinities for fluorous media; and (iii) transition metal derivatives that offer probes of their donor/acceptor properties. To our knowledge, these constitute the first chiral, non-racemic fluorous phosphines to be reported in the literature.[11] However, one other chiral fluorous metal complex is known, and has been applied in catalytic enantioselective alkene epoxidation.[12] Applications of our systems in enantioselective transformations will be described in future reports.

2. Results

The starting materials (menthyl)PCl_2 (**3**)[13] and (menthyl)PH_2 (**4**)[14] were prepared on twenty gram scales by literature procedures. As shown in Scheme 1, different approaches for introducing $CH_2CH_2R_{fn}$ groups were then evaluated. Earlier, we had investigated several routes to the phosphines **1** and **2**.[4] We found that free radical chain additions of PH_3 to commercially available terminal alkenes $H_2C{=}CHR_f$ were far superior to Grignard or related constructs involving PCl_3. Thus, similar additions of the primary phosphine **4** were attempted first.

Accordingly, **4** and $H_2C{=}CHR_{f6}$ or $H_2C{=}CHR_{f8}$ were reacted (1:1 mol ratios) in refluxing THF in the presence of AIBN initiator. After 72 h, fractional distillation gave some unreacted **4** and then the secondary phosphines (menthyl)$PH(CH_2CH_2R_{f6})$ (**5**) or (menthyl)$PH(CH_2CH_2R_{f8})$ (**6**) in 52–56% yields. However, NMR spectra (^1H, $^{31}P\{^1H\}$, ^{31}P) showed three RR′PH species, which were inseparable in our hands. The two major components (always 1:1) had very similar characteristics and were presumed to be diastereomers differing in phosphorus configurations. The third (10–12%) was tentatively assigned as an epimer differing in a carbon configuration, consistent with thermal processes described previously.[15] However, other possibilities (e.g. a regioisomeric addition product) were not rigorously excluded.

Efforts were made to similarly access the target tertiary phosphines (menthyl)$P(CH_2CH_2R_{f6})_2$ (**7**) and



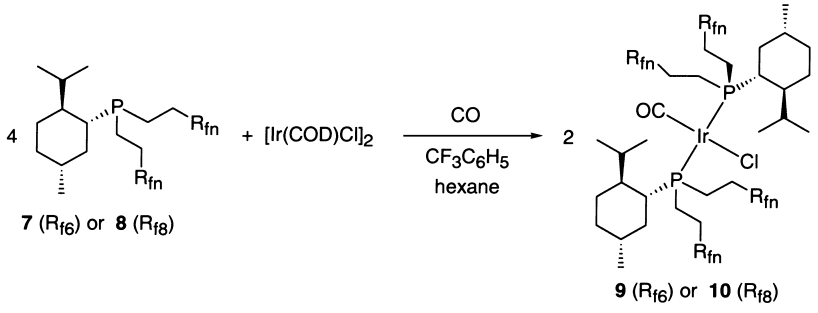
Scheme 1. Syntheses of menthyl-substituted fluorous phosphines

(menthyl)P($CH_2CH_2R_{f8}$)$_2$ (**8**), either from **5** and **6** or in one step from **4**. However, several problems were encountered. First, the secondary phosphines **5** and **6** underwent much less efficient free radical chain additions than **4**. Complete reaction required 200 h at 70°C, with fresh alkene and initiator charges every 15 h. Fractional distillation gave **7** and **8** in 44–53% yields. However, a tertiary phosphine by-product was always present (20–25%), and could not be removed by chromatography or further distillation. Hence, an alternative Grignard strategy was explored, modeled upon one successfully applied by another group to achiral fluorous phosphines.[11c]

Reactions of the commercially available iodides $ICH_2CH_2R_{f6}$ and $ICH_2CH_2R_{f8}$ with ether slurries of magnesium that had been activated by bromoethane gave the fluorous Grignard reagents $IMgCH_2CH_2R_{fn}$. However, subsequent reactions with **3** required exacting conditions to ensure reasonable phosphine yields. First, it proved best to replace the ether by $CF_3C_6H_5$, an 'ambiphilic' solvent that can dissolve appreciable concentrations of both fluorous and non-fluorous species.[3c,16] Second, Grignard concentrations were checked titrimetrically (versus 0.1 M HCl and phenolphthalein indicator; 78–84% conversions). Third, Grignard reagents were used immediately, and only in slight excess (2.1–2.2 equiv.). Fourth, some of the coupled by-product $R_f(CH_2)_4R_f$[17] always formed (even before addition of **3**), and complicated product distillation unless first removed by crystallization.

With the precautions outlined above and in the Experimental section, reactions of **3** and $IMgCH_2CH_2R_{fn}$ reproducibly gave 1–2 gram quantities of **7** and **8** as moderately air-sensitive, analytically pure, colorless oils in 28–32% yields. Interestingly, literature yields for reactions of **3** and other Grignard reagents are often low ($XMgCH_3$, $XMgCH_2CH_3$, $XMgCH(CH_3)_2$, 20%; $XMgC_6H_5$, 51%).[18] Attempts to employ fluorous zinc reagents such as $IZnCH_2CH_2R_{fn}$ and $(THF)_2Zn(CH_2CH_2R_{fn})_2$[11a,b] gave in our hands much poorer yields of **7** and **8**. In view of the absence of precedent for menthyl group racemization (as opposed to the epimerization of individual stereocenters),[15] all of the new compounds in this paper were presumed to be enantiomerically pure.

Next, transition metal complexes of **7** and **8** were sought. We had previously prepared iridium carbonyl derivatives of the fluorous phosphines **1** and **2** that are analogous to Vaska's complex.[19,20] The IR ν_{CO} values of such species reflect phosphine donor/acceptor properties (higher values indicate lower iridium to CO backbonding and lower phosphine basicity). As shown in Scheme 2, similar reactions with $[Ir(COD)Cl]_2$, CO, and **7** or **8** were conducted. Workups gave *trans*-$[(menthyl)P(CH_2CH_2R_{fn})_2]_2Ir(Cl)(CO)$ (*n*=6, **9**; *n*=8, **10**) as analytically pure oils in 71 and 51% yields. Key IR ν_{CO} data are summarized in Table 1. These show that **7** and **8** are much more basic than **1**. This reflects the modest insulating ability of the CH_2CH_2 spacer segment in the pony tail that the menthyl group replaces. Overall, the basicities of **7** and **8** are close to that of $P((CH_2)_4R_{f8})_3$, in which the spacer segment in each pony tail is twice as long.



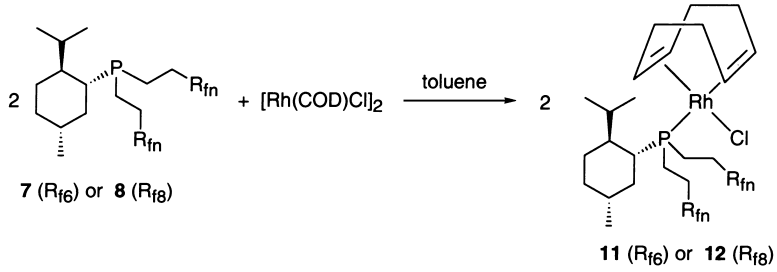
Scheme 2. Syntheses of iridium complexes

As noted above, we have prepared rhodium derivatives of **1** and **2** that are analogous to Wilkinson's catalyst.[5] As shown in Scheme 3, similar reactions of $[Rh(COD)Cl]_2$ and **7** or **8** were conducted. However, only the monophosphine complexes $[(menthyl)P(CH_2CH_2R_{fn})_2]Rh(Cl)(COD)$ (*n*=6, **11**; *n*=8, **12**) were obtained, even with excess ligand under forcing conditions (70°C, 20 h). Reactions conducted with a 1:1 Rh:P stoichiometry gave **11** and **12** as orange oils in 69 and 70% yields. Both of these compounds could be crystallized, and their structures followed from their analytical and spectroscopic properties. Other complexes of the formula $(R_3P)Rh(Cl)(COD)$ have been isolated.[21] We have not been able to locate any report of a menthyl-substituted phosphine that gives a tris(adduct) of rhodium,[15] which suggests that the reactions in Scheme 3 may be under steric control.

Attention was turned to physical measurements. First, the $CF_3C_6F_{11}$/toluene partition coefficients of **7** and **8** were determined by GLC as described earlier.[4] The data are compared with previously reported values in Table 2. As would be intuitively expected, the fluorous phase affinities dropped significantly when a pony tail was replaced by a menthyl group. In all cases, phosphines with longer $(CF_2)_{n-1}$ segments showed greater fluorous phase affinities (**8** versus **7**). Finally, specific rotations of the preceding

Table 1
IR ν_{CO} values for *trans*-$(L)_2Ir(Cl)(CO)$

L	ν_{CO}, cm^{-1}	solvent	reference
$P(CH_2CH_2R_{f6})_3$ (**1**)	1975	$CF_3C_6F_{11}$	19
	1974	$CF_3C_6H_5$	20
$P(CH_2CH_2CH_2R_{f8})_3$	1962	$CF_3C_6H_5$	20
$P(CH_2CH_2CH_2CH_2R_{f8})_3$	1957	$CF_3C_6H_5$	20
$(menthyl)P(CH_2CH_2R_{fn})_2$ (**7**, **8**)	1958	hexane	this work



Scheme 3. Syntheses of rhodium complexes

Table 2
Partition coefficients (27°C)

analyte	$CF_3C_6F_{11}$ / toluene
$P(CH_2CH_2R_{f6})_3$ (**1**)	98.8:1.2
$P(CH_2CH_2R_{f8})_3$ (**2**)	>99.7:<0.3
$P(CH_2CH_2CH_2R_{f8})_3$	98.8:1.2
(menthyl)$P(CH_2CH_2R_{f6})_2$ (**7**)	78.4:21.6
(menthyl)$P(CH_2CH_2R_{f8})_2$ (**8**)	93.7:6.3

compounds were measured,[22] as tabulated in the experimental section. All values were levorotatory, and slightly low ($[\alpha]_{589}^{20}$=−28.6 to −6.4) relative to common (menthyl)PR_2 species (R=CH_3, CH_2CH_3, C_6H_5, $CH(CH_3)_2$: −84.6, −122.3, −87.8, −88.5).[18a] This is an expected consequence of the greater molecular weights, for mathematical reasons outlined earlier.[22]

3. Discussion

This study has provided reasonably efficient syntheses of the first chiral and non-racemic fluorous phosphines. Somewhat higher yields would be desirable, but gram-scale quantities are nonetheless easily prepared. However, the menthyl substituents employed diminish the fluorous phase affinities (Table 2), to the point where significant leaching might be expected in many applications. We remain optimistic that pony tails with longer and/or branched CF_2 segments would give partition coefficients as high as 99:1. Regardless, our data do not auger particularly well for the naturally occurring terpenoid chiral pool in fluorous phase enantioselective catalysis, and indicate the desirability of more highly fluorinated stereogenic units.

The title phosphines readily form metal complexes that exhibit good solubilities in conventional organic solvents, and there is no reason not to anticipate effective conventional homogeneous enantioselective catalysts. Although catalysts that rely solely upon menthyl-based chirality have seldom been top performers, some spectacular breakthroughs have recently been announced.[9b] Finally, there is the companion question of how fluorous media and/or pony tail substituents affect enantioselectivities. The one relevant report available shows a diminution.[12] These and other issues will be carefully probed in future studies from this laboratory.

4. Experimental

4.1. General

All reactions and workups were conducted under inert atmospheres unless noted. Solvent/reagent data: $CF_3C_6F_{11}$ (Oakwood) and $CF_3C_6H_5$ (Aldrich), distilled from P_2O_5; CH_2Cl_2, distilled from CaH_2; toluene, hexanes, ether, THF, distilled from Na/benzophenone; dioxane, distilled from Na; (menthyl)Cl[23] and (menthyl)MgCl,[24] prepared by literature procedures; $ICH_2CH_2R_{fn}$ (n=6, 8; Aldrich), freeze–pump–thaw degassed; $H_2C{=}CHR_{fn}$ (Oakwood), vacuum distilled; $[M(COD)Cl]_2$ (M=Ir, Rh; Lancaster), used as received. Glassware was dried at 120°C and cooled under vacuum. Silica gel and Celite were dried at 180°C and 0.02 mmHg (12 h). Optical rotations[22] and spectroscopic measurements[6a] were conducted as described previously.

4.2. (Menthyl)P($CH_2CH_2R_{f6}$)$_2$ **7**

A Schlenk flask was charged with $CF_3C_6H_5$ (40 mL), dioxane (2.5 mL), and (menthyl)PCl_2 (**3**;[13] 1.40 g, 5.80 mmol), and cooled to −30°C. Then a $CF_3C_6H_5$ solution of $IMgCH_2CH_2R_{f6}$ (0.313 M; 39 mL, 12.2 mmol)[25] was added dropwise with stirring. The suspension was allowed to warm to room temperature. After 16 h, the pale brown mixture was filtered through Celite. The Celite was washed with $CF_3C_6H_5$ (2×20 mL). The filtrate was chromatographed on silica gel. The product fraction was concentrated in vacuo to ca. 5 mL. Toluene (30 mL) was added, and the sample stored in a freezer. After 2 h, white crystals were removed by filtration.[25b] Solvent was removed from the filtrate in vacuo and the residue distilled (145–146°C, 0.02 mmHg) to give **7** (1.52 g, 1.76 mmol, 30%) as a colorless oil. Calcd for $C_{26}H_{26}F_{26}P$: C, 36.17; H, 3.04. Found: C, 35.89; H, 3.04. $[\alpha]_{589}^{20}$=−27.9±0.6 (*c* 1.45 mg/mL, hexane). MS (EI, *m/z*; relative intensities above 280, %) 864 (M^+, 93), 845 (M^+−F, 44), 821 (M^+−$CHMe_2$, 69), 807 (M^+−$CHMe_2$−CH_2, 36), 795 (M^+−CF_3, 55), 753 (67), 727 (38), 518 (32), 462 (39), 405 (46), 394 (100); no other peaks of >30%.

NMR (δ, $CDCl_3$):[26] ^{1}H 0.80 (d, J=6.8 Hz, CH*Me*Me′), 0.82–0.89 (m, 2H), 0.93 (d, J=6.5 Hz, CH*Me*′′), 0.94 (d, J=6.8 Hz, CHMe*Me*′), 1.01–1.19 and 1.30–1.56 (2 m, 2H and 3H, 2CCH_2C+C*H*Me′′), 1.64–1.80 (m, 1CCH_2C+2PCH_2), 2.06–2.24 (m, 2C$H_2$$CF_2$), 2.38–2.50 (m, C*H*MeMe′); ^{31}P{^{1}H} −24.1 (s); ^{13}C{^{1}H} 123.2–104.8 (m, 10CF_2+2CF_3), 45.2 (d, J_{CP}=8.4 Hz), 36.6 (d, J_{CP}=15.6 Hz), 35.1 (s), 34.7 (d, J_{CP}=4.7 Hz), 33.9 (s), 29.3 and 28.8 (two apparent q, J=23.3 Hz), 28.2 (d, J_{CP}=21.0 Hz), 25.7 (d, J_{CP}=7.8 Hz), 22.6 (s, CH_3), 21.5 (s, CH_3), 15.2 (s, CH_3), 14.6 (d, J_{CP}=14.7 Hz), 12.1 (d, J_{CP}=17.6 Hz); ^{19}F −81.3 (t, J=9.9 Hz, 2CF_3), −115.3 (dt, J_d=102.9 Hz, J_t=16.1 Hz, 2CF_2), −122.3 (br s, 2CF_2), −123.3 (br s, 2CF_2), −123.8 (br apparent d, J=46.5 Hz, 2CF_2), −126.6 (br s, 2CF_2).

4.3. (Menthyl)P($CH_2CH_2R_{f8}$)$_2$ **8**

A Schlenk flask was charged with $CF_3C_6H_5$ (40 mL), dioxane (2 mL), and **3** (1.18 g, 4.91 mmol),[13] and cooled to −30°C. Then a $CF_3C_6H_5$ solution of $IMgCH_2CH_2R_{f8}$ (0.246 M; 42 mL, 10.33 mmol)[27] was added dropwise with stirring. The suspension was allowed to warm to room temperature. After 16 h, the pale yellow-brown mixture was filtered through Celite. The Celite was washed with $CF_3C_6H_5$ (2×20 mL). The filtrate was chromatographed on silica gel. The product fraction was concentrated in vacuo to ca. 10 mL. Toluene (30 mL) was added, and the sample stored in a freezer. After 1 h, white crystals were removed by filtration.[27b] Solvent was removed from the filtrate in vacuo and the yellow oil distilled (157–160°C, 0.02 mmHg) to give **8** (1.53 g, 1.44 mmol, 30%) as a colorless oil. Calcd for $C_{30}H_{26}F_{34}P$:

C, 33.88; H, 2.47. Found: C, 34.08; H, 2.56. $[\alpha]_{589}^{20}$=−28.6±0.5 (*c* 1.58 mg/mL, hexane). MS (EI, *m/z*; relative intensities above 200, %) 1064 (M^+, 9), 855 (15), 744 (28), 652 (18), 617 (52), 525 (22), 505 (100), 485 (37), 441 (28), 377 (70); no other peaks of >15%.

NMR (δ, $CDCl_3$):[26] ^{1}H 0.79 (d, *J*=6.8 Hz, CH*Me*Me′), 0.84–0.89 (m, 2H), 0.93 (d, *J*=6.6 Hz, CH*Me*′′), 0.94 (d, *J*=6.8 Hz, CHMe*Me*′), 1.01–1.19 and 1.30–1.58 (2 m, 2H and 3H, 2CCH_2+C*H*Me′′), 1.65–1.79 (m, 1CCH_2C+2PCH_2), 2.08–2.24 (m, 2C$H_2$$CF_2$), 2.38–2.50 (m, C*H*MeMe′); ^{31}P{^{1}H} −24.0 (s); ^{13}C{^{1}H} 123.1–105.1 (m, 14CF_2+2CF_3), 45.2 (d, J_{CP}=7.9 Hz), 36.6 (d, J_{CP}=15.8 Hz), 35.1 (s), 34.7 (d, J_{CP}=4.5 Hz), 33.9 (s), 29.3 and 28.8 (two apparent q, J_{CP}=23.5 Hz), 28.1 (d, J_{CP}=22.6 Hz), 25.6 (d, J_{CP}=7.8 Hz), 22.6 (s, CH_3), 21.5 (s, CH_3), 15.2 (s, CH_3), 14.7 (d, J_{CP}=15.6 Hz), 12.1 (d, J_{CP}=18.4 Hz); ^{19}F −81.3 (t, *J*=8.9 Hz, 2CF_3), −115.3 (dt, J_d=99.1 Hz, J_t=15.9 Hz, 2CF_2), −122.1 (br s, 2CF_2), −122.3 (br s, 4CF_2), −123.2 (br s, 2CF_2), −123.7 (br apparent d, *J*=43.7 Hz, 2CF_2), −126.6 (br s, 2CF_2).

*4.4. Reactions of (menthyl)PH_2 **4** and H_2C=CHR_{fn}*

The following is representative of the phosphorus–hydrogen bond additions in Scheme 1. A Schlenk flask was charged with **4** (2.11 g, 12.3 mmol),[14] H_2CH=CHR_{f6} (4.26 g, 12.3 mmol), and THF (25 mL). The AIBN (dried under vacuum) was added and the solution refluxed. After 63 h, a ^{31}P NMR spectrum (aliquot) indicated 67% completion. Solvent was removed under reduced pressure and the yellow oil distilled (1.5 mmHg). The first fraction (57–59°C) gave unreacted **4** (0.62 g, 29%). The second fraction (115–119°C) gave (menthyl)PH($CH_2CH_2R_{f6}$) as a colorless oil (2.51 g, 4.84 mmol, 56%). ^{31}P NMR (δ, $CDCl_3$) −50.4 (d, J_{PH}=206 Hz; 44–45%), −60.3 (d, J_{PH}=206 Hz; 44–45%), −66.7 (d, J_{PH}=217 Hz; 10–12%). See text for signal assignments.

4.5. trans-*[(Menthyl)P($CH_2CH_2R_{f6}$)$_2$]$_2$Ir(Cl)(CO)* ***9***

A Schlenk flask was charged with $[Ir(COD)Cl]_2$ (0.044 g, 0.066 mmol) and hexane (3 mL). Then a solution of **7** (0.227 g, 0.263 mmol) in $CF_3C_6H_5$ (3 mL) was added with stirring. After 20 min, the flask was flushed with CO (1 atm). The orange solution turned yellow. After 20 h, the sample was taken to dryness in vacuo. The residue was chromatographed on a silica gel column (15 g) in hexane. The second colored band was collected, concentrated, and dried (0.2 mmHg, overnight) to give **9** as a pentane-soluble yellow oil that could not be induced to crystallize (0.185 g, 0.047 mmol, 71%). $[\alpha]_{589}^{20}$=−6.4±0.2 (*c* 2.40 mg/mL, hexane). Calcd for $C_{53}H_{54}ClF_{52}IrOP_2$: C, 32.08; H, 2.74. Found: C, 32.07; H, 2.70. IR (cm^{-1}, hexane) ν_{CO} 1958 (s).

NMR (δ, $CDCl_3$):[26] ^{1}H 0.85 (d, *J*=6.8 Hz, CH*Me*Me′), 0.94 (d, *J*=6.5 Hz, CH*Me*′′), 0.97 (d, *J*=6.8 Hz, CHMe*Me*′), 1.10–1.48 (m, 3H), 1.55–1.67 (m, 2H), 1.76–1.89 (m, 4H), 2.20–2.45 (m, 6H), 2.68 (m, C*H*MeMe′); ^{31}P{^{1}H} 16.72 (s); ^{13}C{^{1}H} 171.7 (t, J_{CP}=10.9 Hz, CO), 123.8–104.1 (m, 20CF_2+4CF_3), 46.2 (s), 37.7 (t, *J*=14.5 Hz), 36.7 (s), 34.2 (s), 33.5 (apparent t, *J*=5.1 Hz), 29.2 (s), 27.8 and 27.0 (2 t, *J*=22.8 Hz), 25.3 (apparent t, *J*=5.1 Hz), 22.7 (s, CH_3), 21.7 (s, CH_3), 16.3 (s, CH_3), 16.5 and 13.4 (2 t, *J*=14.7 Hz); ^{19}F −81.4 (br s, 2CF_3), −115.5 (br d, *J*=68.0 Hz, 2CF_2), −122.4 (br s, 2CF_2), −123.4 (br s, 2CF_2), −123.9 (br s, 2CF_2), −126.7 (br s, 2CF_2).

4.6. trans-*[(Menthyl)P($CH_2CH_2R_{f8}$)$_2$]$_2$Ir(Cl)(CO)* ***10***

A Schlenk flask was charged with $[Ir(COD)Cl]_2$ (0.041 g, 0.060 mmol) and hexane (6 mL). Then a solution of **8** (0.263 g, 0.247 mmol) in $CF_3C_6H_5$ (6 mL) was added with stirring. After 1 h, the flask was flushed with CO (1 atm). After 20 h, the solution was taken to dryness in vacuo. The residue was

chromatographed on a silica gel column (15 g) in hexane. After the first colored band eluted, the eluent was changed to CH_2Cl_2. The next band was collected, concentrated, and dried (0.2 mmHg, overnight) to give **10** as a yellow oil (0.133 g, 0.030 mmol, 51%). Calcd for $C_{61}H_{54}ClF_{68}IrOP_2$: C, 30.72; H, 2.28. Found: C, 30.66; H, 2.34. $[\alpha]_{589}^{20}=-12.1\pm0.2$ (*c* 3.33 mg/mL, hexane). IR (cm^{-1}, CH_2Cl_2) ν_{CO} 1958 (s).

NMR (δ, $CDCl_3$):[26] ^1H 0.85 (d, *J*=6.5 Hz, CH*Me*Me′), 0.94 (d, *J*=6.0 Hz, CH*Me*′′), 0.97 (d, *J*=6.5 Hz, CHMe*Me*′), 1.09–1.32 (m, 3H), 1.35–1.58 (m, 2H), 1.60–1.95 (m, 4H), 2.21–2.45 (m, 6H), 2.64 (m, C*H*MeMe′); $^{31}P\{^1H\}$ 17.04 (s); $^{13}C\{^1H\}$ 171.7 (t, J_{CP}=11.1 Hz, CO), 123.8–104.2 (m, $28CF_2+4CF_3$), 46.3 (s), 37.8 (t, *J*=13.8 Hz), 36.7 (s), 34.3 (s), 33.6 (apparent t, *J*=4.7 Hz), 29.2 (s), 28.0 and 27.0 (2 t, *J*=20.9 Hz), 25.3 (apparent t, *J*=5.1 Hz), 22.6 (s, CH_3), 21.7 (s, CH_3), 16.3 (s, CH_3), 16.5 and 13.4 (2 t, *J*=16.1 Hz); ^{19}F −81.7 (br s, $2CF_3$), −115.6 (br d, *J*=77.7 Hz, $2CF_2$), −121.4 (br s, $2CF_2$), −122.7 (br s, $4CF_2$), −123.5 (br s, $2CF_2$), −124.2 (br s, $2CF_2$), −127.0 (br s, $2CF_2$).

4.7. [(Menthyl)P($CH_2CH_2R_{f6}$)$_2$]Rh(Cl)(COD) ***11***

A Schlenk flask was charged with $[Rh(COD)Cl]_2$ (0.087 g, 0.176 mmol) and toluene (5 mL). Then a solution of **7** (0.305 g, 0.356 mmol) in toluene (5 mL) was added with stirring. After 3 h, the solution was taken to dryness in vacuo (aerobic workup). The residue was chromatographed on a silica gel column (20 cm) in CH_2Cl_2:hexane (1:3 v/v). The second colored band was collected, concentrated, and dried (0.2 mmHg, 18 h) to give **11** (0.269 g, 0.121 mmol, 69%) as an orange oil. A portion was dissolved in hexane (1 mL), layered with methanol (1 mL), and stored in a refrigerator. After 20 h, orange platelets were collected by filtration and dried in vacuo (0.2 mmHg, 3 h), mp 93–95°C. Calcd for $C_{34}H_{39}ClF_{26}PRh$: C, 36.76; H, 3.54. Found: C, 36.73; H, 3.55. $[\alpha]_{589}^{20}=-7.5\pm0.4$ (*c* 1.50 mg/mL, hexane).

NMR (δ, $CDCl_3$):[26] ^1H 0.90 (d, *J*=6.6 Hz, CH*Me*Me′), 1.06 (d, *J*=6.5 Hz, CH*Me*′′), 1.10 (d, *J*=6.6 Hz, CHMe*Me*′), 1.38 (br s, 1H), 1.65–2.15 (m, 12H), 2.33–2.68 (3 overlapping m, 10H), 3.10 (m, 1H), 3.38 (m, 1H), 3.49 (br s, 1H), 5.35 (br s, 4 =CH); $^{31}P\{^1H\}$ 16.23 (d, J_{RhP}=151 Hz); $^{13}C\{^1H\}$ 124.2–107.1 and 104.4 (overlapping m and dt, J_d=12.2 Hz, J_t=6.7 Hz, $10CF_2+2CF_3$), 69.0 (dd, J_{CRh}=77.1 Hz, J_{CP}=13.9 Hz, =CH), 44.6 (s), 39.0 (d, *J*=21.6 Hz), 37.9 (d, *J*=6.3 Hz), 34.4 (s), 33.7 (s), 33.6 (s), 33.0 (s), 30.1 (d, *J*=10.9 Hz), 28.8 (s), 28.3 (s), 27.3 (t, *J*=23.3 Hz), 25.5 (d, *J*=10.9 Hz), 22.7 (s, CH_3), 22.3 (s, CH_3), 17.0 (s, CH_3), 13.2 (d, *J*=22.3 Hz), 8.8 (d, *J*=15.5 Hz); ^{19}F −81.0 (t, *J*=9.9 Hz, $2CF_3$), −115.0 (m, $2CF_2$), −122.2 (br s, $2CF_2$), −123.2 (br s, $2CF_2$), −123.5 (br apparent d, *J*=37.6 Hz, $2CF_2$), −126.4 (br s, $2CF_2$).

4.8. [(Menthyl)P($CH_2CH_2R_{f8}$)$_2$]Rh(Cl)(COD) ***12***

Toluene (5 mL), $[Rh(COD)Cl]_2$ (0.074 g, 0.150 mmol), and a solution of **8** (0.32 g, 0.30 mmol) in toluene (5 mL) were combined in a procedure analogous to that for **11**. An identical workup gave **12** (0.277 g, 0.105 mmol, 70%) as an oily orange semi-solid. An analogous crystallization gave orange platelets, mp 92–94°C. Calcd for $C_{38}H_{39}ClF_{34}PRh$: C, 34.81; H, 3.00. Found: C, 34.90 H, 2.97. $[\alpha]_{589}^{20}=-9.9\pm0.5$ (*c* 1.74 mg/mL, hexane).

NMR (δ, $CDCl_3$):[26] ^1H 0.92 (d, *J*=6.5 Hz, CH*Me*Me′), 1.07 (d, *J*=6.4 Hz, CH*Me*′′), 1.11 (d, *J*=6.5 Hz, CHMe*Me*′), 1.40 (br s, 1H), 1.58–2.20 (m, 12H), 2.34–2.70 (3 overlapping m, 10H), 3.10 (m, 1H), 3.38 (m, 1H), 3.50 (br s, 1H), 5.37 (br s, 4 =CH); $^{31}P\{^1H\}$ 16.26 (d, J_{RhP}=146 Hz); $^{13}C\{^1H\}$ 123.2–106.5 and 104.5 (overlapping m and dt, J_d=12.5 Hz, J_t=6.6 Hz, $14CF_2+2CF_3$), 69.0 (dd, J_{CRh}=75.1 Hz, J_{CP}=13.5 Hz, =CH), 44.6 (s), 39.1 (d, *J*=21.6 Hz), 37.9 (d, *J*=6.2 Hz), 34.5 (s), 33.8 (s), 33.7 (s), 33.0 (s), 30.1 (d, *J*=10.1 Hz), 28.8 (s), 28.3 (s), 27.4 (t, *J*=22.1 Hz), 25.5 (d, *J*=10.1 Hz), 22.6 (s, CH_3), 22.2 (s, CH_3), 17.0 (s, CH_3), 13.2 (d, *J*=22.1 Hz), 8.9 (d, 15.9 Hz); ^{19}F −81.4 (t, *J*=10.2 Hz, $2CF_3$), −115.2 (m, $2CF_2$),

−122.2 (br s, $2CF_2$), −122.4 (br s, $4CF_2$), −123.3 (br s, $2CF_2$), −123.7 (br apparent d, J=41.4 Hz, $2CF_2$), −126.7 (br s, $2CF_2$).

4.9. Partition coefficients[4]

(**A**) A 1 dram vial was charged with **7** (0.0450 g), $CF_3C_6F_{11}$ (2.0 mL), and toluene (2.0 mL), capped with a mininert valve, vigorously shaken (5 min), and kept at 40°C for 16 h. The vial was transferred to a dry box (27°C). After 2 h, 0.4 mL aliquots of each layer were added to separate stock solutions of octadecane in hexane (2.0 mL, 0.00417 M). GLC analyses (Hewlett–Packard model 5890, SBP capillary column, injector/detector (flame ionization) 250°C, oven 200°C, average of 4–7 injections; **7**/octadecane retention times 7.03/8.18 min; detector response factors determined from standard solutions) gave the data in Table 2 (total **7** recovered 0.0399 g). The conversion of **7** to the corresponding phosphine oxide (retention time 11.52 min) is rapid. (**B**) A similar procedure was conducted with **8** (0.0477 g; 48 h at 27°C, **8**/phosphine oxide retention times 11.31/20.10 min, total **8** recovered 0.0433 g).

Acknowledgements

We thank the NIH for support of this research, and the Swiss National Science Foundation for a Fellowship (A.K.).

References

1. Representative references: (a) Hutchings, G. J. *J. Chem. Soc., Chem. Commun*. **1999**, 301 (mini-review). (b) Pu, L. *Chem. Rev*. **1998**, *98*, 2405. (c) Annis, D. A.; Jacobsen, E. N. *J. Am. Chem. Soc.* **1999**, *121*, 4147. (d) Bolm, C.; Gerlach, A. *Angew. Chem., Int. Ed. Engl*. **1997**, *36*, 741; *Angew. Chem*. **1997**, *109*, 773.
2. (a) Horváth, I. T.; Rabái, J. *Science* **1994**, *266*, 72. (b) Horváth, I. T.; Kiss, G.; Cook, R. A.; Bond, J. E.; Stevens, P. A.; Rabái, J.; Mozeleski, E. J. *J. Am. Chem. Soc.* **1998**, *120*, 3133. (c) Horváth, I. T. *Acc. Chem. Res*. **1998**, *31*, 641.
3. Other reviews: (a) Curran, D. P. *Angew. Chem., Int. Ed. Engl*. **1998**, *37*, 1174; *Angew. Chem*. **1998**, *110*, 1230. (b) de Wolf, E.; van Koten, G.; Deelman, B.-J. *Chem. Soc. Rev*. **1999**, 37. (c) Barthel-Rosa, L.; Gladysz, J. A. *Coord. Chem. Rev*. **1999**, in press.
4. Alvey, L. J.; Rutherford, D., Juliette, J. J. J.; Gladysz, J. A. *J. Org. Chem*. **1998**, *63*, 6302.
5. (a) Juliette, J. J. J.; Horváth, I. T.; Gladysz, J. A. *Angew. Chem., Int. Ed. Engl*. **1997**, *36*, 1610; *Angew. Chem*. **1997**, *109*, 1682. (b) Juliette, J. J. J.; Rutherford, D.; Horváth, I. T.; Gladysz, J. A. *J. Am. Chem. Soc*. **1999**, *121*, 2696.
6. (a) Rutherford, D.; Juliette, J. J. J.; Rocaboy, C.; Horváth, I.; Gladysz, J. A. *Catalysis Today* **1998**, *42*, 381. (b) Dinh, L.; Gladysz, J. A., manuscript in preparation.
7. This includes the free phosphines: Meier, R. unpublished results, University of Utah and Universität Erlangen–Nürnberg.
8. Throughout this paper, 'menthyl' designates the more readily available 1*R*,3*R*,4*S* (L) enantiomer.
9. (a) Brunner, H.; Janura, M. *Synthesis* **1998**, 45. (b) Stinson, S. C. *Chemical & Engineering News* **1999**, 18 January issue, p. 69 (see: proprietary Heck catalyst, p. 74).
10. Bartik, T.; Ding, H.; Bartik, B.; Hanson, B. E. *J. Mol. Catal. A* **1995**, *98*, 117.
11. References to other groups active in the synthesis of fluorous phosphines or metal complexes thereof: (a) Benefice-Malouet, S.; Blancou, H.; Commeyras, A. *J. Fluorine Chem*. **1985**, *30*, 171. (b) Langer, F.; Püntener, K.; Stürmer, R.; Knochel, P. *Tetrahedron: Asymmetry* **1997**, *8*, 715. (c) Battacharyya, P.; Gudmunsen, D.; Hope, E. G.; Kemmitt, R. D. W.; Paige, D. R.; Stuart, A. M. *J. Chem. Soc., Perkin Trans. 1* **1997**, 3609. (d) Kainz, S.; Koch, D.; Baumann, W.; Leitner, W. *Angew. Chem., Int. Ed. Engl*. **1997**, *36*, 1628; *Angew. Chem*. **1997**, *109*, 1699. (e) Haar, C. M.; Huang, J.; Nolan, S. P.; Peterson, J. L. *Organometallics* **1998**, *17*, 5018. (f) Mathivet, T.; Monflier, E.; Castanet, Y.; Montreux, A.; Couturier, J.-L. *Tetrahedron Lett*. **1998**, *39*, 9411. (g) Fawcett, J.; Hope, E. G.; Kemmitt, R. D. W.; Paige, D. R.; Russell, D. R.; Stuart, A. M. *J. Chem. Soc., Dalton Trans*. **1998**, 3751. (h) Hope, E. G.; Kemmitt, R. D. W.; Stuart, A. M. *J. Chem. Soc., Dalton Trans*. **1998**, 3765. (i) Sinou, D.; Pozzi, G.; Hope, E. G.; Stuart, A. M. *Tetrahedron Lett*. **1999**, *40*, 849.

12. Pozzi, G.; Cinato, F.; Montanari, F.; Quici, S. *J. Chem. Soc., Chem. Commun*. **1998**, 877.
13. (a) Hinke, A.; Kuchen, W. *Phosphorus and Sulfur* **1983**, *15*, 93. (b) Detailed NMR assignments: Feigel, M.; Haegele, G.; Hinke, A.; Tossing, G. *Z. Naturforsch*. **1982**, *37b*, 1661.
14. Marinetti, A.; Buzin, F. X.; Ricard, L. *Tetrahedron* **1997**, *53*, 4363.
15. Valentine Jr., D.; Blount, J. F.; Toth, K. *J. Org. Chem*. **1980**, *45*, 3691.
16. Ogawa, A.; Curran, D. P. *J. Org. Chem*. **1997**, *62*, 450.
17. A related reaction gives $R_{f6}(CH_2)_4R_{f6}$ as a by-product: Kainz, S.; Luo, Z.; Curran, D. P.; Leitner, W. *Synthesis* **1998**, 1425.
18. (a) Hidai, M.; Mizuta, H.; Yagi, H.; Nagai, Y.; Hata, K.; Uchida, Y. *J. Organomet. Chem*. **1982**, *232*, 89. (b) Tanaka, M.; Ogata, I. *Bull. Chem. Soc. Jpn*. **1975**, *48*, 1094.
19. Guillevic, M.-A.; Rocaboy, C.; Arif, A. M.; Horváth, I. T.; Gladysz, J. A. *Organometallics* **1998**, *17*, 707.
20. Alvey, L. J. PhD Thesis, University of Utah, 1999.
21. (a) Crabtree, R. H.; Gautier, A.; Giordano, G.; Khan, T. *J. Organomet. Chem*. **1977**, *141*, 113. (b) Denise, B.; Pannetier, G. *J. Organomet. Chem*. **1978**, *148*, 155. (c) Petrucci-Samija, M.; Guillemette, V.; Dasgupta, M.; Kakar, A. K. *J. Am. Chem. Soc.* **1999**, *121*, 1968.
22. Dewey, M. A.; Gladysz, J. A. *Organometallics* **1993**, *12*, 2390.
23. Smith, J. G.; Wright, G. F. *J. Org. Chem*. **1952**, *17*, 1116.
24. Krause, H. W.; Kinting, A. *J. Prakt. Chem*. **1980**, *3*, 485.
25. (a) Our preparation of $IMgCH_2CH_2R_{f6}$ closely models one reported by another group.[11c] Important details regarding this sequence are described in the text. (b) The by-product $R_{f6}(CH_2)_4R_{f6}$ is evident upon ether removal, prior to reaction with **3**.[17]
26. All ^{1}H NMR assignments given were confirmed via COSY experiments. The ^{13}C NMR chemical shifts and J_{CP} values of the menthyl carbons do not change much from compound to compound, and assignments would be analogous to those determined elsewhere.[13b] The ^{19}F NMR chemical shifts behave similarly, and assignments (R_{f6}) would be analogous to those given elsewhere.[11g] Note that the $CH_2CH_2R_{fn}$ groups are diastereotopic.
27. (a) The preparation of $IMgCH_2CH_2R_{f8}$ is analogous to that of $IMgCH_2CH_2R_{f6}$.[25] (b) Similar to the lower homolog, the by-product $R_{f8}(CH_2)_4R_{f8}$ forms. A sample was crystallized from layered $CF_3C_6H_5$/hexane (ca. 67% mass recovery). Calcd for $C_{20}H_8F_{34}$: C, 26.86; H, 0.90. Found: C, 26.39; H, 0.86. ^{1}H NMR (δ, $CF_3C_6F_{11}$, external $CDCl_3$ lock) 1.69 (br m, 4H), 2.06 (br m, 4H). MS (EI, *m/z*) 893 (M^+, 1%), 855 (17), 525 (16), 505 ($M^+-2F-5CF_2$, 100), 485 (45), 441 (40), 427 (15), 395 (24), 377 (92); no other peaks above 200 of >15%.