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FULL PAPER

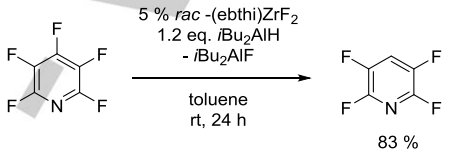
Organocatalytic C-F Bond Activation with Alanes

Alma D. Jaeger,[a] Christian Ehm*[b] and Dieter Lentz*[a]

Abstract: Hydrodefluorination reactions (HDF) of per- and polyfluorinated olefins and arenes by cheap aluminum alkyl hydrides in non-coordinating solvents can be catalyzed by O and N donors. TONs with respect to the organocatalysts of up to 87 have been observed. Depending on substrate and concentration, high selectivities can be achieved. For the prototypical hexafluoropropene, however, low selectivities are observed (*E*/*Z* ~ 2). DFT studies show that the preferred HDF mechanism for this substrate in the presence of donor solvents proceeds from the dimer $Me_4Al_2(\mu\text{-}H)_2\cdot THF$ via nucleophilic vinylic substitution (S_NV) like transition states with low selectivity and without formation of an intermediate, not via hydrometallation or σ-bond metathesis. In the absence of donor solvents, hydrometallation is preferred but this is associated with inaccessibly high activation barriers at low temperatures. Donor solvents activate the aluminium hydride bond, lower the barrier for HDF significantly and switch the product preference from *Z* to *E*. The exact nature of the donor has only a minimal influence on the selectivity at low concentrations, as the donor is located far away from the active center in the transition states. The mechanism changes at higher donor concentrations and proceeds from $Me_2AlH\cdot THF$ via S_NV and formation of a stable intermediate from which elimination is unselective, which results in a loss of selectivity.

Introduction

The introduction of fluorine into organic compounds leads to remarkable changes of their properties and therefore to a broad field of application.[1] For example, fluorination increases hydrophobicity and metabolic stability, making fluorine-containing pharmaceutical drugs and agrochemicals valuable synthetic targets.[2] Nonetheless, the high thermodynamic stability and kinetic inertness of the C-F bond also leads to environmental concerns.[3] Hence, it is of great interest to find new ways to selectively construct and deconstruct C-F bonds. The introduction of a defined substitution pattern remains challenging, but significant progress has been made in recent years.[4] Selective fluorination is especially promising, if the final fluorine content in the molecule is low. However, if the desired fluorine content is high, it is more promising to selectively cleave C-F bonds of commercially available perfluorinated compounds via hydrodefluorination (HDF) reactions. Several transition-metal-catalyzed systems for the activation of olefinic and aromatic fluorinated compounds have been reported.[5] Just recently Ito reported the stereodivergent HDF of *gem*-difluoroalkenes to *E*- and *Z*-terminal monofluoralkenes by copper(I) catalysts and diboron or hydrosilane with high stereoselectivity.[6] However, the high costs of most catalysts, often based on late transition metals, can limit their broad application.[7] Only a few examples of early transition metal catalyzed processes are known[5a, 8]; for example, Rosenthal described the catalytic hydrodefluorination of pentafluoropyridine by a zirconium-hydrido-complex and diisobutylaluminum hydride (DIBAL, Scheme 1).[5c] In addition, the titanium-catalyzed HDF offers great opportunities in organic synthesis.[9]



Scheme 1. HDF of pentafluoropyridine with a zirconium catalyst and diisobutylaluminum hydride.

However, the strong affinity between transition metals and fluorine atoms often leads to catalyst deactivation. An example for transition-metal-free, photocatalytic HDF of several polyfluoroarenes by pyrene-based photocatalyts was recently given by Zhang.[10] Ogoshi reported the transition-metal-free HDF of polyfluoroarenes catalyzed by hydrosilicates.[11]

C-F bond activation using main group Lewis acids represents a new promising way to selectively activate C-F bonds.[12][13] The group of Ozerov described for example the hydrodefluorination of $C(sp^3)$-F bonds with electrophilic silylium species, e.g. $Et_3Si^+B(C_6F_5)_4^-$ or $Et_3Si^+[CHB_{11}H_5Cl_6]^-$.[14] Similarly, Rosenthal, Krossing and coworkers postulated that the aluminum ion iBu_2Al^+ is the active catalyst (generated in situ from diisobutylaluminum hydride and a molecular activator, e.g. $Ph_3C^+B1(C_6F_5)_4^-$), in HDF of 1-fluorohexane.[15] Nicolau reported HDF of a glycosyl monofluoride with an equimolar amount of AlH_3 in diethylether.[16] Terao and Kambe showed that diisobutylaluminum hydride is able to hydrodefluorinate *n*-octyl fluoride without a catalyst in hexane.[17] However, these systems are limited to monofluorinated hydrocarbons. To the best of our knowledge, there is only one literature example for HDF of highly fluorinated systems using aluminum hydrides. Douvris and Ozerov have shown that the CF_3 group in benzotrifluoride can react with diisobutylaluminum hydride, using $Et_2Al[HCB_{11}H_5Br_6]$ as catalyst in hexane.[18] However, as a result of competition between alkyl and hydride transfer from iBu_2AlH only product mixtures were obtained.

In the following, we want to demonstrate that simple N or O donor molecules facilitate the HDF of per- and polyfluorinated olefins

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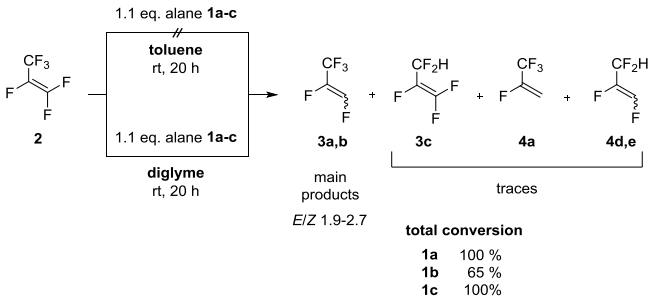
and arenes. Kinetic and DFT studies are then used to clarify the mechanism and the role of the donor molecule.

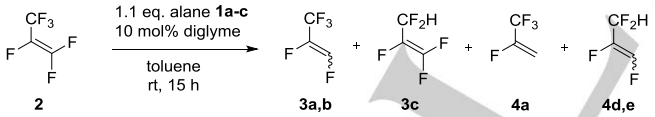
Results and Discussion

When alanes like DIBAL (**1a**), dimethylalane (**1b**) or bis(trimethylsilylmethyl)alane (**1c**) are reacted with hexafluoropropene (**2**) in a non-coordinating solvent, e.g. toluene, no HDF is observed. However, if toluene is replaced by diglyme, **2** is hydrodefluorinated using **1a,c** within 20 h, but a mixture of products is observed (Scheme 2).



Scheme 2. HDF of hexafluoropropene with alanes in diglyme and toluene.

Interestingly, only catalytic amounts of diglyme are sufficient to catalyze the HDF reaction to obtain predominantly the *E*- and *Z*-isomer of 1,2,3,3,3-pentafluoropropene (**3a, b**, Scheme 3). The *E*/*Z*-ratio varies around 2, i.e. the thermodynamically less stable *E*-isomer is favored. This stands in contrast to the titanium catalyzed systems, which we have reported before.[19] While the *E*/*Z* ratio appears to be only slightly influenced by the choice of alane, the choice influences the TON.



Alane	*E*/*Z*	Conversion	TON
HAl^iBu_2 (**1a**)	1.9	99.8 %	9.5
$HAl(CH_2SiMe_3)_2$ (**1c**)	2.0	92.1 %	8.1
$HAlMe_2$ (**1b**)	2.2	61.3 %	5.6

Scheme 3. Catalytic HDF of hexafluoropropene with alanes and diglyme as organocatalyst.

HDF of Fluorinated and Perfluorinated Substrates

Diglyme plays the role of an organocatalyst; no transition metal is needed. Nearly 100 % conversion was observed using DIBAL, bis(trimethylsilylmethyl)alane (92 %) and dimethylalane (61 %) show a lower reactivity. Various donor solvents can be used as organocatalysts, but diglyme yields the highest TON. Tuning of the basicity of the solvent donor atom has little influence on the TON (entries 1-4, Table 1), although 1,4-dioxane (74 % conversion, entry 5) and pyridine (64 % conv., entry 6) show somewhat lower TON. Increasing the steric bulk close to the donor atom decreases the TON (entry 7, Table 1). For the two other alanes the same trend was observed (see supporting information). Diglyme (b.p. 162 °C) was chosen as organocatalyst for further HDF studies with olefinic and aromatic substrates.

Table 1. HDF of hexafluoropropene with 1.1 eq. DIBAL and various organocatalysts in toluene at rt.

Entry	Organocat.	mol%	Time [h]	Conv. [%]	TON [%]
1	diglyme	11	18	99.8	9.5
2	THF	11	17	99.8	9.1
3	Et_2O	11	23	97.8	8.6
4	DME	11	15	97.5	8.6
5	1,4-dioxane	11	17	74.0	6.7
6	pyridine	11	15	64.3	5.8
7	MTBE	9	21	17.1	1.9

The scope and limitations of the HDF using alanes and catalytic amounts of diglyme were studied using the substrates shown in Table 2. DIBAL is the most reactive alane, except for octafluorotoluene (**10**). Conversion for 1,1,3,3,3-pentafluoropropene (**3d**) is lower than for **2**, but the thermodynamically more stable *E*-isomer of 1,3,3,3,-tetrafluoropropene (**4b**) is obtained in high selectivity (*E*/*Z* ratios up to 11.6, entry 4). The *E*/*Z* selectivity for HDF of **3d** follows the same trend as observed for the Ti-catalyzed systems. Hydrodefluorinated products of trifluoroethene (**6**) could only be observed in trace amounts (<1%). Pentafluoropyridine (**8**) gives selectively the *para*-hydrodefluorinated tetrafluoropyridine (**9a**) as product in conversions up to 91 % (entry 10). **10** yields the *para*-hydrodefluorinated heptafluorotoluene (**11a**) in high selectivity, but the conversion is low (up to 15 %, entry 15).

Conversion, TON numbers and *E*/*Z* selectivity can be influenced via the choice of reaction conditions. In general, it appears that the conversion can be increased by increasing the reaction time, temperature and amount of diglyme (see SI for full tables). For example, 100 °C and 1 mol% diglyme yield a TON of 87 (entry 1a) for substrate **2** within 21 hours. Increasing the amount of diglyme to 11 % leads to 79 % conversion (TON 7.3) within 15 min (entry 1b). An increase in *E*/*Z* selectivity and conversion can be observed for substrate **3d** at 100 °C (entry 4a). A similar increase in conversion was found for substrate **10** at 100 °C (entry 13a). For substrate **8** however, we observe a decrease in conversion at higher temperatures (entry 10a).

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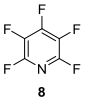
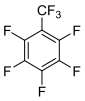
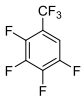
Table 2. Catalytic HDF of various substrates with alanes **1a-c** and diglyme as organocatalyst in toluene.

Entry	Substrate	Alane	Diglyme [mol%]	T [°C]	Time [h]	Main Products [%]				E/Z	Conv.	TON
	 **2**					 **3a,b**	 **3c**	 **4d,e**	 **4a**			
1		**1a**	11	25	18	96.0	1.2	2.4	*	1.9	99.8	9.5
1a		**1a**	1	100	21	90.8	1.1	1.1	0.1	2.1	93.0	87.0
1b		**1a**	11	100	0.25	76.0	2.6	0.5	*	2.0	79.2	7.3
2		**1b**	11	25	22	57.2	3.2	0.8	-	2.2	61.3	5.6
3		**1c**	12	25	20	82.7	2.3	7.0	0.1	2.0	92.1	8.1
	 **3d**					 **4b**	 **4c**	 **4f**				
4		**1a**	12	25	18	50.8	4.4	4.1		11.6	59.3	4.5
4a		**1a**[a]	12	100	22	76.7	5.7	1.9		13.4	87.2	7.4
5		**1b**	12	25	22	51.8	5.3	1.7		9.8	58.8	5.0
6		**1c**	13	25	16	67.1	6.8	0.1		9.9	74.0[b]	5.5
	 **6**					 **7a**	 **7b**	 **7c**				
7		**1a**	11	25	18	0.02	0.07	0.05			0.14	0.02
8		**1b**	8	25	21	0.04	0.07	0.12			0.23	0.04
9		**1c**	14	25	17	0.16	0.03[c]	-			0.19	0.02
	 **8**					 **9a**	 **9b**					
10		**1a**	12	25	23	90.5	-				90.5	7.7
10a		**1a**	12	100	23	50.9	0.1				51.0	4.4
11		**1b**	10	25	22	48.8	0.2				49.0	4.9
12		**1c**	11	25	21	86.4	-				86.4[d]	7.6
	 **10**					 **11a**	 **11b**					
13		**1a**	11	25	24	5.6	0.5				6.1	0.6
13a		**1a**	11	100	20	25.7	1.0				26.7	2.4
14		**1b**	11	25	18	6.5	0.7				7.2	0.7
15		**1c**	12	25	20	14.0	1.0				15.1	1.3

[a] and 2.4 % of CF_3-CH=CH_2 (**5a**). [b] the control reaction without diglyme gave already 16 % conversion to the HDF products. [c] Conversion to CF_2=CH_2. [d] the control reaction without diglyme gave already 31 % conversion to HDF products. *traces (< 0.1 %); full tables see SI.

Competition of Hydrodefluorination and other Hydrodehalogenation Reactions

The chemoselectivity of the alane HDF was tested using chlorotrifluoroethene, bromotrifluoroethene and iodotrifluoroethene. The results presented in Table 3 show that C-F activation is preferred over C-Cl or C-Br bond activation yielding predominantly the *E*- and *Z*-isomers of the chlorinated and brominated difluoro ethene. However, while the chemoselectivity is relatively high, regioselectivity of the HDF is poor in these substrates (*E*/*Z* ~ 1). HDF of iodotrifluoroethene in contrast leads mainly to **6**, the C-I bond is preferably activated.

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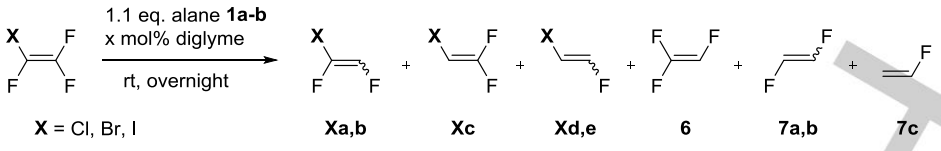


Table 3. HDF of chloro-, bromo- and iodotrifluoroethene with 1.1 eq. alane at rt, overnight.

Entry	X	Alane	Diglyme [mol%]	Solvent	Products [%]						*E*/*Z*[a]	Conv. [%]	TON
					Xa,b	**Xc**	**Xd,e**	**6**	**7a,b**	**7c**			
1	**Cl**	**1a**	9.8	toluene	13.5	1.5	1.1	-	0.8	0.8	1.0	17.7	2.3
2		**1a**	-	diglyme	59.9	3.6	7.2	-	9.4	1.4	1.2	81.4	-
3		**1b**	11	toluene	20.2	4.0	6.5	-	1.2	1.7	1.1	33.6	4.4
4	**Br**	**1a**	11	toluene	48.3	-	5.1	-	2.6	0.6	1.3	56.6	6.0
5		**1a**	-	diglyme	61.9	-	4.3	-	9.9	1.1	1.2	77.2	-
6		**1b**	10	toluene	27.9	-	3.6	-	6.4	1.3	1.2	39.2	5.0
7	**I**	**1a**	12	toluene	0.2	-	-	23.8	-	-	0.6	24.0	1.9
8		**1a**	-	diglyme	-	-	-	71.1	-	-	-	71.1	-
9		**1b**	11	toluene	0.4	-	-	14.4	-	-	1.0	14.7	1.4

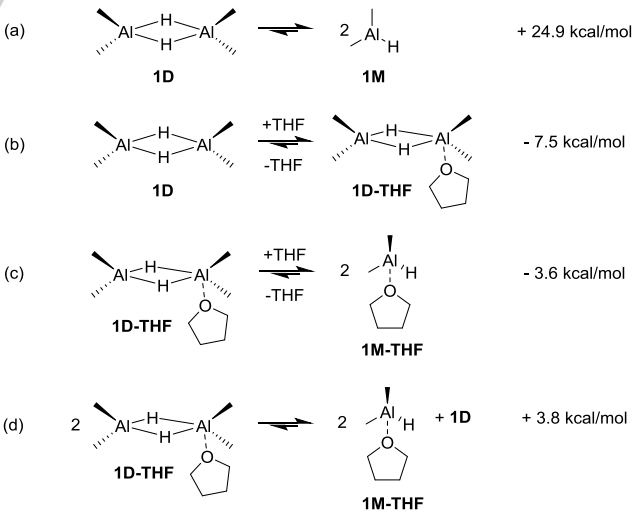
[a] *E*/*Z* ratio of Xa,b. [b] Full tables in the SI.

Mechanistic DFT Investigations and Kinetic Studies

To model the donor influence in the HDF reaction we chose perfluoropropene (**2**), the aluminum hydride $HAlMe_2$ (**1b**) and the donor THF, paying particular attention to the role of the donor in facilitating the HDF reaction and to the reasons behind the *E*-selectivity at low THF concentration and the change of selectivity at high concentration. Aluminum hydrides form strongly bridged dimers or oligomers, which is a testament to the electron deficiency of Al(III).[20] **1b** can exist in different oligomeric forms $[Me_2AlH]_n$, but the dimer dominates at low concentration in hydrocarbon solution (< 0.2 M).[21] Therefore, we included only the dimer in DFT studies, not possible higher order oligomers; this also ensures comparability of results in comparison to **1a**, which only exists in dimeric form. Donor coordination was modelled with a substoichiometric amount of THF, i.e. one THF molecule and two molecules **1b.**

THF is added in experiments only in catalytic quantities. Donor addition does not lead to preferred formation of the donor-monomer complex **1M-THF** as long as its concentration is smaller than the concentration of the dimeric aluminum hydride (Scheme 4d). Instead, the donor is bound to one aluminum of the dimer **1D-THF**. As a result, one of the Al-H-Al bridges is weakened and the system becomes asymmetric (see Figure 1). One bridge is nearly unaffected by the THF-coordination, while the bridge opposite to the coordinated THF shows two different Al-H bond lengths (Δ 0.3 Å). Neither free **1M** (Scheme 4a) nor free THF (Scheme 4b) is expected in considerable amounts under the experimental conditions as a result of the large dimerization and coordination energies. The equilibrium between **1D-THF** and **1M-THF** (Scheme 4d) is concentration dependent and the former is favored at low THF concentrations and high alane concentrations.

Figure 1. 1D and the THF adduct **1D-THF**.



Scheme 4. Gibbs free energies for the $HAlMe_2$ monomer-dimer-donor equilibria. T = 273 K.

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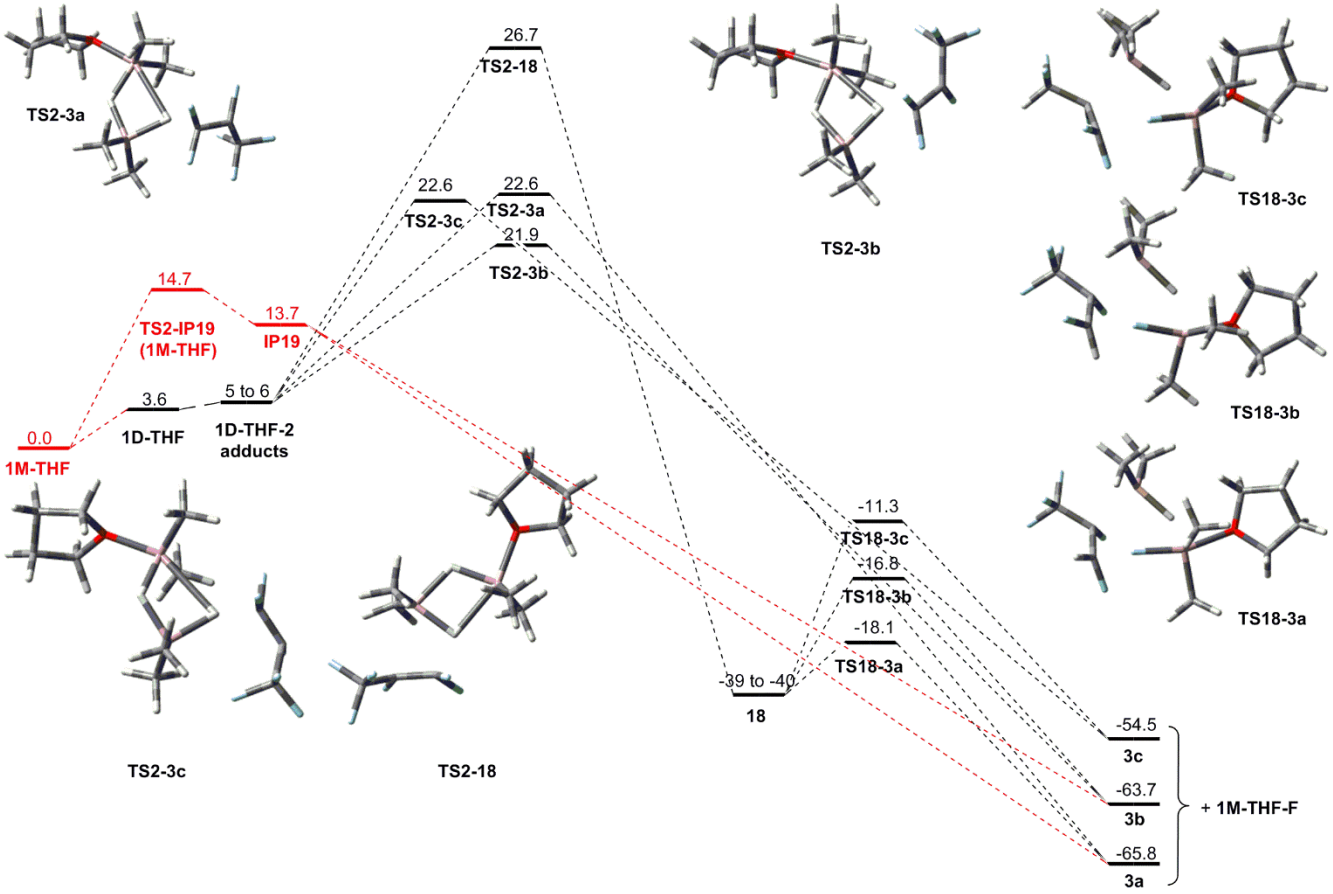
Nonetheless, we considered that HDF may take place from all four possible aluminum species, i.e. **1M**, **1M-THF**, **1D** and **1D-THF**. Details for the analysis of the reaction pathways for **1M**, **1M-THF** and **1D** can be found in the supporting information. Activation barriers involving **1M** and **1D** are higher than for **1M-THF** and **1D-THF**. In order to understand the role that the donor plays, it is instructive to first highlight some key findings for the HDF involving **1M**, **1D** and **1M-THF.**

HDF via the aluminum hydride monomer **1M** proceeds preferentially via a hydrometallation-elimination sequence associated with high barriers (40-48 kcal/mol, when the dimerization equilibrium is factored in and predominantly enthalpic). Hydrometallation is rate limiting but elimination is selectivity determining and would yield the thermodynamically most stable *Z*-isomer **3a** in high selectivity; as all elimination TS are energetically early but geometrically late their relative energy differences reflect those found in the products, very similar to HDF using Cp_2TiH.[8d]

THF binds strongly to the electron deficient aluminum center of **1M** (ΔG_{Diss} = 18 kcal/mol) forming **1M-THF** and leads to significant changes in selectivity and mechanism. The donor 'blocks' the coordination vacancy at aluminum and reduces the electrophilicity of Al which leads to some notable mechanistic changes. It hinders σ-bond metathesis character of transition states, instead, the transition states now resemble S_NV character. HDF barriers (14.7 to 20.9 kcal/mol) are lowered in comparison to **1M**. HDF via S_NV is strongly preferred over hydrometallation (3-6 kcal/mol) and the lowest lying transition state proceeds via ion pair formation. Elimination of fluoride from this ion pair via rotation of the CF_2H group likely is a statistical process leading to an expected *E*/*Z* ratio of 1:1.

Similar to **1M**, HDF via the aluminum hydride dimer **1D** proceeds preferentially via a hydrometallation-elimination sequence associated with high barriers. Hydrometallation is rate limiting but elimination is selectivity determining and would yield the *Z*-isomer **3a** in high selectivity.

HDF from 1D-THF. THF coordination to **1D** forming **1D-THF** activates one Al-H bond. Adduct formation of **1D-THF** and **2** is endergonic and HDF proceeds directly from the reactants. HDF proceeds via S_NV and not σ-bond metathesis, as judged by the long Al-F distances and the only mildly elongated C-F bonds (Table 4), or hydrometallation. Activation barrier heights are low and accessible at rt and HDF via S_NV **TS2-3b(1D-THF)** (21.9 kcal/mol) is preferred over all other pathways (Scheme 5). HDF



Scheme 5. Possible reaction pathways for HDF of **2** and **1D-THF** and transition state geometries. Competitive unselective reaction pathway via **1M-THF** shown for comparison (red traces). Gibbs free energies in kcal/mol, 273 K, solvent toluene. Reaction via **1M-THF** is disfavored at low THF concentrations. For reasons of clarity TS and resting state names are shortened in the Scheme, for example **TS2-18** is **TS2-18(1D-THF)**.

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Table 4. Bond distances [Å] in reactants and HDF σ-bond metathesis and hydrometallation TS using **1D-THF**. TS sorted by decreasing $\Delta G_{273K}^{\ddagger}$.

	Al-H	C-F	C=C	C-H	Al-F	Al-Al	Shortest H-F	ΔG‡
TS2-18(1D-THF)	1.712/2.278	-	1.383	1.533	-	2.918	2.648	23.1
TS2-3a(1D-THF)	1.759/2.699	1.340	1.390	1.395	2.837	3.021	2.548	19.0
TS2-3c(1D-THF)	1.741/2.745	1.379	1.391	1.438	2.796	3.010	2.765	18.9
TS2-3b(1D-THF)	1.777/2.518	1.355	1.387	1.376	2.790	2.957	2.684	18.3
C_3F_6	-	1.303/1.328-1.336[a]	1.326	-	-	-		
1D-THF	1.670/1.935	-	-	-	-	2.686		

[a] C-F bond length C1/C3.

via **1M-THF** (S_NV **TS2-IP19**, see SI) is competitive (14.7 kcal/mol) and proceeds via ion pair formation from which elimination is unselective. The balance between these two TS depends on both the THF concentration and overall [Al]. The more selective reaction via the dimer **1D-THF** is favored at high [Al] and low [THF].

All S_NV TS are geometrically earlier than it is the case for **1M**, as judged by the less elongated C=C bonds (~ +0.06 Å vs. +0.08-0.10 Å) and Al-Al distances (~ 2.8-2.9 Å vs. ~ 3.0 Å) and the primary Al-H distance (~ +0.1 Å vs. 0.1-0.3 Å). Most importantly, the secondary Al-H distance increases much more than it does for **1D** (~ 0.7 Å vs. ~ 0.3 Å), indicating that coordination of THF facilitates opening of the aluminum dimer.

It should however be noted that all S_NV barriers lie within 1 kcal/mol. Hydrometallation via **TS2-18(1D-THF)** is now strongly disfavored and the predominantly formed isomer is the *E*-isomer by an S_NV reaction.

Preliminary kinetic experiments for reaction of **1a** and **2** gave an activation enthalpy $\Delta H^{\ddagger}$ of 9.7 ± 1.2 kcal/mol and an activation entropy $\Delta S^{\ddagger}$ of 39 ± 5 cal mol^{-1} K^{-1}, indicating a bimolecular reaction (Table 5, Figure 2). This compares well with the calculated values of $\Delta H^{\ddagger}$ = 11.1 and $\Delta S^{\ddagger}$ of 26 cal mol^{-1} K^{-1} for

Table 5. HDF of **2** with DIBAL. Kinetic constants, temperatures and conditions.

T [°C]	Al/donor ratio	k[:10^{-4}]	Error [:10^{-6}]	$\Delta H^{\ddagger}$ [kcal/mol]	$\Delta S^{\ddagger}$ [cal mol^{-1} K^{-1}]
-30	10:1	0.48	0.79		
-15	10:1	1.33	1.65	9.7 ± 1.2	39 ± 5
0	10:1	4.93	3.52		

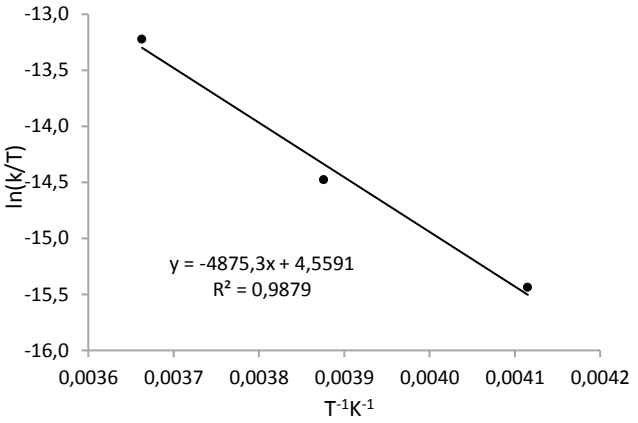

Figure 2. Eyring plot for HDF of **2** with DIBAL.

reaction of **1b** via the dimer **1D-THF**. The experimentally observed *E*/*Z* selectivity of 2.3 translates to a 0.5 kcal/mol difference between both pathways at 273 K. This compares very well with the calculated difference of 0.7 kcal/mol. However, calculations appear to underestimate the barrier for HDF forming **3c**, which should lie 2 kcal/mol above the preferred *E* pathway.

Role of donor solvents in HDF using aluminum hydrides. Table 6 shows the expected selectivities for HDF for **1M**, **1M-THF**, **1D** and **1D-THF** within the hydrometallation and σ-bond metathesis/S_NV pathways.

Without donor solvent, the *Z*-isomer **3a** would be preferentially produced via a hydrometallation reaction of **1D** and **2**, followed by subsequent selectivity determining but not rate limiting elimination. Significant amounts of **3c** would also be expected from an S_NV pathway for **1D**. Nonetheless, barriers are very high (>31.5 kcal/mol), hindering HDF, in line with the experimental

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observation that donor solvents are critically needed for the HDF reaction to take place.
In summary, donor solvents lower the HDF barrier and switch the selectivity. However, the donor is located on the opposite site of the aluminum hydride dimer from which the reaction takes place and changing the donor identity should have only very limited influence on the selectivity of the HDF reaction at low concentrations. This was indeed observed.
The **1M-THF** vs. **1D-THF** equilibrium can of course be tuned by varying the amount of donor solvent. DFT indicates that a shift towards **1M-THF** should be accompanied by a loss of selectivity. This can indeed be observed experimentally, as shown in Table 7.

Table 6. Comparison of selectivities (273 K) for HDF via **1M**, **1D**, **1M-THF** and **1D-THF**.

	1M	**1D**	**1M-THF**	**1D-THF**
Selectivity **HM** pathway *Z*/*E*	13/1	16/1	6/1	11/1
Selectivity **SBM**/**S_NV** pathways Z/E	3c(SBM)	3c(S_NV)	1:1(S_NV)	1:4(S_NV)
Preferred mechanism	HM	HM/S_NV	S_NV	S_NV
Preferred isomers	*Z*/*E*	*Z*/*3c*	*Z*/*E*	*Z*/*E*
Selectivity *Z*:*E*	13/1	4/1	1/1	1/4

Finally, we have demonstrated that the choice of solvent can influence the selectivity in HDF reactions. Non-polar solvents disfavor charge delocalization, which increases S_NV barrier heights, thereby increasing selectivity. A similar strategy cannot be used here, as the donor solvent is critically needed to lower the HDF activation barriers. However, the higher selectivity observed for **3d** indicates that partially fluorinated substrates which form poorly stabilized anions should react via a hydrometallation pathway which increases selectivity.

Table 7. HDF of hexafluoropropene with 1.2 eq. DIBAL and THF as organocatalysts in toluene at rt, 15 min.

Entry	mol% THF	*E*/*Z*	Conv. [%]
1	11	2.4	15.9
2	117	1.7	93.1
3	456	1.2	91.1

Conclusions

Hydrodefluorination of vinylic and aromatic C-F bonds using aluminum hydrides is facilitated by O and N donor molecules. The organocatalyst activates Al-H bonds, lowers barriers for HDF and can influence the selectivity. HDF selectivities are substrate and concentration dependent. The reaction occurs under mild conditions. The exact nature of the donor has only limited influence on the selectivity at low concentration, as the donor is located far away from the active center in the transition state. High concentration of the donor shifts the equilibrium towards the monomeric aluminum hydride, which results in a change of mechanism and a loss of selectivity.
Aluminum hydrides are commonly used as hydride sources in transition metal catalyzed HDF. Direct HDF at the aluminum hydride facilitated by the organocatalyst offers a cheaper alternative. Tuning the selectivity remains an issue due to the complex balance of mechanistic pathways. However, the dimerization energies for group 13 hydrides as well as metal-hydride bond energies decrease for the heavier group homologues. This makes them interesting candidates for analogous HDF reactions catalyzed by organocatalysts that hold the potential of offering higher selectivity. We are currently investigating this issue in our lab.

Experimental Section

All preparations and reactions were performed using standard Schlenk-type and vacuum line techniques, or by working in an argon-filled glove box. The amount of gaseous compounds was determined by using pVT technique or by condensing the gas into a weighted J. Young flask. Diglyme, THF, diethyl ether and toluene were distilled from sodium or potassium. DME, 1,4-dioxane, pyridine and MTBE were distilled from calcium hydride. **1a** (Sigma Aldrich), **3d** (Syn-Quest Labs), **6** (SCM Specialty Chemicals), **12** (J. T. Baker Chemical Co.), **14** (Apollo scientific LTD), **16** (abcr) were obtained from commercial sources and used as received. **8**, **10** were purchased from abcr and distilled from calcium hydride. **2** (Solvay) was obtained free of charge. **1b**[22], **1c**[23] were synthesized as described in the corresponding literature.

Catalytic hydrodefluorination: Reaction conditions and substrates are listed in Table 1-3, 7 and in Table S1-S11 of the SI. A single-necked flask equipped with a J. Young valve was charged with alane **1a**, **1b** or **1c**, organocatalyst and solvent (2 ml). The substrate was added with a syringe and the mixture was degassed. Gaseous substrates were condensed into the flask to the prior degassed mixture. The corresponding reaction conditions were applied. The crude reaction mixture was purified by fractional condensation under vacuum to a trap kept at -80 °C (for liquid substrates) or through two subsequent traps kept at -80 °C and -196 °C, respectively, for gaseous substrates. Fluorobenzene was added to the contents of the trap (liquid substrates) and a defined amount of that mixture was added to an NMR tube containing C_6D_6. The contents of the second trap (gaseous substrates) were condensed into a NMR tube containing a standard C_6D_6 solution of fluorobenzene. The conversion of the substrates was determined by NMR spectra by integration of product resonances versus the internal standard (fluorobenzene). The products were identified by ^{19}F NMR spectroscopy (benzene-d_6), using available literature data for **3a-b**[24], **3c**[19a], **4d-e**[25], **4a-c**[26], **4f**[19a], **5b**[27], **7a-c**[28], **9a**[29], **11a**[30], **11b**[31], **13a-b**[32], **13c-d**[33], **15a-c**[34], **15d-e**[35], **17a**[36], **17b**[37] or by comparison with an authentic sample (**5a**, **6**, **7d**, **9b-c**).

Kinetic experiments: For a stock solution, **1a** (0.72 g, 5.1 mmol), diglyme (72 µl, 0.5 mmol) and toluene (6 ml) were mixed in the glove box. For each sample, 500 µl stock solution was filled in a J. Young NMR tube containing a glass capillary tube filled with acetone-d_6. The solution was degassed and **2** (63 mg, 0.42 mmol) was added by vacuum transfer. To determine ΔG/ΔH/ΔS, the reaction progress was monitored by ^{19}F NMR spectroscopy at -30, -15, 0 °C, respectively. The conversion of the substrate was determined from ^{19}F NMR spectra by integration of product and starting material resonances (detailed data is given in the Supporting Information).

Calculations. All structures were fully optimized at the M06-2X(PCM)[38] /6-31+(2d,p) level using Gaussian09[39] coupled to an external optimizer (PQS, OPTIMZE routine)[40] within the BOPT software package.[41] An ultrafine grid (Int(Grid=ultrafine)) and standard SCF convergence quality settings (Scf=tight) for Gaussian single point calculations were used. The nature of each stationary point was checked with an analytical second-derivative calculation (no imaginary frequency for minima, exactly one imaginary frequency for transition states, corresponding to the reaction coordinate) and the accuracy of the TS was confirmed with an IRC scan Solvent influence (toluene, ε=2.3741) was modelled explicitly, using the polarizable continuum model (PCM) implemented in the Gaussian 09 software suite. The M06-2X functional has been shown to yield accurate results for systems involving aluminium systems.[42]

Transition states were located using a suitable guess and the Berny algorithm (Opt=TS)[43] or the Synchronous Transit-Guided Quasi-Newton (STQN) Method, developed by H. B. Schlegel and coworkers[44] (Opt=QST2 or QST3) or a relaxed potential energy scan to arrive at a suitable transition state guess, followed by a quasi-Newton or eigenvector-following algorithm to complete the optimization).

Vibrational analysis data derived at this level of theory were used to calculate thermal corrections (enthalpy and entropy, 298 K, 1 bar) for all species considered. Final single-point energies (SP) were calculated at the M06-2X(PCM)[45] level of theory employing triple-ζ Dunning basis sets (cc-pVTZ) from the EMSL basis set exchange library,[46] to minimize BSSE contributions.[47]

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