Catalytic Hydrogenation of Organic Compounds in Liquid Hydrogen Fluoride

Andrew E. Feiring

Contribution No. 2482 from the Central Research and Development Department Experimental Station, E. I. duPont de Nemours and Co., Inc., Wilmington, Delaware 19898

Received March 14, 1977

The noble metal catalyzed hydrogenation of certain aliphatic ketones, acids, esters, and anhydrides and various aromatic compounds in liquid HF is described. For example, 4-methyl-2-pentanone is reduced at 16 psi H_2 pressure over PtO_2 to 2- and 3-methylpentane, and dodecanoic acid is reduced at 5000 psi H_2 pressure to dodecane, dodecyl ether, and dodecyl dodecanoate. Skeletal rearrangements, suggesting the presence of carbonium ion intermediates, are observed in many cases.

The noble metal catalyzed hydrogenation of many organic functional groups is known to be effected by the use of acidic solvents.[1] Anhydrous hydrogen fluoride is a strong acid, inert to reduction, and a good solvent for many organic compounds.[2] Furthermore, the low boiling point of anhydrous HF should facilitate product recovery and recycle of the solvent. Despite these advantages, relatively little has been reported on hydrogenations in HF. The reduction of nitrobenzenes to *p*-fluoroanilines in HF has been described.[3] More recently, several reports on hydrogenations in HF–super acid systems have appeared.[4-7] In this paper, the noble metal catalyzed hydrogenation of several organic functional groups in anhydrous HF is described. Most noteworthy are the observations that certain aliphatic carboxylic acids are reduced over PtO_2 in HF and that aliphatic ketones are reduced to hydrocarbons in HF under extremely mild conditions. Rearrangements typical of carbonium ion intermediates are observed in many systems.

Results

Aliphatic Ketones (Table I). The catalytic hydrogenation of ketones is well known.[1] Expect for aryl ketones, where reduction to methylene is observed, the normal reduction product is the corresponding alcohol. In anhydrous HF, however, reduction of a representative aliphatic ketone, 4-methyl-2-pentanone, took a different course. Stirring a mixture of the ketone and a catalytic amount of PtO_2 under 16 psi of H_2 at room temperature resulted in a rapid uptake of hydrogen. Workup as described in the Experimental Section

$$CH_3\overset{O}{\overset{\|}{C}}CH_2CH(CH_3)_2 \xrightarrow[HF]{H_2/PtO_2} \underset{71\%}{CH_3CH_2CH_2CH(CH_3)_2} + \underset{29\%}{CH_3CH_2CH(CH_3)CH_2CH_3} \quad (1)$$

gave an essentially quantitative yield of two hydrocarbons, identified as 2- and 3-methylpentane. As indicated in Table I, this novel reduction was explored under a variety of conditions. In addition to PtO_2, RuO_2 was found to be an active catalyst for the hydrogenation. In this case, however, 2- and 3-methylpentane comprised only ca. 73% of the product, the remainder being a mixture of at least six other C_5 to C_7 hydrocarbons. Other catalysts (Pd/C, Pt/C, Rh/Al_2O_3, PdO_2, nickelocene, Re_2O_7, $Co_2(CO)_8$, and $PtCl_2$) were not effective. Using PtO_2, variation of the hydrogen pressure from 16 to 5000 psi had little effect on the ratio of rearranged to unrearranged products. An attempted reduction in the presence of carbon monoxide gave only unreacted starting material.

The corresponding alcohol, 4-methyl-2-pentanol, was not detected in any of the reductions using pure HF as the solvent. In a mixed solvent of ethyl ether/HF (5/1 v/v), however, hydrogenation of the ketone over PtO_2 gave the alcohol in 94%

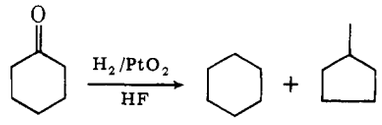
$$CH_3\overset{O}{\overset{\|}{C}}CH_2CH(CH_3)_2 \xrightarrow[HF/ether]{H_2/PtO_2} \underset{94\%}{CH_3\overset{OH}{\overset{|}{C}}HCH_2CH(CH_3)_2} + \underset{6\%}{CH_3CH_2CH_2CH(CH_3)_2}$$

$$\downarrow \overset{HF}{H_2/PtO_2} \quad (2)$$

$$CH_3CH_2CH_2CH(CH_3)_2 + CH_3CH_2CH(CH_3)CH_2CH_3$$

yield together with 6% of 2-methylpentane. No hydrogenation occurred in pure ether under these conditions. Treatment of the alcohol in pure HF with PtO_2 and hydrogen under the above conditions resulted in little H_2 uptake. The product was an undistillable oil showing only saturated hydrocarbon absorption in its infrared and NMR spectra.

A representative alicyclic ketone was also briefly studied. Hydrogenation of cyclohexanone in HF at 16 psi H_2 pressure



(3)

over PtO_2 gave a mixture of cyclohexane (62%) and methylcyclopentane (38%) as the only detectable products.

The hydrogenation is not entirely general however. Attempted reduction of the electronegatively substituted ketone, ethyl acetoacetate, under the above conditions gave only unreacted starting material.

Aliphatic Carboxylic Acids and Derivatives. Carboxylic acids are generally considered among the most difficult functional groups to hydrogenate.[1] They normally require high temperatures and high pressures using ruthenium, rhenium, or copper–barium–chromium catalysts which only give reduction to the alcohol. The facile reduction of ketones over PtO_2 in HF suggested the possibility that carboxylic acids could be reduced under these conditions. Using dodecanoic

$$CH_3(CH_2)_{10}COOH \xrightarrow[5000\ psi,\ HF,\ 20\ h]{H_2/PtO_2} \underset{21\%}{CH_3(CH_2)_{10}CH_3} + \underset{42\%}{[CH_3(CH_2)_{10}CH_2]_2O} + \underset{6\%}{CH_3(CH_2)_{10}\overset{O}{\overset{\|}{C}}OCH_2(CH_2)_{10}CH_3} \quad (4)$$

Table I. Hydrogenation of Ketones in HF[b]

Substrate (g)	Catalyst (g)	Conditions	% conversion	Products (%)[a]
4-Methyl-2-pentanone (6.0)	PtO_2 (0.5)	25 °C, 5 h, 16 psi H_2	100	2-Methylpentane (71)
4-Methyl-2-pentanone (6.0)				3-Methylpentane (29)
4-Methyl-2-pentanone (0.6)	PtO_2 (0.04)	25 °C, 2 h, 1000 psi H_2	100	2-Methylpentane (73)
4-Methyl-2-pentanone (0.6)				3-Methylpentane (27)
4-Methyl-2-pentanone (0.6)	PtO_2 (0.05)	25 °C, 3 h, 5000 psi H_2	100	2-Methylpentane (71)
4-Methyl-2-pentanone (0.6)				3-Methylpentane (29)
4-Methyl-2-pentanone (5.0)	PtO_2 (0.5)	50 °C, 4 h, 5000 psi 1:1 H_2/CO	0	
4-Methyl-2-pentanone (3.0)	10% Pd/C (0.3)	25 °C, 19 h, 16 psi H_2	0	
4-Methyl-2-pentanone (3.0)	10% Pt/C (0.3)	25 °C, 5 h, 16 psi H_2	0	
4-Methyl-2-pentanone (3.0)	5% Rh/Al_2O_3 (0.3)	25 °C, 4 h, 16 psi H_2	0	
4-Methyl-2-pentanone (3.0)	RuO_2 (0.3)	25 °C, 4 h, 16 psi H_2	87	2-Methylpentane (52)
				3-Methylpentane (21)
				+ 6 other hydrocarbons
4-Methyl-2-pentanone (3.0)	PdO_2 (0.3)	25 °C, 5 h, 16 psi H_2	0	
4-Methyl-2-pentanone (3.0)	Nickelocene (0.3)	25 °C, 5 h, 16 psi H_2	0	
4-Methyl-2-pentanone (3.0)	Re_2O_7 (0.3)	25 °C, 6 h, 16 psi H_2	0	
4-Methyl-2-pentanone (3.0)	$Co_2(CO)_8$ (0.3)	25 °C, 5 h, 16 psi H_2	0	
4-Methyl-2-pentanone (3.0)	$PtCl_2$ (0.3)	25 °C, 5 h, 16 psi H_2	0	
4-Methyl-2-pentanone (3)	PtO_2 (0.3)	25 °C, 1 h, 16 psi H_2 5 mL HF, 25 mL ether	100	2-Methylpentane (6) 4-Methyl-2-pentanol (94)
Cyclohexanone (6)	PtO_2 (0.5)	25 °C, 4 h, 16 psi H_2	100	Cyclohexane (62) Methylcyclopentane (38)
Ethyl acetoacetate (6)	PtO_2 (0.5)	25 °C, 4 h, 16 psi H_2	0	

[a] Percentages by GLC analysis of the distilled product. [b] Registry no.: HF, 7664-39-3; 4-methyl-2-pentanone, 108-10-1; cyclohexanone, 108-94-1; ethyl acetoacetate, 141-97-9.

acid as a representative aliphatic carboxylic acid, no reduction was observed over PtO_2 in HF at 16 psi. Under higher pressures (5000 psi H_2), however, a slow but smooth uptake of H_2 occurred at room temperature. Workup as described in the Experimental Section gave three products, identified as dodecane, dodecyl ether, and dodecyl dodecanoate. Under the same conditions, both dodecyl anhydride and dodecyl dodecanoate were reduced only to dodecyl ether in 77 and 78%

$$CH_3(CH_2)_{10}\overset{O}{\overset{\|}{C}}OCH_2(CH_2)_{10}CH_3 \xrightarrow[\text{HF}\\ \text{5000 psi}\\ \text{20 h}]{H_2/PtO_2} [CH_3(CH_2)_{10}CH_2]_2O \quad 77\% \qquad (5)$$

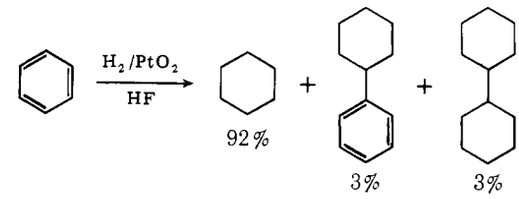
isolated yield, respectively. Thus, the anhydride formed by HF-catalyzed condensation of two acid molecules is the likely precursor to the ester and ether in the hydrogenation of the carboxylic acid. The corresponding alcohol, dodecanol, was not detected in the reduction of the acid, ester, or anhydride. Treatment of dodecanol under the hydrogenation conditions gave only high molecular weight oils. The hydrogenation of

$$[CH_3(CH_2)_{10}\overset{O}{\overset{\|}{C}}\frac{}{}_2O \xrightarrow[\text{HF}\\ \text{5000 psi}\\ \text{20 h}]{H_2/PtO_2} [CH_3(CH_2)_{10}CH_2]_2O \quad 78\% \qquad (6)$$

acetic anhydride (0.6 g) over 0.1 g of PtO_2 in 5 g of HF at room temperature and 5000 psi H_2 pressure gave a mixture of ethyl acetate (40%) and diethyl ether (5%) plus unreacted anhydride. Under similar conditions, the mixed anhydride of acetic and propionic acids gave a mixture of all three possible ether products (ethylpropyl, diethyl, and dipropyl) plus propyl acetate and ethyl acetate.

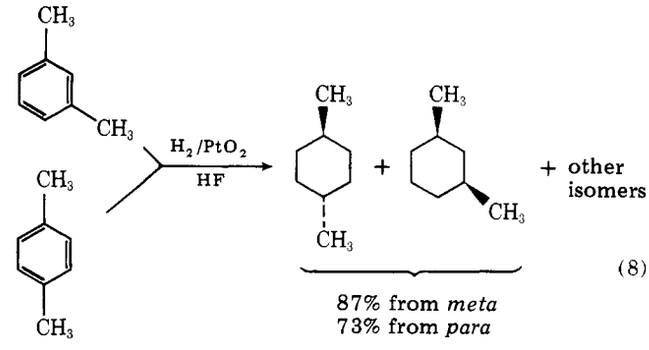
The reduction of acids or anhydrides in HF appears to suffer from three major limitations as a preparative process. First, rather large amounts of catalyst were required to achieve acceptable reaction rates. With dodecanoic acid in HF at room temperature and 5000 psi H_2 pressure, the conversions after 20 h using 10 and 17% (w/w) of PtO_2 relative to substrate were 41 and 69%, respectively. Second, the reduction of α-branched acids or anhydrides resulted in the isolation of extremely complex product mixtures. Thus, the hydrogenation of either cyclohexane carboxylic acid anhydride or trimethylacetic acid gave 30+ products as analyzed by GLC. Finally, as in the case of the ketone hydrogenations, substitution of the molecule by a second electronegative function appears to inhibit the reduction process. The reduction of maleic anhydride proceeded smoothly to succinic anhydride, but no further reduction was detected. Oxalic acid was inert.

Aromatic Compounds (Table II). Benzene was reduced in HF over PtO_2 at 16 psi H_2 pressure to cyclohexane plus small amounts of cyclohexylbenzene and bicyclohexyl. Chlorobenzene was reduced to cyclohexane; toluene was reduced to methylcyclohexane. Both *m*- and *p*-xylene under-



(7)

went rearrangements during hydrogenation in HF. Six dimethyl cyclohexanes were detected by GLC with *cis*-1,3- and



(8)

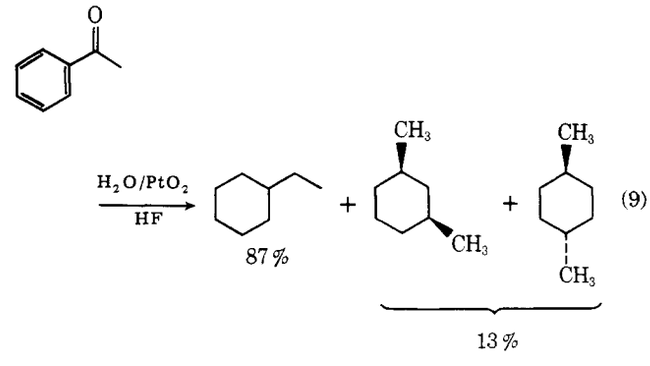
Table II. Hydrogenation of Aromatic Compounds in Liquid HF

Substrate (g)	Registry no.	Catalyst (g)	Conditions	% conversion	Products (%)[a]
Benzene (2.6)	71-43-2	PtO_2 (0.3)	25 °C, 5 h, 16 psi H_2	67	Cyclohexane (92) Cyclohexylbenzene (4) Bicyclohexyl (4)
Benzene (5.2)		PtO_2 (5.2)	25 °C, 2 h, 16 psi H_2	60	Cyclohexane (89) Cyclohexylbenzene (11)
Toluene (3)	108-88-3	PtO_2 (0.3)	25 °C, 2 h, 16 psi H_2	43	Methylcyclohexane (100)
p-Xylene (3)	106-42-3	PtO_2 (0.3)	25 °C, 3 h, 16 psi H_2	95	*cis*-1,3-Dimethylcyclohexane, *trans*-1,4-Dimethylcyclohexane (73) *cis*-1,2-Dimethylcyclohexane, *trans*-1,2-Dimethylcyclohexane (8) *trans*-1,3-Dimethylcyclohexane (6) *cis*-1,4-Dimethylcyclohexane (5)
m-Xylene (3)	108-38-3	PtO_2 (0.3)	25 °C, 3 h, 16 psi H_2	100	*cis*-1,3-Dimethylcyclohexane, *trans*-1,4-Dimethylcyclohexane (87) + 4 other Dimethylcyclohexanes (13)
Chlorobenzene (3)	108-90-7	PtO_2 (0.3)	25 °C, 5 h, 16 psi H_2	29	Cyclohexane (100)
Phenol (3)	108-95-2	PtO_2 (0.3)	25 °C, 5 h, 16 psi H_2	88	Cyclohexane (70) Cyclohexanone (30)
Phenol (3)		PtO_2 (0.3)	25 °C, 17 h, 16 psi H_2	100	Cyclohexane (85) Methylcyclopentane (15)
Acetophenone (4)	98-86-2	PtO_2 (0.2)	25 °C, 1.5 h, 16 psi H_2	30	Ethylcyclohexane (87) *cis*-1,3-Dimethylcyclohexane, *trans*-1,4-Dimethylcyclohexane (13)
Nitrobenzene (6.2)	98-95-3	PtO_2 (0.05)	25 °C, 5 h, 16 psi H_2	100	Aniline (36), 4-Fluoroaniline (19) *b*
4-Chloronitrobenzene (4)	100-00-5	PtO_2 (0.2)	25 °C, 7 h, 16 psi H_2	92	4-Fluoroaniline (28), 4-Chloroaniline (57) *b*
Quinoline (3)	91-22-5	PtO_2 (0.3)	25 °C, 1.5 h, 16 psi H_2	83	4,5,6,7-Tetrahydroquinoline (90) 1,2,3,4-Tetrahydroquinoline (10)
Quinoline (3)		PtO_2 (0.3)	25 °C, 17 h, 16 psi H_2	100	4,5,6,7-Tetrahydroquinoline (50) Decahydroquinoline (50)
Isoquinoline (12.9)	119-65-3	PtO_2 (0.6)	25 °C, 18 h, 5000 psi H_2	66	4,5,6,7-Tetrahydroisoquinoline
Benzonitrile (3.0)	100-47-0	PtO_2 (0.3)	25 °C, 5 h, 16 psi H_2	100	Benzaldehyde (76) Benzamide (3) $PhCH{=}NCH_2Ph$ (14) $PhCH{=}NCH_2C_6H_{11}$ (6)
p-Xylene (3.0)		PtO_2 (0.3)	25 °C, 2 h, 16 psi H_2 5 mL HF, 25 mL ether	100	*cis*-1,4-Dimethylcyclohexane (67) *trans*-1,4-Dimethylcyclohexane (33)
Benzene (2.6) Pyridine (14)	110-86-1	PtO_2 (0.3)	25 °C, 5 h, 16 psi H_2	47 (benzene) 0 (pyridine)	Cyclohexane

[a] GLC analysis of distilled product unless otherwise indicated. [b] Percent yield.

trans-1,4-dimethylcyclohexane predominating from both xylenes. These isomers could not be separated by GLC, but were detected by careful infrared examination of the major GLC product peak. In a mixture of HF and ether (1/5, v/v) *p*-xylene was reduced over PtO_2 at 16 psi H_2 pressure to a mixture of 67% *cis*-1,4- and 33% *trans*-1,4-dimethylcyclohexane. In pure ether, no reduction was observed under these conditions.

The reduction of acetophenone in pure HF at 16 psi H_2 pressure occurred with extensive rearrangement. Hydrogenation of the compound to 30% conversion over PtO_2 gave the expected ethylcyclohexane (87%) plus a mixture (13%) of *cis*-1,3- and *trans*-1,4-dimethylcyclohexane.



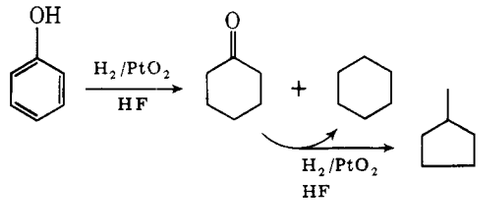
(9)

Table III. Reduction of Quinoline over PtO_2 in Strong Acids

Acid	Wt % catalyst	Pressure H_2, psi	Reaction time, h	% yield[c]
Concentrated HCl[a]	12	50	30	70
12 N H_2SO_4[a]	12	50	4.5	74
Trifluoroacetic acid[a]	12	50	0.45	84
Trifluoroacetic acid[a]	12	16	8.5	80
HF[b]	10	16	1.5	75

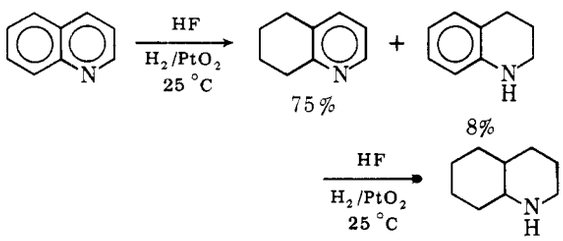
[a] Reference 8. [b] This study. [c] Yield of 4,5,6,7-tetrahydroquinoline by GLC.

The hydrogenation of phenol to 88% conversion gave a product mixture containing 70% cyclohexane and 30% cyclohexanone. If the reaction was allowed to continue until H_2 uptake ceased, the product mixture consisted of cyclohexane (85%) and methylcyclopentane (15%).



(10)

The regiospecific reduction of unsubstituted quinoline or isoquinoline to the 1,2,3,4-tetrahydro isomers over PtO_2 under mildly acidic conditions is well known.[1] By contrast, in anhydrous HF, at 16 psi H_2 pressure, quinoline was selectively hydrogenated over PtO_2 to 4,5,6,7-tetrahydroquinoline with only 10% of the 1,2,3,4-tetrahydro isomer produced. Further hydrogenation gave decahydroquinoline. With isoquinoline,



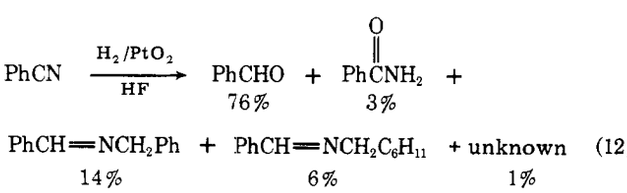
(11)

hydrogenation in HF gave only 4,5,6,7-tetrahydroisoquinoline; none of the 1,2,3,4-tetrahydro isomer was detected.

Recently, Vierhapper and Eliel[8] reported similar results using concentrated HCl, H_2SO_4, or trifluoroacetic acid. A comparison of the various strong acids used in the hydrogenation of quinoline is contained in Table III. The reduction in HF appears faster than in H_2SO_4, HCl, or trifluoroacetic acid with comparable selectivities.

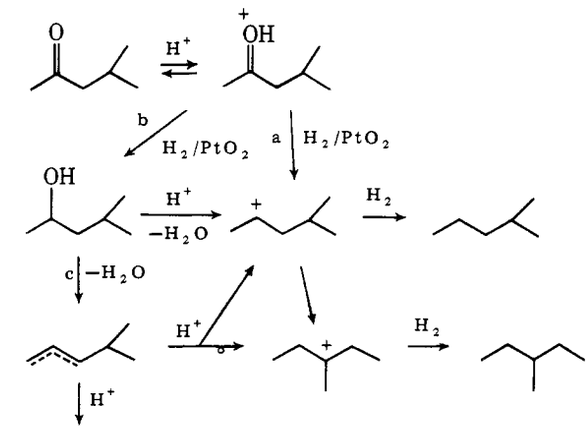
In line with these results, hydrogenation of a mixture of 3 mL of benzene and 15 mL of pyridine in HF over PtO_2 resulted only in the reduction of the benzene to cyclohexane; no piperidine or other products from the reduction of pyridine could be detected.

Reduction of benzonitrile over PtO_2 in HF at 16 psi H_2 pressure followed by treatment of the crude mixture with dilute aqueous base gave five products (12) which were identified by GLC and GC/MS. The major product, obtained in 76% yield, was benzaldehyde, presumably formed by hydrolysis of an intermediate imine.[9]



(12)

Scheme I



Discussion

Any mechanistic proposal on catalytic hydrogenations in HF must account for the following observations: (1) HF has a catalytic effect, i.e., many of the reported reductions are faster in HF than in less acidic media. (2) A carbonyl is reduced to methylene, while the corresponding alcohol gives polymeric products. (3) Extensive skeletal rearrangements, characteristic of carbonium ion intermediates, are observed in many cases. (4) Reduction of a group is inhibited by the presence of an electronegative function elsewhere in the molecule.

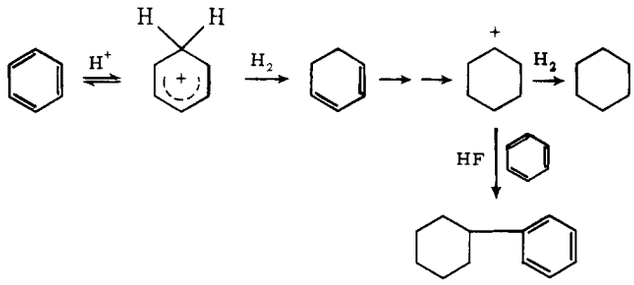
A potential mechanistic scheme for carbonyl reduction in HF using 4-methyl-2-pentanone as a model is shown in Scheme I. Ketones are known to protonate in HF, usually without further reaction.[2] The catalytic effect of the strong acid suggests that the protonated carbonyl is more easily reduced than the neutral molecule. Several pathways are available for reduction of the protonated carbonyl. Direct reduction (pathway a), in effect a hydrogenolysis, would generate water and the 4-methyl-2-pentyl cation. Partition of this species between reduction and rearrangement followed by reduction would give the observed products. The reduction of carbonium ions by hydrogen in acidic media is well known.[4-7]

Alternatively, the protonated carbonyl might be reduced to the alcohol (pathway b) as a discrete intermediate followed by protonation and loss of water to give the same carbonium ions. Loss of water from the alcohol to give olefin(s) (pathway c) followed by protonation would also form the carbonium ions.

At first glance, pathways b and c are ruled out by the observation that reaction of the alcohol under hydrogenation conditions gives only nonvolatile hydrocarbon with little or no methylpentane formation. However, a simple concentration factor might account for this discrepancy. If in the reduction of the carbonyl, step b is the slow step, the concentration of polymerizable intermediate(s) is kept small, favoring the formation of monomeric products. With the preformed alcohol, a large concentration of polymerizable intermediate(s) might be produced, resulting in formation of the nonvolatile hydrocarbon residue. Olefins polymerize readily in HF. A similar scheme can be proposed for the reduction of carboxylic acids and their derivatives in HF.

The failure of ethyl acetoacetate, oxalic acid, and succinic anhydride to undergo reduction may be due to the decreased

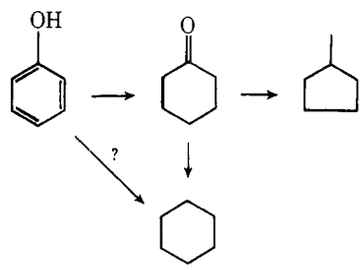
Scheme II



basicity of these compounds from the presence of two electronegative functions in the molecule.[11]

The reduction of the aromatic systems is also catalyzed by HF, probably again by protonation of the substrate, followed by a metal-catalyzed hydride donation. Although the concentration of protonated benzene in pure HF is not detectable by physical methods,[12] a kinetically significant amount could still be present in solution (Scheme II). The intervention of carbonium ion intermediates is further suggested by the formation of cyclohexylbenzene in the reduction of benzene and by the formation of the methyl shift products in the xylene and acetophenone hydrogenations.

The complete hydrogenation of both phenol and cyclohexanone gives cyclohexane and methylcyclopentane. The ratio of unrearranged products is larger, however, from phenol than from cyclohexanone. Furthermore, partial conversion of phenol gives cyclohexanone and cyclohexane (no methyl-



cyclopentane). Thus, at least two pathways are indicated in the reduction of phenol, one preceding through cyclohexanone to give cyclohexane and methylcyclopentane and a second which gives only cyclohexane. Details of this latter process remain obscure.

The results obtained in the reduction of quinoline and the benzene/pyridine mixture in HF can be explained if N protonation of the nitrogen lone pair on the heteroatom ring inhibits formation of a more easily reduced π-protonated species. Thus, a weak acid catalyzes reduction of the pyridine ring in quinoline, whereas a strong acid catalyzes reduction of the benzene ring because of a change in mechanism for the reduction step.

In summary, the evidence suggests that the reduction of many functional groups in HF proceeds at least in part by a sequence of proton addition–hydride donations rather than by a concerted addition of molecular hydrogen.

Finally, some comment should be made concerning the practicality of running catalytic hydrogenations in HF.

A major disadvantage of HF is the inability to use common laboratory glassware, but widespread availability of laboratory apparatus constructed from HF-resistant polymers largely overcomes this problem. Most of the reactions reported here are run at moderate temperatures and pressures where this equipment is very satisfactory. On the other hand, HF lacks some of the problems encountered with other strong acids. Workup is facilitated by its low boiling point. A simple distillation can often be used in place of messy and hazardous dilution and extraction procedures. The reactions reported here were in most cases remarkably clean with little or no by-product formation. Side reactions common with other strong acids such as sulfuric acid (sulfonation and/or oxidation of the substrate or products) are generally absent.

Experimental Section

Caution! Hydrogen fluoride is extremely corrosive to human tissue, contact resulting in painful, slow healing burns. Laboratory work with HF should be conducted only in an efficient hood with the operator wearing full face shield and protective clothing.

General. Anhydrous hydrogen fluoride (Air Products) and other reagents were used as received. Gas chromatographic analyses (GC) were preformed on a Hewlett-Packard 5700 instrument equipped with a thermal conductivity detector. Peak areas were measured by the cut and weigh technique and unless otherwise indicated are not corrected for relative detector response. Gas chromatographic/mass spectroscopic measurements (GC/MS) were performed on a Du Pont 21490 instrument equipped with a VG2040 data system.

Procedure. Reactions at pressures above 16 psi or temperatures above room temperature were run in 80 or 200 mL Hastelloy C shaker tubes. Other reactions were run in Kel-F vessels attached to a vacuum line constructed from Kel-F and Teflon fluorocarbon resin. In general, the organic reagent and catalyst were loaded to the reaction vessel, which was cooled in dry ice/acetone or liquid N_2, evacuated, and charged with HF (10–30 times the volume of organic reagent) by vacuum transfer from the commercial cylinder. The reaction vessel was pressured with H_2 and heated to the required reaction temperature. After suitable reaction time, the excess H_2 pressure was vented and the product was worked up by one of three techniques. If the desired product was relatively nonvolatile, the HF was pumped out of the reaction vessel using an aspirator. The residue was dissolved in an organic solvent and washed with water or dilute base or was treated with sodium fluoride powder, as appropriate, to remove traces of HF. If a volatile product was expected, the reaction vessel was attached in series to a copper trap containing NaF pellets, a glass trap cooled in dry ice/acetone or liquid N_2, and a source of vacuum. The NaF pellets quantitatively scrubbed the HF from the gas stream and the organic product was isolated from the glass trap. Rarely (because of the potential hazards involved) a well-chilled reaction mixture was slowly poured over ice, the aqueous solution neutralized with 20% aqueous KOH and the product extracted with an organic solvent.

After appropriate processing, usually distillation, the reaction products were analyzed and identified by GLC comparison with authentic samples, GC/MS, and/or NMR spectroscopy. The results are contained in Tables I and II and in the Results section. Three representative experiments are reported in detail below.

Hydrogenation of Dodecanoic Acid. An 80-mL Hastelloy shaker tube was charged with 6.0 g (0.03 mol) of dodecanoic acid and 1.0 g of PtO_2. The vessel was cooled in dry ice/acetone, evacuated, and charged with 40 g of HF. The vessel was pressured to 5000 psi with H_2 and agitated at 30 °C for 17 h. The H_2 pressure was released and the HF was evaporated using an aspirator. The residue was taken up in 150 mL of ether, filtered, washed with several portions of water, dried ($MgSO_4$), and concentrated on a rotary evaporator to 4.8 g of clear oil. GLC analysis (6 ft × 1/8 in. 10% UCW-982 column, temperature programmed from 100 to 250 °C at 16°/min) showed four peaks: A (retention time = 4.5 min, 21%); B (retention time = 7.5 min, 31%, identified as dodecanoic acid by comparison with authentic sample); C (retention time = 21 min, 42%); and D (retention time = 25 min, 6%).

A 4.0-g sample of the product was chromatographed over 100 g of silica gel. Elution of the column with petroleum ether gave pure dodecane (0.70 g), followed by 1.5 g of pure dodecyl ether: NMR (δ, CCl_4) 0.89 (t, 6 H), 1.28 (brs, 40 H), 3.30 (4 H, t); IR (CCl_4) 1110 cm^{-1} (s). Anal. Calcd for $C_{24}H_{50}O$: C, 81.28; H, 14.21; O, 4.52. Found: C, 81.18; H, 14.13; O, 4.14. Elution of the column with 10% ether in petroleum ether gave 1.8 g of oily solid, a mixture by GLC of dodecanoic acid and component D. D was isolated by preparative GLC and identified as dodecycl dodecanoate by NMR, IR, and GLC comparison with an authentic sample.

Hydrogenation of 4-Methyl-2-pentanone. A 200-mL Kel-F vessel attached to a vacuum line constructed from Kel-F and Teflon fluorocarbon resin was charged with 6.0 g of 4-methyl-2-pentanone and 0.5 g of PtO_2. The vessel was cooled in liquid N_2, evacuated on a vacuum pump, and charged with 50 mL of HF by vacuum transfer from a commercial cylinder. The vessel was pressured to 6 psi with H_2 and the reaction mixture was allowed to warm to room temperature. The H_2 pressure was adjusted to 16 psi. Magnetic stirring of the HF mixture initiated uptake of hydrogen. When the system pressure

fell to 8 psi, the vessel was repressurized to 16 psi from the hydrogen cylinder. After 11 such repressurizations, H_2 uptake ceased (~5 h). The reaction vessel was connected in series to a copper trap containing ~300 g of NaF pellets, a calibrated glass trap cooled in liquid N_2, and a vacuum pump. The contents of the reaction vessel were slowly (~2 h) pumped through the trap system. When the reaction vessel had pumped dry, the vacuum was disconnected and the glass trap was warmed to room temperature. It contained 6.5 mL of colorless liquid. GLC analysis (6 ft × 1/8 in. 10% UCW-982 column, oven temperature = 25 °C, He carrier gas at 40 mL/min) showed two components in a 71:29 ratio. They were identified by comparison of their GLC retention time and mass spectroscopic cracking pattern (GC/MS) as 2-methylpentane and 3-methylpentane, respectively.

Hydrogenation of Quinoline. Following the preocedure employed for 4-methyl-2-pentanane, 3.0 g (0.023 mol) of quinoline was reduced over 0.3 g of PtO_2 for 1.5 h at 8–16 psi hydrogen pressure. After removing the HF by aspirator, the residue was dissolved in 50 mL of H_2O, made alkaline by the addition of 20% aqueous KOH, and extracted with three 100-mL portions of ether. The combined ether extracts were dried ($MgSO_4$) and concentrated on a rotary evaporator. Bulb-to-bulb distillation of the residue (0.1 mm) gave 2.7 g of oil. GLC analysis (10 ft × 1/4 in. 10% SE-30 column at 200 °C) showed three well-resolved peaks: A (retention time = 6 min, 75%), B (retention time = 9 min, 17%), C (retention time = 13 min, 8%). Peaks B and C were identified as quinoline and 1,2,3,4-tetrahydroquinoline, respectively, by co-injection with authentic samples. Peak A was collected by preparative GLC and identified as 5,6,7,8-tetrahydroquinoline: mass spectrum *m/e* 133.0895, calcd for $C_9H_{11}N$ 133.0891; NMR δ 8.32 (d, 1 H), 6.8–7.3 (m, 2 H), 1.1–1.6, and 2.0–2.5 (m, 8 H).

Registry No.—Dodecanoic acid, 143-07-7; dodecyl ether, 4542-57-8; 5,6,7,8-tetrahydroquinoline, 10500-57-9.

References and Notes

(1) (a) R. L. Augustine, "Catalytic Hydrogenation", Marcel Dekker, New York, N.Y., 1965. (b) P. N. Rylander "Catalytic Hydrogenation over Platinum Metals", Academic Press, New York, N.Y., 1967.
(2) M. Kilpatric and J. C. Jones in "The Chemistry of Non Aqueous Solvents", Vol. II, J. Lagowski, Ed., Academic Press, New York, N.Y., 1967.
(3) D. A. Fidler, J. S. Logan, and M. M. Boudakian, *J. Org. Chem.*, **26**, 4014 (1961); D. A. Fidler, U.S. Patent 2 884 458 (1959); J. W. Churchhill, E. H. Kober, and P. H. Scott, U.S. Patent 3 639 482 (1972); also see V. Weinmayr, *J. Am. Chem. Soc.*, **77**, 1962 (1955).
(4) M. Siskin, *J. Am. Chem. Soc.*, **96**, 3641 (1974).
(5) J. Wristers, *J. Am. Chem. Soc.*, **97**, 4312 (1975).
(6) R. Jacquesy and G. Joly, *Tetrahedron*, **31**, 2237 (1975).
(7) H. Hogeveen, G. J. Gaasbeek, and A. F. Beckel, *Recl. Trav. Chim. Pays-Bas*, **88**, 703 (1969); H. Hogeveen, *ibid.*, **89**, 74 (1970).
(8) F. W. Vierhapper and E. L. Eliel, *J. Org. Chem.*, **40**, 2729 (1975); *J. Am. Chem. Soc.*, **96**, 2256 (1974).
(9) A related reduction in concentrated H_2SO_4 has been reported: P. Tinapp, *Chem. Ber.*, **102**, 2770 (1969).
(10) J. H. Brewster, *J. Am. Chem. Soc.*, **76**, 6361 (1954).
(11) W. Klatt, *J. Anorg. Chem.*, **222**, 225, 285 (1935).
(12) C. Reid, *J. Am. Chem. Soc.*, **76**, 3264 (1954).

Difunctional Derivatives of *syn*-Dimethanoperhydro-*s*-hydrindacene

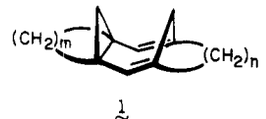
Ludmila Birladeanu,[1a] Ernest Chamot,[1b] William E. Fristad,[1b,c] Leo A. Paquette,*[1b] and Saul Winstein[1a,d]

Departments of Chemistry, The Ohio State University, Columbus, Ohio 43210, and The University of California, Los Angeles, California 90024

Received March 29, 1977

Prompted by a desire to prepare a bisannulated homotropilidene whose localized *cis*-divinylcyclopropane structure might be sufficiently destabilized to force adoption of neutral homoaromatic character, a study of the reducibility of difunctional *syn*-dimethanoperhydro-*s*-hydrindacenes was undertaken. Thus, 4-acetyl-*s*-hydrindacene was converted to the quinone **5** by two different series of reactions. The first consisted of a sequence involving Baeyer–Villiger oxidation, hydride reduction, and Fremy salt oxidation of the resulting phenol. The second involved Beckmann rearrangement, hydrolysis, and dichromate oxidation of the aniline. The quinone adds 2 mol of diazomethane exclusively from the same surface but in opposite senses to give bispyrazoline **8**, photolysis of which provides the desired bishomoquinone **10**. The structure and stereochemistry of **8** and **10** follow unequivocally from their subsequent conversion to **11**, **12**, and **13** and the ^{13}C NMR spectra of the entire series of compounds. All attempts to force these difunctional derivatives to undergo either reductive 1,4-elimination or cleavage have proven uniformly unsuccessful.

Each of our groups has had an interest in molecules capable of rapid degenerate valence isomerization and, in particular, in the question of possible removal of the barrier to Cope rearrangement to arrive at a neutral homoaromatic ground state species. These interests overlapped in work on the attempted synthesis of doubly annulated 3,4-homotropilidenes of general formula **1** and, more specifically, the hydrocarbon



1

with $m = n = 3$. This paper describes the results of those experiments which have provided access to several disubstituted *syn*-dimethanoperhydro-*s*-hydrindacene precursors to **1** and outlines the difficulties encountered in our attempts to subsequently introduce the divinylcyclopropane part structure.

4-Acetyl-*s*-hydrindacene (**2**) has previously been synthesized in connection with Arnold and Rondestvedt's study of Mills–Nixon effects.[2] Although Baeyer–Villiger oxidation of **2** proved to be typically sluggish, prolonged refluxing with *m*-chloroperbenzoic acid in dichloromethane afforded acetate **3** in 84% yield based upon recovered ketone. More vigorous conditions appeared to cause competing decomposition of the ester formed. Treatment of the derived phenol (**4**) with Fremy's salt[4] led in 87% yield to the bright yellow *p*-quinone **5**, access to which could also be gained by sequential Beckmann rearrangement of **2**-oxime, hydrolysis of **6**, and sodium dichromate oxidation of aniline **7**.

As in the case of duroquinone,[5] **5** enters into dipolar cycloaddition with diazomethane to form a single bispyrazoline in >80% isolated yield. Analysis of the symmetry required by