hexane-1,1-dicarboxylic acid in 7.5 ml. of collidine was heated to the given temperature for the desired time. The cooled solution was taken up in 100 ml. of ether and extracted with two 40-ml. portions of 10% sodium hydroxide solution. The aqueous layer was acidified with 20% hydrochloric acid to a congo red end-point and extracted twice with 75-ml. portions of ether. The ether phase was washed twice with water and subjected to an eight funnel fractional extraction using in each flask 50 ml. of ether and 50 ml. of a *p*H 7.0 buffer prepared from 41.20 ml. of 0.2 *M* disodium phosphate and 8.80 ml. of 0.1 *M* citric acid as described previously.[4] When all eight funnels had been utilized, each aqueous phase was acidified with hydrochloric acid to a congo red end-point and extracted with the accompanying ether phase. The monoacids were found in the first two or three fractions; fractions four and five contained negligible material. Unreacted diacid was found in the last two or three fractions. The monoacid fraction was analyzed by the quantitative infrared method.

Equilibration of *cis*- and *trans*-2-Phenylcyclohexanecarboxylic Acids.—A sample of 60 mg. of *cis*-2-phenylcyclohexanecarboxylic acid was sealed in a Pyrex tube which was then heated to 200° for 102 hr. Infrared analysis indicated the mixture of *cis*- and *trans*-2-phenylcyclohexanecarboxylic acids to contain 8.5% *cis* isomer.

When the time of heating was only 64 hr. the product contained 13.7% *cis*-acid. At the end of 20 hr. 39.2% *cis*-acid was indicated while after 6 hr. there was 74.0% *cis* isomer. On this basis less than 2% isomerization of *cis*-acid is calculated for heating for 8 minutes.

Similarly, heating of 60 mg. of *trans*-2-phenylcyclohexanecarboxylic acid to 200° for 102 hr. resulted in a mixture containing 8.9% *cis* isomer.

Stability of *cis*-2-Phenylcyclohexanecarboxylic Acid in Collidine under Decarboxylation Conditions.—Four 60.0-mg. samples of *cis*-2-phenylcyclohexanecarboxylic acid in 1.0 ml. of collidine were heated to 60°, 90°, 110° and 160° for 60, 30, 20 and 20 minute periods, respectively. The acidic product was separated from the collidine as in the decarboxylation experiments except that the fractional extraction was omitted. Analysis by infrared indicated the fractions converted to *trans*-2-phenylcyclohexanecarboxylic acid to be 0.0472, 0.0298, 0.0396, 0.0698 in the four runs, respectively. These were used in correcting the percentage *cis*-2-phenylcyclohexanecarboxylic acid obtained from the collidine decarboxylation experiments for isomerization.

Infrared Analyses.—The method was that described earlier[5] except that carbon disulfide was used. The analytical wave lengths used were 7.71 and 7.98 μ. Calibration data are recorded in Table II. The optical density of all mixtures, known and unknown, was taken as zero at 2.0 μ.

TABLE II

KNOWN MIXTURES

Actual % *cis*-isomer	D'	D''	Q	Actual R	Calcd. F	Calcd. R	Calcd. % *cis*-isomer
0.0	0.431	0.136	...	...	..	...	..
25.0	.337	.251	0.314	0.333	1.06	0.327	24.6
50.0	.296	.408	0.979	1.00	1.02	1.02	50.4
75.0	.244	.569	2.86	3.00	1.05	2.98	74.8
100.0	.180	.720	...	...	..	...	..

Here D' and D'' are the optical densities at 7.71 and 7.98 μ, respectively. $Q = \frac{D''_m D'_t - D'_m D''_t}{D'_m D''_c - D''_m D'_c}$ where the subscripts c, t and m refer to pure *cis* isomer, *trans* isomer and a given mixture, respectively. R is the ratio of *cis* to *trans* isomer in a mixture. F is defined by $R = QF$ and determined empirically from values of Q and R for known mixtures. The average value of $F = 1.04$ was used in calculating the results in the last two columns of Table II and the composition of unknown mixtures.

EVANSTON, ILLINOIS

[CONTRIBUTION FROM THE DEPARTMENT OF CHEMISTRY AND CHEMICAL ENGINEERING, UNIVERSITY OF ILLINOIS]

Reduction of Organic Compounds by Mixed Hydrides. II. Hydrogenolysis of Ketones and Alcohols[1]

BY ROBERT F. NYSTROM AND C. RAINER A. BERGER

RECEIVED OCTOBER 28, 1957

Diaryl ketones, alkyl aryl ketones and certain aryl alcohols are smoothly reduced to the corresponding hydrocarbon by the lithium aluminum hydride–aluminum chloride reagent in ether solution at 35°. There are notable differences in the ease and extent of reduction which varies with the order of mixing the reactants and with the groups present in the organic component.

The mixed hydride, prepared from equimolar quantities of aluminum chloride and lithium aluminum hydride,[2] has been found effective in promoting hydrogenolysis reactions. Certain aromatic ketones and alcohols were reduced in high yield to the corresponding hydrocarbon, using one to four hour reaction times at 35°. Other methods, such as the Clemmensen, Wolff–Kishner, or palladium–hydrogen, can now be considered obsolete for the small-scale reduction of diaryl and alkyl aryl ketones. Dialkyl ketones, however, are reduced only to the alcohol stage.

Conover and Tarbell[3] have reported the conversion of aromatic acid and carbonyl compounds to the hydrocarbons in moderate yield, when treated with a large excess of lithium aluminum hydride, at 60 to 90°, for periods ranging from one hour to eleven days. Recently, the hydrogenolysis of aromatic carbonyl compounds and alcohols by aluminum chloride and lithium aluminum hydride has been reported. In one publication,[4] reduction was accomplished by adding an aluminum chloride solution of the ketone to the lithium aluminum hydride in ether. In another,[5] one mole of lithium aluminum hydride was introduced into a solution containing two moles of aluminum chloride before addition of the organic compound.

In this Laboratory we have found that the extent of hydrogenolysis of aryl and alkyl aryl ketones by the lithium aluminum hydride–aluminum chloride reagent varies with the experimental operations and nature of the organic compound. Some

(1) C. R. A. Berger and R. F. Nystrom, Abstracts of Papers, 131st Meeting, American Chemical Society, Miami, Fla., April 7–12, 1957, 51-O.

(2) R. F. Nystrom, THIS JOURNAL, **77**, 2544 (1955).

(3) L. H. Conover and D. S. Tarbell, *ibid.*, **72**, 3586 (1950).

(4) J. Broome and B. R. Brown, *Chemistry & Industry*, 1307 (1956).

(5) B. R. Brown and A. M. S. White, *J. Chem. Soc.*, 3755 (1957).

TABLE I

REDUCTION OF DIARYL KETONES

Compound reduced	Product	Yield, %	Method	$\frac{ArCOAr}{LiAlH_4-AlCl_3}$
Benzophenone	Diphenylmethane	92	1	1
Benzophenone	Diphenylmethane	65	2	2
Benzophenone	Diphenylmethane	59	2[a]	2[a]
Benzophenone	Diphenylmethane	43	2[b]	2[b]
4,4'-Dimethylbenzophenone	Bis-(*p*-methylphenyl)-methane	89	2	1.3
4,4'-Dimethoxybenzophenone	Bis-(*p*-methoxyphenyl)-methane	92	2	0.7[c]
4,4'-Dichlorobenzophenone	Bis-(*p*-chlorophenyl)-methane	83	2	0.7[c]
2,4'-Dichlorobenzophenone	2,4'-Dichlorobenzhydrol	70	2	1
2,4'-Dichlorobenzophenone	2,4'-Dichlorodiphenylmethane	82	3	1
1-Acetonaphthone	1-Naphthylmethylcarbinol	80	2	1
	1-Ethylnaphthalene	Trace		
1-Acetonaphthone	1-Ethylnaphthalene	90	3	1
2-Acetonaphthone	2-Naphthylmethylcarbinol	70	3	1
Phenyl 2-thienyl ketone	2-Benzylthiophene	94	2	1

[a] Ketone reduced by $LiAlH_4$–$AlBr_3$. [b] Ketone reduced by $LiAlH_4$–AlI_3. [c] Organic compound added by Soxhlet technique.

TABLE II

REDUCTION OF ALKYL ARYL KETONES

Compound reduced	Product	Yield, %	Method	$\frac{ArCOR}{LiAlH_4-AlCl_3}$
Acetophenone	Methylphenylcarbinol	91	1	1
Acetophenone	Methylphenylcarbinol	93	2	1.3
Acetophenone	Ethylbenzene	25	3	1.3
Acetophenone	Ethylbenzene	56	[a]	1.3
Phenyl ethyl ketone	*n*-Propylbenzene	24	3	1.3
p-Methylacetophenone	*p*-Ethyltoluene	19	2	1
p-Dimethylaminoacetophenone	*p*-Dimethylaminoethylbenzene	84	2	1
2,4-Dimethylacetophenone	2,4-Dimethylethylbenzene	96	1	1
2,4-Dimethylacetophenone	2,4-Dimethylethylbenzene	90	2	1
2,5-Dimethylacetophenone	1,4-Dimethyl-2-ethylbenzene	11	1	1
2,5-Dimethylacetophenone	1,4-Dimethyl-2-ethylbenzene	52	2	1
2,5-Dimethylacetophenone	1,4-Dimethyl-2-ethylbenzene	82	3	1
3,4-Dimethylacetophenone	1,2-Dimethyl-4-ethylbenzene	53	2	1
3,4-Dimethylacetophenone	1,2-Dimethyl-4-ethylbenzene	75	3	1
1-Indanone	Indane	45	2	1
α-Tetralone	Tetralin	68	2	1
α-Tetralone	Tetralin	85	3	1

[a] 0.1 mole of ketone and 0.2 mole of $AlCl_3$ in 200 cc. of ether were added to 0.075 mole of $LiAlH_4$ and 0.075 mole of $AlCl_3$ in 200 cc. of ether.

ketones, for example, are reduced to the alcohol stage under the mildest conditions while others yield the desired hydrocarbon. The different procedures developed for hydrogenolysis are listed below:

Method 1. After the addition of one to two moles of ketone in ether to one mole of lithium aluminum hydride solution, an ethereal solution containing one mole of aluminum chloride is added.

Method 2. An ethereal solution of one mole of ketone is introduced into the reagent, prepared by the addition of one mole of aluminum chloride in ether to one mole of lithium aluminum hydride solution.

Method 3. An equimolar mixture of the ketone and aluminum chloride in ether is added to the reagent made by the introduction of one mole of aluminum chloride solution to one mole of lithium aluminum hydride in ether.

The reducing power appears to increase from method 1 to 3. For example, 2,5-dimethylacetophenone gives an 11% yield of 1,4-dimethyl-2-ethylbenzene by method 1, a 52% yield by method 2 and an 82% yield by method 3. Likewise, α-tetralone furnishes a 68% yield of tetralin by method 2 and an 85% yield by method 3. Also, both 2,4'-dichlorobenzophenone and 1-acetonaphthone give predominantly the respective alcohols by method 2, but the desired hydrocarbons are formed by method 3.

Benzophenone is converted to diphenylmethane in 92% yield even under the mildest condition (method 1). Similarly, 2,4-dimethylacetophenone furnished a 96% yield of 2,4-dimethylethylbenzene by this method.

Acetophenone, however, is reduced to only methylphenylcarbinol by methods 1 and 2, and gives but a 25% yield of ethylbenzene by method 3. The yield of the latter was increased to 56% by adding an ethereal solution containing 1.3 moles of ketone and 2.6 moles of aluminum chloride to 1.0 mole of the lithium aluminum hydride–aluminum chloride reagent in ether.

The presence of activating groups in the ketone facilitates hydrogenolysis as demonstrated in the conversion of *p*-dimethylaminoacetophenone to *p*-

dimethylaminoethylbenzene in 84% yield. In addition, in the dimethylacetophenone series, using method 2, 2,4-dimethylacetophenone gives a 90% yield of 2,4-dimethylethylbenzene whereas both 3,4-dimethylacetophenone and 2,5-dimethylacetophenone furnish approximately a 50% yield of 1,2-dimethyl-4-ethylbenzene and 1,4-dimethyl-2-ethylbenzene, respectively. Also, by employing method 3, 1-acetonaphthone and α-tetralone give the corresponding hydrocarbons while 2-acetonaphthone yields only the alcohol.

The effect of varying the aluminum halide was studied under various conditions

$C_6H_5COC_6H_5 + {}^1/_2LiAlH_4\text{–}AlCl_3 \longrightarrow 65\%\ C_6H_5CH_2C_6H_5$

$C_6H_5COC_6H_5 + {}^1/_2LiAlH_4\text{–}AlBr_3 \longrightarrow 59\%\ C_6H_5CH_2C_6H_5$

$C_6H_5COC_6H_5 + {}^1/_2LiAlH_4\text{–}AlI_3 \longrightarrow 43\%\ C_6H_5CH_2C_6H_5$

Evidently the replacement of aluminum chloride by the bromide or iodide is not advantageous.

Experimental results on the reduction of ketones are summarized in Tables I and II.

Certain alcohols have been converted to the hydrocarbon stage by use of methods 1–3. The tertiary aryl alcohol, triphenylcarbinol, was reduced by the mixed hydride to triphenylmethane. Also, a secondary aryl alcohol, benzhydrol, furnished diphenylmethane. Benzyl alcohol, a primary aryl alcohol, has resisted reduction. These results are summarized in Table III.

TABLE III
REDUCTION OF ALCOHOLS

Compound reduced	Product	Yield, %	Method	Alcohol / $LiAlH_4$–$AlCl_3$
Triphenylcarbinol	Triphenylmethane	98	2	1
Benzhydrol	Diphenylmethane	70	2	1.5
Benzyl alcohol	No reduction		2,3	1.3
Methylphenylcarbinol	No reduction		3	0.6

A number of miscellaneous reductions were examined and are reported in Table IV. The most interesting result, however, is the reduction of N-acetylpyrrole. The lithium aluminum hydride reduction of this compound results in a reductive decomposition to pyrrole and ethanol.[6] In contrast to this, N-acetylpyrrole is reduced to N-ethylpyrrole in 35% yield by the mixed hydride.

Our investigation into the reaction of the mixed hydride with various carbonyl compounds revealed certain properties contributing to its uniqueness. The reduction is an exceptionally clean reaction and products of high purity can be obtained. All the procedures carried out required a temperature of only 35°. The ease of reduction of the carbonyl group in aryl and alkyl aryl ketones is determined by the group or groups present in the adjacent aromatic ring. Finally, the mode of addition of reactants influences the extent of reduction.

TABLE IV
MISCELLANEOUS REDUCTIONS

Compound reduced	Product	Yield, %	Method	Compd. / $LiAlH_4$–$AlCl_3$
Benzil	*m*-Hydrobenzoin	95	2	0.5
Anthranilic acid	*o*-Toluidine	50	2	0.5[a]
2-Octanone	2-Octanol	84	3	1.4
9-Fluorenone	9-Fluorenol	90	2	1
9-Fluorenone	9-Fluorenol	94	3	1
Benzoyl chloride	Benzyl alcohol	81	3	1.3
N-Acetylpyrrole	N-Ethylpyrrole	35	2	0.8
Acetanilide	N-Ethylaniline	80	2	1
N,N-Diethylbenzamide	Diethylbenzylamine	68	2	1

[a] Organic compound added by Soxhlet technique.

(6) V. M. Micovic and M. L. Mihailovic, *J. Org. Chem.*, **18**, 1190 (1953).

Experimental

Experimental results are summarized in Tables I, II, III and IV. Products were further identified, in all but two cases, by suitable derivatives. The experimental techniques for the preparation of the hydride solution and determining the stoichiometry are given in a previous paper.[2]

Following procedures similar to those outlined below, modified only to the extent necessitated by the individual problems of isolating and purifying the products, a number of ketones and alcohols were reduced using the concentration of organic material and hydride shown in the tables.

Method 1. Reduction of Benzophenone to Diphenylmethane.—A one-liter, three-necked flask was equipped with a reflux condenser, a mechanical mercury-sealed stirrer and a dropping funnel. The gas outlet tube on the condenser was attached to two traps cooled at −80° and then to a wet-test meter. A solution of 0.1 mole of lithium aluminum hydride in 195 ml. of ether was placed in the flask. Through the dropping funnel, a solution of 18.2 g. (0.1 mole) of benzophenone in 200 ml. of ether was added at a rate such as to produce gentle reflux. After 30 minutes the addition of 13.3 g. (0.1 mole) of granular aluminum chloride in 100 ml. of ether was made. One-half hour later 40 ml. of water and 40 ml. of 6 *N* sulfuric acid were added. The clear solution was transferred to a separatory funnel and, after removing the ether layer, the aqueous layer was extracted with four 100-ml. portions of ether. From the combined ether extracts there was obtained, after drying over Drierite and removal of ether, crude diphenylmethane. This material was purified by fractional distillation through a Nester–Faust 18″ micro spinning band column under reduced pressure and there was obtained a 92% yield of diphenylmethane, b.p. 165° (24 mm.), 259–260° uncor. (750 mm.), m.p. 24.5°. The 2,4,2′,4′-tetranitrodiphenylmethane derivative melted at 172–173°.

Method 2. Reduction of 2,4-Dimethylacetophenone to 2,4-Dimethylethylbenzene.—The apparatus described above was employed. A solution of 0.1 mole of lithium aluminum hydride in 91 ml. of ether was placed in the three-necked flask. Through the dropping funnel, a solution of 13.3 g. (0.1 mole) of granular aluminum chloride in 100 ml. of ether was introduced. After five minutes, a solution of 15.8 g. (0.1 mole) of 2,4-dimethylacetophenone in 200 ml. of ether was added at a rate such as to produce gentle reflux. Then after 30 minutes an addition of 20 ml. of water and 50 ml. of 6 *N* sulfuric acid was made. The reaction mixture was treated as described in the previous example. The crude product was purified by fractional distillation through a 12-inch column under reduced pressure and there was obtained a 90% yield of 2,4-dimethylethylbenzene, b.p. 68° (12 mm.), 187–189° (750 mm.), $n^{20}D$ 1.5040, infrared conformation.

Method 3. The Reduction of α-Tetralone to Tetralin.—The apparatus described above was employed. A solution of 0.1 mole of lithium aluminum hydride in 100 ml. of ether was placed in the three-necked flask. Through the dropping funnel, a solution of 13.3 g. (0.1 mole) of granular aluminum chloride in 100 ml. of ether was added rapidly. Five minutes later, a solution containing 12 g. (0.08 mole) of α-tetralone and 10.9 g. (0.08 mole) of granular aluminum chloride in 200 ml. of ether was introduced at a rate such as to produce gentle reflux. Thirty minutes after the last addition, 150 ml. of water was added and then 100 ml. of 6 *N* sulfuric acid. The reaction mixture was treated as described in the first example. The crude product was purified by fractional distillation through a Nester–Faust 18″ micro spinning band column under reduced pressure and there was obtained an 85% yield of tetralin, b.p. 100° (20 mm.). The 2-(tetrahydronaphthoyl)-benzoic acid derivative melted at 154–155°.

URBANA, ILLINOIS