

Conformational Analysis. X.¹ The Conformational Energy of Alkyl Groups

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The conformational energies of methyl, ethyl, and isopropyl have been determined by equilibration of the appropriate 3- and 4-alkylcyclohexanols with lithium aluminum hydride-aluminum chloride. Since the resulting complex (probably $ROAlCl_2$) exists with the complexed alcohol group virtually exclusively in the equatorial position, the desired conformational equilibrium constant is obtained readily from the position of equilibrium of epimeric alcohols. The values of the conformational energies (1.56 kcal./mole for Me, 1.67 for Et, 1.90 for *i*-Pr) derived in the 4-series differ significantly from those (1.75 kcal./mole for Me, 1.86 for Et, 2.30 for *i*-Pr) derived in the 3-series. The method is apparently not generally applicable to groups other than alkyl.

By "conformational energy" of a group⁴ is meant the difference in free energy of the group between equatorial and axial positions in a monosubstituted cyclohexane, *i.e.*, the standard free-energy change $-\Delta G^\circ$ for the process shown in Figure 1. Since this equilibrium is established extremely rapidly, it is generally not possible to measure its position by direct chemical methods; of the numerous indirect methods⁵⁻⁸ which have been used to obtain $-\Delta G^\circ$, that of measuring the position of configurational equilibrium in a "biased"⁴ system, such as one of those shown in Figure 2 is now quite widely used. One of the requisites for using this approach is that the equilibria indicated in Figure 2 can, in fact be established chemically. This has been achieved at or near room temperature with chemically reactive groups such as carbethoxyl^{9,10} or hydroxyl^{1,11,12} but with unreactive groups, such as alkyl, there are problems. The dimethylcyclohexanes have been equilibrated¹³ by means of concentrated sulfuric acid at

25 and 40° or by means of aluminum chloride at 100°, but the equilibrium is complicated by the fact that positional as well as stereochemical isomerization occurs and, as a result, the derived thermodynamic data for the equilibrium between *cis*- and *trans*-1,3-dimethylcyclohexane (or the 1,4-dimethyl isomers) are somewhat lacking in accuracy. A more clean-cut equilibration of *cis*- and *trans*-1,3-dimethyl- (as well as diethyl- and diisopropyl-) cyclohexanes is achieved over palladium catalysts, but the method requires high temperatures (usually 200–300°) and while the experiments give accurate values for ΔG° at these temperatures, the values for ΔH° and ΔS° (derived from the temperature dependence of the equilibrium) are less accurate and the calculation of ΔG° at temperatures other than those of the equilibration experiments (*e.g.*, at room temperature) consequently also lacks in accuracy. The difficulty is not very serious for the methyl group for which, because of its spherical symmetry, it is probably adequate to assume that $\Delta S^\circ = 0$ so that $\Delta G^\circ = \Delta H^\circ$ is essentially temperature invariant. Therefore, the ΔH° value found by Allinger and co-workers by palladium-catalyzed equilibration of 1,3-dimethylcyclohexane (1.75 ± 0.10 kcal./mole in the liquid phase¹⁴) is probably quite accurate, as is the value of 2.0–2.1 kcal./mole in the gas phase derived from equilibration of the epimeric 1,3,5-trimethylcyclohexanes.¹⁵ In fact, these values are in excellent agreement with the carefully determined thermochemical values of Rossini, *et al.*,¹⁶ *viz.* 1.62–1.72 kcal./mole in the liquid phase and 1.90–1.96 kcal./mole in the vapor phase, derived from differences in heat of combustion of *cis*- and *trans*-1,3- and -1,4-dimethylcyclohexanes.¹⁶ However, the situation is much less satisfactory with the ethyl

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(2) From the Ph.D. Dissertation of Thomas J. Brett. Presented at the 145th National Meeting of the American Chemical Society, New York, N. Y., Sept. 1963.

(3) The Radiation Laboratory is operated under contract with the Atomic Energy Commission. This is AEC Document No. COO-38-429.

(4) E. L. Eliel, N. L. Allinger, S. J. Angyal, and G. A. Morrison, "Conformational Analysis," Interscience Publishers, Inc., New York, N. Y., 1965.

(5) E. L. Eliel, *J. Chem. Educ.*, **37**, 126 (1960).

(6) E. L. Eliel, "Stereochemistry of Carbon Compounds," McGraw-Hill Book Co., Inc., New York, N. Y., 1962, Chapter 8.

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(9) E. L. Eliel and H. Haubenstock, *J. Am. Chem. Soc.*, **83**, 2351 (1961). See also ref. 23.

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(11) E. L. Eliel and R. S. Ro, *J. Am. Chem. Soc.*, **79**, 5992 (1957).

(12) G. Chiurdoglu and W. Masschelein, *Bull. soc. chim. Belges*, **70**, 767 (1961).

(13) (a) A. K. Roebuck and B. L. Evering, *J. Am. Chem. Soc.*, **75**, 1631 (1953); (b) G. Chiurdoglu, P. J. C. Fierens, and C. Henkart, *Bull. soc. chim. Belges*, **59**, 140 (1950); (c) G. Chiurdoglu, J. Versluys-Evrard, and J. Decot, *ibid.*, **66**, 192 (1957).

(14) (a) N. L. Allinger, W. Szkrybalo, and F. A. VanCatledge, unpublished results cited in ref. 4, superseding earlier, less precise results of (b) N. L. Allinger and S.-E. Hu, *J. Org. Chem.*, **27**, 3417 (1962).

(15) C. J. Egan and W. C. Buss, *J. Phys. Chem.*, **63**, 1887 (1959). In the case of 1,3-dimethylcyclohexanes and 1,3,5-trimethylcyclohexanes, one cannot, of course, assume that $\Delta S^\circ = 0$; in the dimethyl case the *trans* isomer is a *dl* pair and is favored by an entropy of mixing of $R \ln 2$; in the 1,3,5-trimethyl compound, the *cis* isomer has a symmetry number of three and is disfavored by an entropy of symmetry of $R \ln 3$. However, in these cases it is probably quite adequate to make these corrections as calculated. The experimentally determined entropy differences of 1.24 cal./deg. mole for the 1,3-dimethylcyclohexanes (H. M. Huffman, S. S. Todd, and G. D. Oliver, *J. Am. Chem. Soc.*, **71**, 584 (1949)), and of 2.3 cal./deg. mole for the 1,3,5-trimethylcyclohexanes (Egan and Buss) are in excellent agreement with the calculated values of $R \ln 2$ or 1.38 cal./deg. mole and $R \ln 3$ or 2.18 cal./deg. mole, respectively.

(16) (a) J. E. Kilpatrick, H. G. Werner, C. W. Beckett, K. S. Pitzer, and F. D. Rossini, *J. Res. Natl. Bur. Std.*, **39**, 523 (1947); (b) E. J. Prosen, W. H. Johnson, and F. D. Rossini, *ibid.*, **39**, 173 (1947); (c) see also C. W. Beckett, K. S. Pitzer, and R. Spitzer, *J. Am. Chem. Soc.*, **69**, 2488 (1947). The difference between the liquid-phase and gas-phase values is quite real; since the equatorial-axial isomer is less volatile and therefore has the higher heat of condensation than the diequatorial isomer, the difference in enthalpy between the diequatorial isomer (of lower enthalpy) and the equatorial-axial isomer (of higher enthalpy) is diminished in the liquid phase.

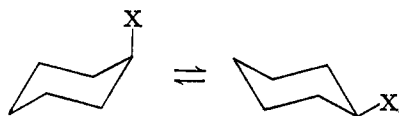


Figure 1.

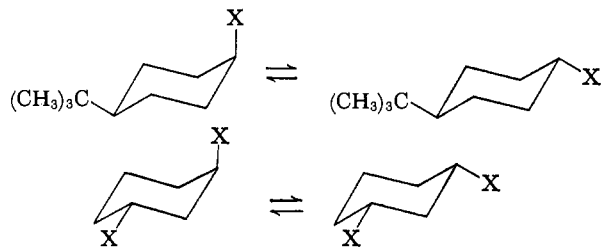


Figure 2.

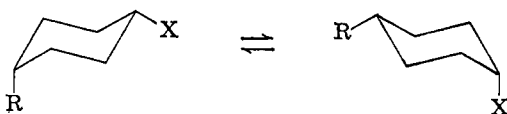


Figure 3.

and isopropyl groups where there is a difference in entropy between equatorial and axial conformations. (In the equatorial conformation there are contributions, from three rotational conformations of the alkyl group whereas in the axial conformation, because of the very high steric compression which results when the ring is confronted with a methyl substituent, the isopropyl group has a single conformation and the ethyl group has two mirror-image conformations.)

In attempts to develop methods applicable at or near room temperature, a variety of indirect equilibrations have been devised.¹⁷⁻²² These methods deal with equilibria of the type shown in Figure 3. In essence, the value of ΔG° (Figure 3) is determined by some measurement (physical or chemical) involving the group X and the value of ΔG°_X (Figure 1) is determined by an analogous measurement for R = H. Assuming, then, that one has additivity of free energies^{6,7} in the case depicted in Figure 3, it follows that $\Delta G^\circ = \Delta G^\circ_R - \Delta G^\circ_X$ whence $-\Delta G^\circ_R = -\Delta G^\circ - \Delta G^\circ_X$. The requisite determinations of conformational equilibria (Figures 1 and 3) have been effected by kinetic,¹⁷ n.m.r.,^{18,19} infrared,²¹ or pK^{21} measurements, as well as by an ingenious method involving the position of equilibrium of alkyl-substituted *cis*-3-hydroxycyclohexanecarboxylic acids with their lactones.²² All these methods have the drawback that *two* equilibrium constants must be determined; hence ΔG° values so determined are strongly dependent on the accuracy of the equilibrium constants *and* on the validity of the postulate that the free energies are additive.

It had occurred to us some time ago¹¹ that conformational equilibrium measurements of disubstituted

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(20) F. R. Jensen and L. H. Gale, *J. Org. Chem.*, **25**, 2075 (1960).

(21) H. van Bekkum, P. E. Verkade, and B. M. Wepster, *Koninkl. Ned. Akad. Wetenschap. Proc.*, **B64**, 161 (1961).

(22) D. S. Noyce and L. J. Dolby, *J. Org. Chem.*, **26**, 3619 (1961).

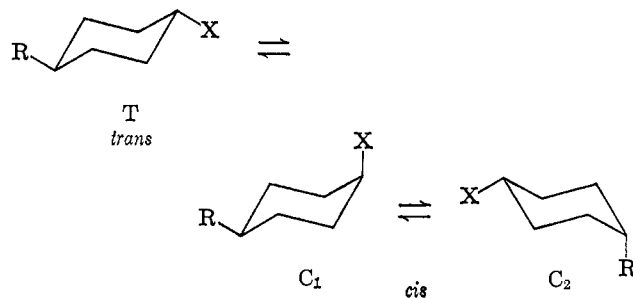


Figure 4.

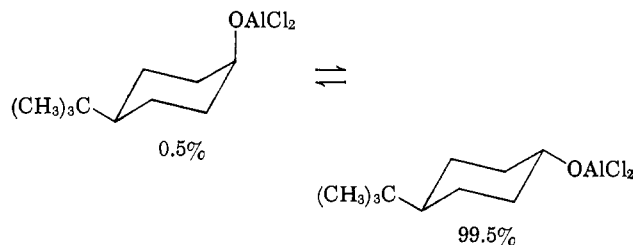


Figure 5.

systems of the type shown in Figure 4 might also be used to determine the conformational equilibrium of the alkyl groups indirectly. Assuming that the *trans* isomer exists exclusively, or very nearly so, in the diequatorial conformation *T* whereas the *cis* isomer can exist in both conformations *C*₁ and *C*₂, the epimerization equilibrium constant for the experimentally determinable equilibrium *trans* \rightleftharpoons *cis* is $K_{\text{epi}} = T/(C_1 + C_2)$. It follows that

$$1/K_{\text{epi}} = C_1/T + C_2/T \text{ or } 1/K_{\text{epi}} = 1/K_X + 1/K_R \quad (1)$$

whence

$$1/K_R = 1/K_{\text{epi}} - 1/K_X \quad (2)$$

It might be noted that it is not necessary for the group R to be epimerizable, since the same result is obtained if epimerization affects the group X.

In principle, equilibration of compounds such as 4-alkylcyclohexanols or 4-alkylcyclohexanecarboxylic esters should lend themselves to the process depicted in Figure 4, since the requisite values for K_{OH} and $K_{\text{COOR}'}$ are known, having, in turn, been determined by equilibrations of systems in which R = *t*-butyl so that *C*₂ is negligible and $K_X = K_{\text{epi}}$. Unfortunately, there is a very serious practical difficulty in that K_X for most epimerizable groups is of the order of 3-6 whereas K_R for alkyl groups is of the order of 15-40. As a result, the value of $1/K_R$ is small compared to $1/K_X$, so that $K_{\text{epi}} \approx K_X$ in eq. 1, K_R being only of the order of a correction term. Or, putting it differently, $1/K_R$ in eq. 2 comes out as a small difference between two numbers large compared to this difference, and values for K_R obtained in this way, *e.g.*, from the equilibration of epimeric ethyl 4-alkylcyclohexanecarboxylates²³ must be considered of limited accuracy.

It is clear that the difficulty described above could be obviated if K_X were rather larger than K_R . In that case the important term in eq. 1 would be $1/K_R$ rather

(23) N. L. Allinger, L. A. Freiberg, and S.-E. Hu, *J. Am. Chem. Soc.*, **84**, 2836 (1962).

than $1/K_X$. In the extreme case where K_X were so large as to make $1/K_X$ negligible, eq. 2 in fact reduces to $K_R = K_{\text{epi}}$.

A group large enough to ensure the above condition and yet capable of epimerization is present in the complex obtained from an alcohol and lithium aluminum hydride-aluminum chloride.²⁴ Presumably this group is the alkoxyaluminum dichloride group, OAlCl_2 . Treatment of 4-*t*-butylcyclohexanol with lithium aluminum hydride-aluminum chloride²⁵ in ether followed by addition of ketone leads to an equilibrium mixture, shown, in the present work, to contain about 99.5% *trans* isomer. Assuming that the *t*-butyl group is always exclusively equatorial,⁴ this result suggests (Figure 5) that the conformational energy $-\Delta G^\circ_X$ of the OAlCl_2 group is about 3.2 kcal./mole. Equilibration of other alkoxyaluminum dichloride complexes (Figure 4, $R = \text{alkyl}$, $X = \text{OAlCl}_2$) thus serves to determine the conformational equilibrium constants of appropriate alkyl groups by eq. 2. The necessary equilibrium data are given in Table V (Experimental Section) and the conformational energies derived from them are given in Table I.

Table I. Conformational Energies (kcal./mole)

Group	e,e isomer, % (average)	K_R	$-\Delta G^\circ$, kcal./mole ^a
Methyl (3)	94.1	17.3	1.75
Methyl (4)	92.3	12.8	1.56
Ethyl (3)	95.0	21.0	1.86
Ethyl (4)	93.4	15.2	1.67
Isopropyl (3)	97.3	43.9	2.30
Isopropyl (4)	95.3	22.6	1.90

^a From eq. 2, taking $K_{\text{OAlCl}_2} = 199$; temperature 35°.

Since our original publication^{24a} one other application of the principle embodied in Figure 4 has appeared in the literature, namely the equilibration of diethyl 5-alkyl-1,3-dicarboxylates.²⁶ The starting materials needed for this equilibration are somewhat more laborious to prepare than some of those used in the present investigation, but the results should otherwise be comparable.

The data in Table I suggest that the $-\Delta G^\circ$ value of ethyl is only about 0.11 kcal./mole larger than that for methyl and that the value for isopropyl is 0.34–0.55 kcal./mole larger. The calculated values for these differences are 0.06 kcal./mole for ethyl²⁷ and 0.20 kcal./mole for isopropyl^{14b} (calculated at 25°); thus the differences between alkyl groups found experimentally are in good agreement with those calculated on first principles,²⁸ using known interaction enthalpies and entropies of mixing. The situation is less clear for the absolute values of $-\Delta G^\circ_R$. Evidently there are significant (and quite real) differences between the values obtained from the 3-alkylcyclohexanol and those from the 4-alkylcyclohexanol series. These differences

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(25) E. L. Eliel, *Record Chem. Progr. (Kresge-Hooker Sci. Lib.)*, **22**, 129 (1961).

(26) B. J. Armitage, G. W. Kenner, and M. J. T. Robinson, *Tetrahedron*, **20**, 747 (1964).

(27) N. L. Allinger and S.-E. Hu, *J. Am. Chem. Soc.*, **84**, 370 (1962).

(28) Cf. ref. 4, pp. 24, 61, and Section 7-2.

are no doubt the result of deformation effects²⁹ to be discussed in greater detail in a forthcoming paper.³⁰ On theoretical grounds, we believe that the data derived in the 4-series are closer to the real $-\Delta G^\circ$ values in a monoalkylcyclohexane (Figure 1). On the other hand, they are in all cases near the lower end of the spectrum of values for methyl, ethyl and isopropyl summarized in Tables II–IV. In recommending “best values”

Table II. Conformational Energies Reported for Methyl

$-\Delta G^\circ$, kcal./mole	Method	Temp., °C.	Solvent	Ref.
1.5 ± 0.1	<i>a</i>	35	Anhyd. ether	24a
1.56	<i>a</i>	35	Anhyd. ether	b
1.54–2.47	<i>a</i>	100	H ₂ O	22
1.60 ± 0.06 ^c	N.m.r.	30	2-D-2-PrOH	18
1.62 ^c	Thermochem.	25	Liquid phase	16b
1.67	<i>a</i>	25	2-PrOH	26
1.68 ± 0.06 ^d	N.m.r.	30	CCl ₄	18
1.69–2.18	<i>a</i>	140	H ₂ O	22
1.70	N.m.r.	32	CCl ₄	19
1.72 ^c	Thermochem.	25	Liquid phase	16b
1.75	<i>a</i>	35	Ether	<i>b</i>
1.75 ± 0.10	Equilib.	200–300	Liquid phase	14
1.87	<i>a</i>	25	EtOH	23
1.90–1.91 ^c	Thermochem.	25	Gas phase	16
1.9–2.1	Equilib.	25	99.8% H ₂ SO ₄	13a
1.96 ^c	Thermochem.	25	Gas phase	16
1.97	Infrared	30	CS ₂	20
2.0–2.1	Equilib.	25–300	Gas phase	15

^a Indirect equilibration. ^b This work. ^c $-\Delta H^\circ$. ^d Recalculated value, see ref. 4.

Table III. Conformational Energies Reported for Ethyl

$-\Delta G^\circ$, kcal./mole	Method	Temp., °C.	Solvent	Ref.
1.67	<i>a</i>	35	Anhyd. ether	<i>b</i>
1.68 ± 0.06 ^c	N.m.r.	30	CCl ₄	18
1.77 ± 0.07	N.m.r.	30	2-D-2-PrOH	18
1.80	<i>a</i>	25	EtOH	23
1.8 ± 0.3	Equilib.	258–320	Liquid phase	27
1.86	<i>a</i>	35	Ether	<i>b</i>
1.86	<i>a</i>	25	2-PrOH	26
2.0	pK	25	50% EtOH–H ₂ O	21
2.09	<i>a</i>	143	H ₂ O	22
2.27	<i>a</i>	100	H ₂ O	22

^a Indirect equilibration. ^b This work. ^c Recalculated value, see ref. 4.

Table IV. Conformational Energies Listed for Isopropyl

$-\Delta G^\circ$, kcal./mole	Method	Temp., °C.	Solvent	Ref.
1.90	<i>a</i>	35	Anhyd. ether	<i>b</i>
1.91 ± 0.01	<i>c</i>	287	Liquid phase	14b
1.91	<i>c</i>	287	?	23
2.1 ± 0.1	Kinetic	100–110	AcOH	17
2.11	<i>a</i>	25	EtOH	23
2.22 ± 0.08 ^d	N.m.r.	30	CCl ₄	18
2.25 ± 0.08	N.m.r.	30	2-D-2-PrOH	18
2.30	<i>a</i>	35	Ether	<i>b</i>
2.43–2.62	<i>a</i>	25	MeOH, 2-PrOH	26
2.5	pK	25	50% EtOH–H ₂ O	21
2.63	<i>a</i>	139	H ₂ O	22
3.55	<i>a</i>	100	H ₂ O	22

^a Indirect equilibration. ^b This work. ^c Direct equilibration. ^d Recalculated value, see ref. 4.

(29) Cf. E. L. Eliel, L. A. Pilato, and J. C. Richer, *Chem. Ind. (London)*, 2007 (1961).

(30) E. L. Eliel, S. H. Schroeter, T. J. Brett, F. J. Biros, and J.-C. Richer, to be published.

for the alkyl groups, we have therefore decided to adopt the average of the values for the 3- and 4-series or 1.65 kcal./mole for methyl (liquid phase). Using the experimentally determined increments in the 4-series, this, then leads to a recommended value of 1.75 kcal./mole for ethyl and 2.0 kcal./mole for isopropyl (values given to nearest 0.05 kcal./mole). These values are close to our experimental averages for the 3- and 4-series (1.765 for ethyl, 2.10 for isopropyl) and they are also close to the calculated values of Allinger and co-workers, 1.86 kcal./mole for ethyl²⁷ and 2.10 kcal./mole for isopropyl,^{14b} especially if one takes into account that Allinger's values are based on $-\Delta G^\circ_{Me}$ of 1.8 kcal./mole in the liquid phase, a value now generally conceded to be too high by about 0.1 kcal./mole.⁴

The conformational energy of *t*-butyl was not studied in this work but must be in excess of 4.4 kcal./mole on the basis of the following argument: ΔH° for the equilibrium *cis*-1,3-di-*t*-butylcyclohexane \rightleftharpoons *trans* isomer is $+5.9 \pm 0.6$ kcal./mole and ΔS° is $+4.9 \pm 1.0$ cal./deg. mole.³¹ From these data, ΔG° at 25° is $+4.4 \pm 0.9$ kcal./mole. However, the high entropy of the *trans* isomer suggests that it is in the flexible form. Therefore, the free energy of the chair conformation of *trans*-1,3-di-*t*-butylcyclohexane must be more than 4.4 kcal./mole greater than that of the chair conformation of the *cis* isomer, due to the presence of the axial *t*-butyl group. That *t*-butyl is so much larger than methyl, ethyl, and isopropyl (*vide supra*) is, of course, not surprising, since all the other alkyl groups confront the ring with a hydrogen (in the case of ethyl and isopropyl this entails a slight loss in entropy, as explained above) whereas *t*-butyl must necessarily confront it with a methyl group, giving rise to severe steric compression with the *syn*-axial hydrogens. Such sudden and severe onsets of steric interactions as one proceeds from isopropyl to *t*-butyl are, of course, not uncommon in organic chemistry.

We had hoped that the indirect equilibration method here developed could be used for groups other than alkyl through a study of appropriately 3- or 4-substituted cyclohexanols. However, with polar groups, complications are encountered. It has already been reported³² that chelate complexes are precipitated in the 3- and 4-methoxycyclohexanol series. Equilibration of 4-chlorocyclohexanol led to an equilibrium in which the *cis* isomer predominated (54.5%). At face value, this would mean that the $-\Delta G^\circ$ value for chlorine is negative. Since other results in the literature^{4,6} clearly rule out this possibility, it is obvious that there is a disturbing factor in the case of the equilibration of the 4-chlorocyclohexanol complex which renders the result meaningless. Probably this factor is a dipole interaction between Cl and $OAlCl_2$, similar to that encountered in 1,4-dichlorocyclohexane.³³

Experimental Section

Alkylcyclohexanols. In general, a sample of alkylcyclohexanol rich in the equatorial-axial isomer was

obtained by catalytic hydrogenation of the corresponding phenol over rhodium on alumina. The pure equatorial isomer was obtained by equilibrating this sample and then purifying further through a derivative. The preparation of 4-ethylcyclohexanol is described as being typical.

A solution of 61.0 g. (0.48 mole) of *p*-ethylphenol (Aldrich, b.p. 103–104° (14 mm.)) in 125 ml. of 95% ethanol was hydrogenated at room temperature in a Parr apparatus at an initial pressure of 51 p.s.i. in the presence of 11.0 g. of 5% rhodium on alumina. The theoretical amount of hydrogen was taken up in 1.5 hr. The solution was filtered, concentrated, taken up in 300 ml. of ether and washed successively with 100-ml. portions of water, 10% sodium hydroxide, and brine. The ethereal solution was dried over magnesium sulfate and concentrated, and the residue was distilled to give 60.2 g. (94%) of 4-ethylcyclohexanol, b.p. 86–90° (14 mm.), n^{20}_D 1.4623, containing 55.3% *cis* isomer and 47.7% *trans* isomer (v.p.c. analysis on a 10-ft. glycerol column at 115° and 60 ml./min. helium flow). The literature³⁴ reports b.p. 193–196° (760 mm.), n^{20}_D 1.4604.

To a solution of 26.70 g. of aluminum chloride (0.20 mole) in 100 ml. of cold ether was added 47.8 ml. of a 1.15 *M* solution of lithium aluminum hydride in ether (0.055 mole), followed by 24.32 g. (0.190 mole) of the above *cis*-rich 4-ethylcyclohexanol in 100 ml. of ether. There was then added 1.51 g. (0.012 mole) of 4-ethylcyclohexanone (see below) in 15 ml. of ether and the solution was boiled at reflux for 48 hr. The solution was then treated with water followed by 10% sulfuric acid to dissolve the precipitated salts. The layers were separated and the aqueous layer was extracted with four 50-ml. portions of ether. The combined ether layers were washed with 50-ml. portions of water, saturated aqueous sodium bicarbonate, and brine. After drying over magnesium sulfate and concentrating there was obtained 25.59 g. of crude material which, upon v.p.c. analysis, was shown to contain 93.2% *trans* and 6.8% *cis* isomer, in addition to low-boiling contaminants.

The 3,5-dinitrobenzoate was prepared from 19.20 g. (0.15 mole) of the crude *trans*-rich alcohol, 31.80 g. (0.15 mole) of 3,5-dinitrobenzoic acid, and 57.21 g. (0.30 mole) of purified *p*-toluenesulfonyl chloride in 550 ml. of dry pyridine at 0° (2 hr. of standing).³⁵ The solution was poured with stirring into 1675 ml. of water and 550 g. of ice and the product was collected and recrystallized from methanol to give 25.5 g. (53%) of *trans*-4-ethylcyclohexyl 3,5-dinitrobenzoate, m.p. 132.5–133.5°.

Anal. Calcd. for $C_{15}H_{18}N_2O_6$: C, 55.90; H, 5.63. Found: C, 55.89; H, 5.85.

The saponification of 22.50 g. (0.07 mole) of the 3,5-dinitrobenzoate was effected by boiling for 3 hr. with 16.83 g. (0.30 mole) of potassium hydroxide in 300 ml. of methanol and 58 ml. of water. The cooled mixture was filtered, concentrated, poured into 750 ml. of water, and extracted five times with 100-ml. portions of ether. The combined ether layers were washed with brine, dried over magnesium sulfate, concentrated, and dis-

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tilled to give 7.04 g. (79%) of *trans*-4-ethylcyclohexanol, b.p. 91.5–92.0° (16 mm.), n_D^{20} 1.4612, shown by v.p.c. to be free of *cis* isomer.

Oxidation of 32.00 g. of *cis*-rich 4-ethylcyclohexanol (0.25 mole) with 27.10 g. (0.091 mole) of sodium dichromate dihydrate, 212.5 ml. of water, and 39.20 g. (0.40 mole) of concentrated sulfuric acid gave 27.34 g. (87%) of 4-ethylcyclohexanone, b.p. 73–74° (14 mm.), n_D^{20} 1.4525 (lit.³⁴ b.p. 80–85° (18 mm.), n_D^{20} 1.4531).

Other Alkylcyclohexanols. *cis*- and *trans*-3- and -4-methylcyclohexanols³⁶ and *cis*-¹¹ and *trans*-4-*t*-butylcyclohexanol^{24b} were obtained as described previously. Other alkylcyclohexanols were prepared from the corresponding phenols in a manner similar to that described above and had the following physical properties: 3-ethylcyclohexanol, *trans*-rich (58.4% *trans*), b.p. 88–91° (22 mm.) (lit.³⁷ b.p. 87–93° (14 mm.)), *cis* (pure), b.p. 90–91° (16 mm.), n_D^{20} 1.4614 (lit.³⁷ b.p. 93° (14 mm.) n_D^{20} 1.4621³⁸), hydrogen phthalate, m.p. 114–115° (lit.³⁷ m.p. 115–116°); 3-isopropylcyclohexanol, *trans*-rich (58.2% *trans*), b.p. 96–104° (16 mm.) (lit.³⁹ b.p. 101–106° (15 mm.)¹), *cis* (pure) b.p. 102–103° (21 mm.), n_D^{20} 1.4645 (lit.³⁹ b.p. 106° (15 mm.) n_D^{20} 1.4651), 3,5-dinitrobenzoate, m.p. 96–97° (lit.³⁹ m.p. 95.5°); 3-*t*-butylcyclohexanol, *trans*-rich (67.1%), b.p. 103–107° (17 mm.), *cis*, m.p. 41.5–43.0° (lit.⁴⁰ m.p. 40–41°), acid phthalate, m.p. 135–136° (lit.⁴⁰ m.p. 136.0–136.8°); 4-isopropylcyclohexanol, *cis*-rich (52.5% *cis*), b.p. 123–124° (40 mm.) (lit.⁴¹ b.p. 123–124° (40 mm.)), *trans* (pure), b.p. 100.5–101.0° (15 mm.), n_D^{20} 1.4652 (lit.⁴² b.p. 94° (5 mm.), n_D^{20} 1.4662).

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4-Chlorocyclohexanol. The *trans* isomer was prepared from 1,4-epoxycyclohexane and hydrogen chloride,⁴³ in 64% yield and had m.p. 83.0–84.0° (lit.⁴³ m.p. 82–83°). *cis*-Rich material containing 74.0% *cis* isomer was obtained by reducing 4-chlorocyclohexanone with lithium aluminum hydride.⁴⁴

Equilibrations and Analyses. The equilibrations were carried out essentially as described above for 4-ethylcyclohexanol except on a smaller scale. The equilibrated products, after stripping of most of the ether, were analyzed by gas chromatography on 10-ft. glycerol (methyl- and ethylcyclohexanol) Carbowax (isopropyl- and chlorocyclohexanol) or Tide columns (*t*-butylcyclohexanols). In all cases, equilibrium was approached from both sides. The results are shown in Table V.

Table V. Equilibrations with Lithium Aluminum Hydride–Aluminum Chloride

Substituted cyclohexanol	Stable (e,e) isomer in material, %	Product, %
3-Methyl	100	94.4
3-Methyl	71.9	93.8
3-Ethyl	100	95.3
3-Ethyl	57.0	94.8
3-Isopropyl	100	97.4
3-Isopropyl	41.8	97.8
3- <i>t</i> -Butyl	32.9	99.5
4-Methyl	100	93.1
4-Methyl	29.0	91.6
4-Ethyl	100	93.8
4-Ethyl	44.7	93.1
4-Isopropyl	100	95.0
4-Isopropyl	94.3	95.5
4- <i>t</i> -Butyl	71.6	99.5
4-Chloro	51.5	44.0
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