2. **Reaction with Base.**—The reaction of ketone (0.47 g.) and aqueous sodium hydroxide was carried out as described for III (or V). A small amount of starting material, but no base-soluble component, was recovered.

3. **Attempted Nitration.**—The procedure described by Fernholz[26] for the nitration of 4,5-benztropolone (nitric acid in glacial acetic acid) only led to high recovery of starting material XII.

4. **Reaction with Hydroxylamine.**—The oxime of the ketone was prepared in the usual manner; yellow crystals, m.p. 216–217° (from ethanol–water).

Anal. Calcd. for $C_{11}H_8NOCl$: C, 64.24; H, 3.92; N, 6.81. Found: C, 64.08; H, 4.16; N, 7.21.

4,5-Benztropolone was prepared as described by Tarbell and Bill[27] (m.p. 158–160°, reported 158–160°; acetate m.p. 105–106°, reported 103–104°), and numerous unsuccessful attempts to replace the hydroxyl group by chlorine were made as described above for 3,4-benztropolone. Recovered starting material was generally obtained; Infrared spectrum: bands at 1638(m), 1618(m), 1575(s) and 1542(m). cm.$^{-1}$.[28]

Reaction of Dichlorocarbene with 9-Methoxyphenanthrene.—A modification in the procedure described for reaction with 1-methoxynaphthalene using two equivalents of dichlorocarbene precursor was possible since the initial adduct XIX contains unsaturation relatively inert to further attack by dichlorocarbene. From 9-methoxyphenanthrene[29] (m.p. 90–92°, reported 95–97°, 6.07 g., 0.029 mole), pentane (120 ml.), sodium methoxide (3.24 g., 0.06 mole) and ethyl trichloroacetate (11.46 g., 0.06 mole), there was obtained by chromatography: recovered 9-methoxyphenanthrene (eluted with petroleum ether, b.p. 30–60°) and the cyclopropyl adduct XIX (glassy solid, eluted with the same solvent shortly after starting ether). The glassy solid was recrystallized from petroleum ether (b.p. 68°) and XIX was obtained as dense white crystals (m.p. 116–118°, 4.36 g., 52% yield). Further recrystallization of this solid from the same solvent afforded material melting at 120.5–122°; ultraviolet spectrum (95% ethanol): λ_{max} 306 mμ (log ϵ 3.18), λ_{max} 275 mμ (log ϵ 4.05), λ_{max} 246 mμ (log ϵ 4.26), λ_{max} 239 mμ (log ϵ 4.32), λ_{max} 218 mμ (log ϵ 4.48).

Anal. Calcd. for $C_{16}H_{12}OCl_2$: C, 66.00; H, 4.15; Cl, 24.35; mol. wt., 291. Found: C, 65.99; H, 4.43; Cl, 24.23; mol. wt., 283.

Thermal Decomposition of XIX.—A sample of XIX (1.11 g., 0.0058 mole) was heated (140°) for 1 hour under vacuum (0.2 mm.). The effluent gases were trapped in petroleum ether, b.p. 65°, cooled to 75°. The petroleum ether, after the pyrolysis, was subsequently shown, by vapor phase chromatography, to contain appreciable quantities of methyl chloride.

The solid residue from the pyrolysate was separated by elution chromatography (using petroleum ether, b.p. 60–68° as eluent) into two fractions: (1) starting material, 0.29 g.; and (2) a ketonic fraction, 0.76 g.

The ketonic fraction was further purified by recrystallization from petroleum ether (b.p. 65°), and was obtained as a solid melting at 95.5–97°. This product is considered to be XX; ultraviolet spectrum (95% ethanol): λ_{max} 315 mμ (log ϵ 3.58), λ_{max} 265 mμ (log ϵ 4.19), λ_{max} 238 mμ (log ϵ 4.33); infrared spectrum: bands at 1665(s), 1610(m) and 1595(m) cm.$^{-1}$.

Anal. Calcd. for $C_{15}H_9OCl$: C, 74.85; H, 3.77; Cl, 14.78; mol. wt., 240. Found: C, 74.60; H, 3.85; Cl, 14.71; mol. wt., 239.

The 2,4-dinitrophenylhydrazone of XX was prepared by the standard procedure. A reaction time of 48 hours was required for the dinitrophenylhydrazone to precipitate. The orange crystals that formed were recrystallized from acetone–water to yield blocky prisms, m.p. 264–267° (uncor.).

Anal. Calcd. for $C_{21}H_{13}O_4N_4Cl$: C, 59.93; H, 3.11; N, 13.31. Found: C, 59.82; H, 3.40; N, 13.16.

Attempts to hydrolyze XX with aqueous hydrochloric acid, as described for III (or V) and XII, resulted in recovered starting material.

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[26] H. Fernholz, E. Hartwig and I. C. Salfeld, *Ann.*, **576**, 131 (1952).

[27] D. S. Tarbell and J. C. Bill, THIS JOURNAL, **74**, 1234 (1952).

[28] Infrared data in part from D. S. Tarbell, G. P. Scott and A. D. Kemp, *ibid.*, **72**, 379 (1950).

[29] R. F. Schultz, E. D. Schultz and J. Cochran, *ibid.*, **62**, 2902 (1940).

[CONTRIBUTION FROM THE DEPARTMENT OF CHEMISTRY OF THE UNIVERSITY OF WISCONSIN, MADISON 6, WISC.]

The Energy Difference between the Chair and Boat Forms of Cyclohexane. The Twist Conformation of Cyclohexane

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A pair of stereoisomeric lactones (formulas A and B) have been prepared by a stereo-rational synthesis, and they have been submitted to combustion calorimetric and heat of vaporization determinations. These results showed that the enthalpy of B is greater than that of A by 4.1 ± 0.4 kcal./mole in the vapor phase at 25°. Since A and B differ mainly in that the central ring in the former is a chair while that in the latter is a boat, this value can be used to estimate the difference in energy between the chair and boat forms of cyclohexane as about 5.5 kcal./mole. The consequences of these findings are discussed, and arguments are advanced in favor of the stability of the *twist* conformation of cyclohexane as compared with the severe boat form.

The application of conformational principles to systems containing six-membered rings[1] depends upon the basic rule that cyclohexane is more stable in the chair than in the boat conformation. This premise derives conclusive, if only qualitative, support from Raman, infrared and electron diffraction spectroscopy, as well as from thermodynamic considerations.[2] Several theoretical and semi-empirical estimates of the magnitude of this energy difference have been reported; however, the approximations and assumptions implicit in these calculations have led to values ranging from as low as 1.31[3] to as high as 10.6[4] kcal./mole.[5] We disclose, in the present paper, the details[6] of an experimental

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[1] D. H. R. Barton, *Experientia*, **6**, 316 (1950); *Chemistry & Industry*, 664 (1953).

[2] (a) K. W. F. Kohlrausch and W. Stockmair, *Z. physik. Chem.*, **B31**, 382 (1936); (b) R. S. Rasmussen, *J. Chem. Phys.*, **11**, 249 (1943); (c) O. Hassel and H. Viervoll, *Acta Chem. Scand.*, **1**, 149 (1947); (d) C. Beckett, K. S. Pitzer and R. Spitzer, THIS JOURNAL, **69**, 2488 (1947).

[3] The lower value of the range calculated by D. H. R. Barton, *J. Chem. Soc.*, 340 (1948).

[4] The higher value of a range calculated by the Turner semi-empirical method (ref. 5).

[5] For a complete review, see W. G. Dauben and K. S. Pitzer in M. S. Newman's "Steric Effects in Organic Chemistry," John Wiley and Sons, Inc., New York, N. Y., 1956.

[6] Preliminary communication, W. S. Johnson, J. L. Margrave, V. J. Bauer, M. A. Frisch, L. H. Dreger and W. N. Hubbard, THIS

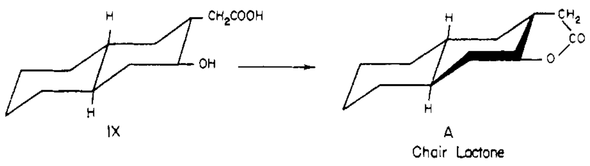
determination of the energy difference between the chair and boat forms of cyclohexane. The value thus obtained not only should find obvious use in quantitative conformational analysis, but has a direct bearing on the question pertaining to the preference for the boat to adopt the twist conformation. This latter matter is considered also in the present work.

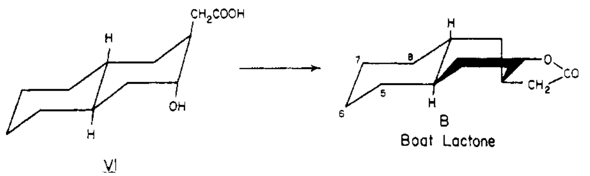
The low energy barrier for the transition between the chair and boat forms of cyclohexane[7] renders the direct experimental approach to the problem exceedingly difficult. An undertaking with the view to preparing pure boat and chair forms of cyclohexane for physical measurements thus was considered ill-advised with the limitations of present-day techniques.

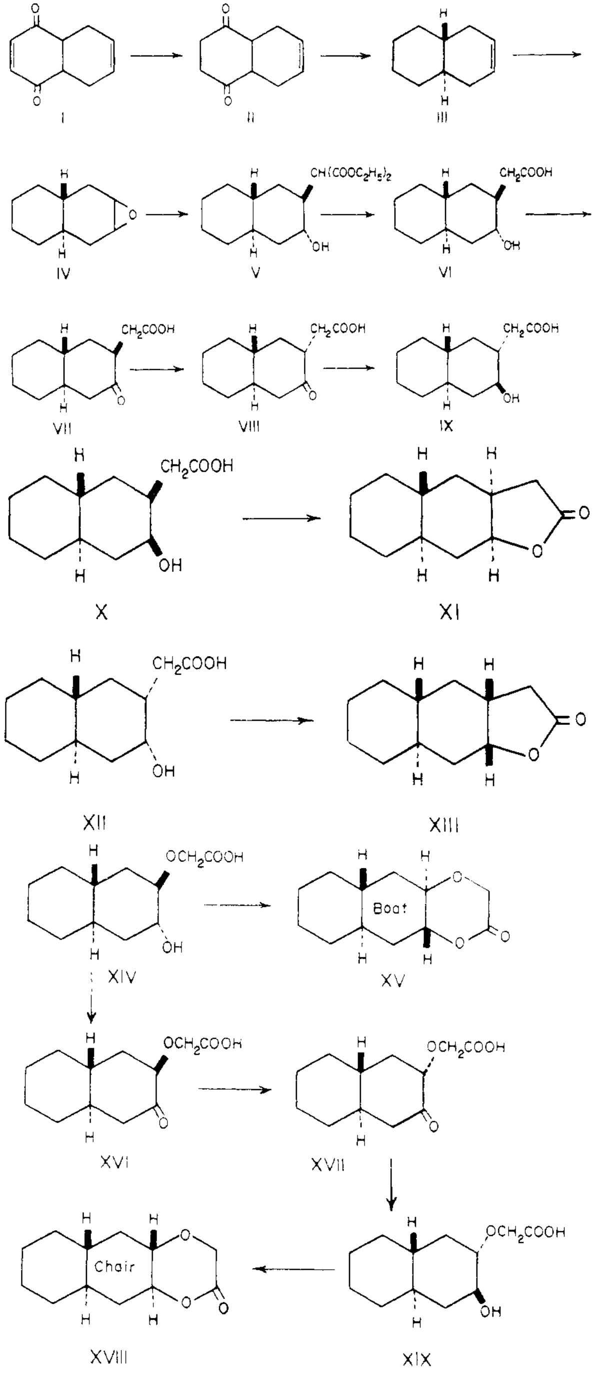
Another approach involves the preparation and determination of thermodynamic properties of two stereoisomeric compounds differing only in that one contains a cyclohexane ring held rigidly in the boat form while the other contains this same ring in the chair conformation. It is difficult to devise a system in which there is complete cancellation of spurious non-bonded interactions resulting from the substituents that are necessary in order to maintain the conformational integrity of the cyclohexane ring. The larger the substituent in question, the greater the non-cancelling errors, and it was partly for this reason that we considered *cis*- and *trans*-1,3-di-*t*-butylcyclohexane, for example, a less suitable pair (see below) than the system used in the present study. Conformational rigidity of the cyclohexane ring can also be maintained by the agency of two appropriately fused rings; thus the central ring of *trans-anti-trans*-perhydroanthracene must assume the boat conformation while this ring is in the chair form in the *trans-syn-trans* isomer.[8] Such systems have the advantage that (1) conformational flipping is precluded, hence there is no question about the conformational integrity of the cyclohexane ring in question; and (2) the effective substituents, *i.e.*, the ring-linking groups (CH_2 in the case at hand), on this cyclohexane ring are small, hence the non-cancelling interactions due thereto are probably relatively insignificant (see below).

At the time this work was initiated, *trans-syn-trans*-perhydroanthracene was available, but the *trans-anti-trans* isomer was unknown and did not promise to be readily accessible.[9] We therefore selected the pair of lactones A and B for study.

We envisaged the preparation, by a stereorational scheme, of the two hydroxy acids IX and VI, which on lactonization were expected to yield the desired lactones A and B, respectively. The cyclization of hydroxy acid VI can occur only if the central ring flips into the boat conformation.







JOURNAL, **82**, 1255 (1960); reported at the Steroid Gordon Conference, New Hampton, N. H., August 6, 1959. Note that the energy difference is revised in the present paper.

[7] Estimated by C. W. Shoppee, *J. Chem. Soc.*, 1138 (1946), to be approximately 9–10 kcal./mole, and recently found to be 9.7 kcal./mole; F. R. Jensen, D. S. Noyce, C. H. Sederholm and A. J. Berlin, THIS JOURNAL, **82**, 1256 (1960).

[8] W. S. Johnson, *Experientia*, **7**, 315 (1951); *ibid.*, **75**, 1498 (1953).

[9] This substance has since been prepared independently by R. L. Clarke and R. K. Hill (in press) and we intend to include it in extension of the present study.

Synthesis of Lactones A and B.—The starting point for the synthesis of both lactones was *trans*-Δ^2-octalin (III). Previous methods of preparation based upon elimination reactions of the *trans*-β-decalols,[10,11] *trans*-β-decalylamines[12] and *trans*-β-decalyl *p*-toluenesulfonates,[12,13] yielded mixtures of *trans*-Δ^2-octalin and *trans*-Δ^1-octalin, as suggested by the fact that mixtures of *trans*-cyclohexane-1,2-diacetic acid and *trans*-cyclohexane-1-propionic-2-carboxylic acid were obtained upon alkaline permanganate oxidation. Although the desired *trans*-Δ^2-octalin was generally the predominating isomer, a more selective synthesis of the olefin was sought.

A promising route appeared to be *via* the diene condensation of *p*-benzoquinone and butadiene.[14] Since this phase of our work was completed, Henbest, Smith and Thomas[15] reported the synthesis of *trans*-Δ^2-octalin by this same route. However, since our yields were somewhat better and the product was purer, we are reporting our experiments herewith. The 1:1 adduct (I) of butadiene and benzoquinone was obtained in 91% yield (reported[15] 94%) and, without appreciable purification, was reduced selectively with zinc dust in 95% acetic acid[16] to give the *cis*-dione II in 97% yield (reported[15] 70%). Henbest, *et al.*, submitted this product to alkali-catalyzed isomerization to give the *trans*-dione which was reduced by the Wolff–Kishner method to afford the *trans*-octalin, n^{20}D 1.4865, in 38% yield. The yield in the isomerization step was 20%, but obviously the conversion should be high based upon recovered *cis*-dione which could be retreated. In the present work, the isomerization step was considered to be unnecessary, since it was expected that the conditions for forming the hydrazone would effect equilibration of the ketones and that the *trans*-dione would react more rapidly than the *cis* isomer with hydrazine giving a preponderance of the *trans*-hydrazone. In accordance with expectation, when the crude *cis*-dione was treated under the Huang-Minlon[17] conditions for reduction, the octalin, n^{25}D 1.4838, was obtained in 78% yield. Since we suspected that this product, as well as that of Henbest, *et al.*, was contaminated with the *cis*-Δ^2-octalin, we converted it to the crystalline dibromide which was carefully purified by repeated recrystallization to give a product melting at 84–84.5° (reported[18] 85°) in 44% yield. Regeneration of the hydrocarbon by treatment with zinc dust in ethanol, followed by fractional distillation, afforded, in 97% yield, what we consider to be the first pure specimen of *trans*-Δ^2-octalin (III), b.p. 59° (8 mm.), n^{25}D 1.4796. Because of the poor agreement of the properties of our specimen with those reported,[19] we felt it necessary to confirm the identity and homogeneity. Oxidation with permanganate gave *trans*-cyclohexane-1,2-diacetic acid; one-mole equivalent of bromine was absorbed by the hydrocarbon, and a dibromide, m.p. 83.5–84.5°, isolated in 94% yield; a single sharp peak was obtained on submission of the hydrocarbon to vapor phase chromatography.

Treatment of *trans*-Δ^2-octalin (III) with perbenzoic acid afforded 2,3-epoxy-*trans*-decalin (IV) as a colorless liquid, n^{25}D 1.4835. The reported[15] substance, n^{24}D 1.4872, was probably contaminated with the *cis* isomer.

Reaction of the epoxide IV with sodiomalonic ester proceeded stereoselectively to give, in 94% yield, an adduct, which after purification melted at 60–63°. On the basis of the known predilection of alicyclic oxiranes for diaxial addition of nucleophiles,[20] this adduct was considered to have the diaxial configuration shown in formula V. That this assumption was correct follows from transformations described below.

Saponification of the diester V afforded, in 71% yield, a crystalline diacid which, because of its instability, was not purified but was thermally decarboxylated to give 3(a)-hydroxy-*trans*-decalin-2(a)-acetic acid (VI).[21] This product, m.p. 113–116.5°, was formed in quantitative yield, and one recrystallization afforded (86% yield) the pure substance which, on heating, underwent three major polymorphic changes as evidenced by a triple melting point at 66–71°, 103–104.5° and 116–117°. The lactonization of this hydroxy acid is described below.

Hydroxy acid IX was produced as follows. Oxidation of hydroxy acid VI under mild conditions with chromium trioxide in acetic acid gave the keto acid VII, m.p. 97.5–98.5° and 106–107°. The unstable (axial) orientation of the acetic acid side-chain was shown by treatment with aqueous sodium hydroxide solution which effected epimerization to give the stable (equatorial) keto acid VIII, m.p. 75–77° and 91.5–92°. For the purpose of preparing this latter substance in quantity, the unstable keto acid VII need not be isolated. Thus, oxidation of hydroxy acid VI with chromium trioxide and excess sulfuric (instead of acetic) acid afforded the keto acid VIII directly in 98% yield. The purity of this product was improved slightly by a short treatment with alkali.

The keto acid VIII, on reduction with sodium in isopropyl alcohol, was converted into a new hydroxy acid, m.p. 156–156.3°. Since this method of reduction is known to give the more stable product, the 156° hydroxy acid may be formulated as the diequatorial isomer, 3(e)-hydroxy-*trans*-decalin-2(e)-acetic acid (IX). The yield of material, m.p. 152–154°, of satisfactory purity for the lactonization step was 66%.

Lactonization of hydroxy acid IX proceeded readily when it was heated for 10 minutes in ben-

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(10) (a) Leroux, *Ann. chim.*, [8] **21**, 458 (1910); (b) W. Hückel, *Ann.*, **441**, 1 (1925); (c) W. Hückel and H. Friedrich, *ibid.*, **451**, 132 (1927).

(11) W. Hückel and H. Naab, *ibid.*, **502**, 136 (1933).

(12) W. Hückel, *ibid.*, **533**, 1 (1938).

(13) W. Hückel and W. Tappe, *ibid.*, **537**, 113 (1939).

(14) O. Diels and K. Alder, *Ber.*, **62**, 2337 (1929).

(15) H. B. Henbest, M. Smith and A. Thomas, *J. Chem. Soc.*, 3293 (1958).

(16) K. Alder and G. Stein, *Ann.*, **501**, 247 (1933).

(17) Huang-Minlon, THIS JOURNAL, **68**, 2487 (1946).

(18) W. Hückel, R. Danneel, A. Schwarz and A. Gercke, *Ann.*, **474**, 121 (1929).

(19) *Cf.* for example the n^{25}D 1.4841 of W. Hückel, *Ber.*, **58**, 1449 (1925), and the n^{25}D 1.4881 of F. Eisenlohr and R. Polenske, *ibid.*, **57**, 1639 (1924).

(20) E. L. Eliel, ref. 5, p. 130.

(21) In order to simplify the nomenclature, the configurations of substituents in the *trans*-decalin ring system are indicated by (a) for axial and (e) for equatorial. In using this convention, the nucleus is considered to have only the all-chair conformation.

zene solution containing a trace of *p*-toluenesulfonic acid. Lactone A, m.p. 38–40°, was thus obtained in 97% yield. For combustion calorimetry studies this material was purified by exhaustive recrystallization, until the m.p. of the residue from evaporation of the mother liquor was identical with that of the crystallizate, namely 41.8–42.5°. Alkaline hydrolysis of a specimen of the lactone regenerated hydroxy acid IX thus proving that the lactonization step occurred without stereochemical inversion; hence the lactone was correctly represented as the *trans-syn-trans* isomer or lactone A.

As expected, hydroxy acid VI proved to be relatively resistant to lactonization; indeed, this acid was completely unaffected by the conditions described above for lactonization of IX. We next turned to the method developed by Woodward[22] for forcing lactonization in a somewhat similar system, namely treating hydroxy acid VI in pyridine solution with N,N′-dicyclohexylcarbodiimide. Crystalline lactone B was thus obtained in 55% yield in a pilot experiment. The yield by this method, however, proved to be capricious, *e.g.*, in a scaled-up experiment the only product isolated was the acyl urea, m.p. 165–166°, from which the hydroxy acid could be recovered by alkaline hydrolysis. We, therefore, sought other conditions for the lactonization. Heating a dilute solution of hydroxy acid VI in toluene with a trace of *p*-toluenesulfonic acid was ineffective, but when xylene was used as the solvent, water was eliminated and lactone B, m.p. 48–49°, was isolated in 73% yield after chromatography. This method was satisfactory for preparing the lactone in quantity sufficient for combustion calorimetric measurements. Lactone B was purified, for this purpose, by repeated recrystallizations until the melting point of the mother liquor residue and the crystallizate were identical, namely 49.6–50.3°. As in the case of the all-chair isomer, lactone B, on hydrolysis, was reconverted into hydroxy acid VI showing that the lactonization step had occurred without stereochemical inversion.

Confirmation of the configurational assignments of the substances described above was afforded by the stereo-rational synthesis of the remaining two *cis*-hydroxy acids X and XII and their lactones XI and XIII. Hydrogenation of the keto acid VII over platinum oxide afforded an oily product from which a new hydroxy acid, m.p. 131–132°, was isolated in 24% yield. This substance, 3(e)-hydroxy-*trans*-decalin-2(a)-acetic acid (X), was easily cyclized, simply by heating in benzene solution, to give the corresponding lactone XI, m.p. 60–60.5°. Hydrolysis of this lactone regenerated the 132° hydroxy acid. The low yield of hydroxy acid obtained in this hydrogenation experiment appeared to be due to its susceptibility to lactonization.

Hydrogenation of the keto acid VIII over platinum oxide similarly gave the fourth stereoisomeric hydroxy acid, m.p. 114–115°, namely 3(a)-hydroxy-*trans*-decalin-2(e)-acetic acid (XII). The yield was only 30%, presumably due to spontaneous lactonization, which could be completed by heating in benzene solution. The corresponding lactone XIII melted at 85.3–85.8°, and was reconverted to the 115° hydroxy acid, on hydrolysis.

Thermodynamic Properties.—The details of this study will be reported elsewhere,[23] and only the results are presented here. The enthalpy of lactone B was found to be greater than that of lactone A in a series of combustions of 0.5–0.8-g. samples in high precision calorimeters (accuracy 0.02% or better). In our original communication,[6] the enthalpy difference was reported as 5.5 kcal./mole. Since that time, we have carried out more extensive calibrations of both the Wisconsin and Argonne calorimeters, developed a computer program for more precise treatment of calorimeter data and applied other special corrections. On the basis of this more refined treatment of the data, we now have carried out a total of five runs on lactone A and eight runs on lactone B, with standard deviations of about 0.01%, which indicate that the enthalpy difference is 4.3 ± 0.2 kcal./mole. In order to obtain a value that would reflect the difference in energy between the chair and boat form of cyclohexane, it was necessary to correct for the heats of vaporization of the two lactones. The vapor pressures of these lactones were measured by the Knudsen effusion technique over the range 240–310°K. with a vacuum balance,[24] and the heats of sublimation evaluated from the slopes of log P *vs.* $1/T$. The values thus determined were practically identical, that for lactone A being 0.2 ± 0.2 kcal./mole greater than that for lactone B. Hence, the enthalpy of the vapor of lactone A is less than that of lactone B by 4.1 ± 0.4 kcal./mole at 25°. From this value ΔH for the conversion of the chair into the boat form of cyclohexane may be calculated as shown below.

Energy Difference between Chair and Boat Form of Cyclohexane.—Allinger and Freiberg[25] have recently obtained a value for this difference by application of their elegant equilibration technique. They determined the relative stabilities of *cis*- and *trans*-1,3-di-*t*-butylcyclohexane by high temperature equilibration experiments, which afforded $\Delta H + 5.9 \pm 0.6$ kcal./mole and $\Delta S + 4.9 \pm 1.0$ e.u. for the system *cis* ⇄ *trans*. This value for ΔH may be regarded also as the enthalpy difference for the boat and chair form of cyclohexane, provided (1) the reasonable assumption is made that the *t*-butyl group is of sufficient bulk to force the *trans* isomer mainly into the boat form, and (2) the effects of the *t*-butyl groups in the two isomers cancel each other. This latter factor is considered below. It is to be noted that the Allinger–Freiberg treatment has the advantage of giving entropy as well as enthalpy values.

In the present study we calculated a value of about 5.5 kcal./mole for this enthalpy difference which is in good agreement with that of Allinger and Freiberg. Our value was obtained by correcting the ΔH for the two lactones for non-cancelling interactions according to the following analysis.

The interactions due to the terminal homocyclic ring (composed of C_5, C_6, C_7 and C_8) all cancel each

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[22] R. B. Woodward, F. E. Bader, H. Bickel, A. J. Frey and R. W. Kierstead, *Tetrahedron*, **2**, 1 (1958).

[23] J. L. Margrave, M. A. Frisch, L. H. Dreger, W. N. Hubbard, V. J. Bauer and W. S. Johnson, *J. Phys. Chem.*, in press.

[24] L. H. Spinar, Ph.D. Thesis, University of Wisconsin, 1959.

[25] N. L. Allinger and L. A. Freiberg, THIS JOURNAL, **82**, 2393 (1960).

other in the boat and chair isomers except for one factor which exerts an additional destabilizing influence on the boat form: in the chair form the C_5- and C_8-methylene groups of this terminal ring define staggered conformations with respect to the hydrogen atoms on C_4 and C_1 (respectively) of the central ring. Now in order for all effects of the terminal homocyclic ring to cancel out, these two methylenes would also have to define a staggered relationship in the boat form, but this is not the case. In the severe boat form, one of these methylenes (C_5 in formula B) is indeed in this staggered conformation, but the other (C_8 in formula B) eclipses an equatorial hydrogen in the central ring (at C_1 in formula B). The increment of destabilization thus introduced is approximately equal to the difference in energy required to eclipse the ethane molecule as compared with propane, *viz.*, the difference between the potential energy barrier of rotation of ethane and propane which is about 0.3–0.5 kcal./mole. In the preferred twist form of the boat (see below), however, this interaction is partially relieved; hence this increment of destabilization may be considered to be not more than 0.3 kcal./mole. In the case of the 1,3-di-*t*-butylcyclohexanes,[25] this destabilizing factor is considerably greater because a *t*-butyl rather than a methylene group is involved in the eclipsing process. It would not be surprising, therefore, to find that a more accurate determination with the 1,3-di-*t*-butylcyclohexanes would show that ΔH actually lies at the higher end of the range 5.3–6.5 kcal./mole. It may be noted that with *cis*- and *trans*-1,4-di-*t*-butylcyclohexanes, the effect of the *t*-butyl groups is more nearly cancelling, and this pair of isomers would be worth examination.

The non-cancelling effects of the lactonic ring on the central ring results in a stabilizing influence on the boat isomer. The dihedral angle, formed by the bonds that constitute the points of attachment of the lactonic ring to the central ring, is readily susceptible to compression below the normal 60° (defined by a skew conformation) only when the central ring is in the boat form. Indeed a small compression of this angle is involved in conversion of the severe boat to the lower energy twist conformation (see below). This dihedral angular compression at the same time relieves some distortion of bond angles in the lactone ring due to the angular requirements of the 5-membered ring. This distortion cannot be so readily relieved when the central ring is in the chair conformation due to the relative non-compressibility of the dihedral angle in question. The effect of the five-membered ring, therefore, is in the direction of stabilization of the boat form. The magnitude of this five-membered ring effect should be about the same as the difference between the ΔH -2.72 ± 0.2 kcal./mole for the conversion of *cis*- to *trans*-decalin[26] and the ΔH -1.07 ± 0.09 kcal./mole for the conversion of *cis*- to *trans*-hydrindane,[27] namely, 1.65 kcal./mole. The difference in enthalpy for the boat and chair forms of cyclohexane is therefore about $4.1 - 0.3 + 1.65$, or 5.5 kcal./mole.

We recognize the necessity of examining a pair of isomers that do not incorporate this five-membered ring effect. Preparatory to this end we have initiated studies directed toward obtaining appropriate pairs of isomers with six-instead of five-membered rings. Our experiments in this direction are as yet incomplete, but some preliminary synthetic studies are reported below.

The epoxide IV was allowed to react with ethyl glycolate in the presence of sulfuric acid, and the adduct saponified. The acidic material, after purification, was obtained in only 16% yield and melted at 122–122.6°. That this was the expected[28] *trans* diaxial product XIV was shown by the reactions described below. The residues from the mother liquors showed lactone absorption at 5.77μ in the infrared spectrum, indicating that some diequatorial opening of the epoxide might have occurred.[29] Alternatively the lactonic material might have been derived from the *trans*-diaxial hydroxy acid XIV which proved to be more susceptible to cyclization than VI. Thus on heating the former in benzene solution containing *p*-toluenesulfonic acid, the corresponding lactone XV, m.p. 51.8–52.5°, was produced in 51% yield.

Oxidation of the hydroxy acid XIV with Jones reagent[30] afforded the keto acid XVI, m.p. 69.5–70.5°, which on treatment with alkali was isomerized to the equatorial epimer XVII, which could not be readily freed of small amounts of the axial epimer XVI with which it appeared to be in equilibrium. The crude isomerized material, m.p. 107–113°, was reduced with sodium and alcohol to yield the diequatorial hydroxy acid XIX, m.p. 136–141°. This substance was relatively susceptible to lactonization which accounted, in part, for the low yield (24%) of XIX obtained in the reduction step. Evaporative distillation of the crude hydroxy acid XIX produced the corresponding lactone XVIII, m.p. 113.3–113.6°, after recrystallization.

The pure lactones XV and XVIII both proved to be sensitive compounds which decomposed on storage; hence they were regarded as unsuitable for combustion calorimetry.

The Twist Conformation of Cyclohexane.—Theoretical treatments[31] have led to the prediction that the boat form of cyclohexane is more stable in the twisted conformation (see Figs. 1 and 2 for two different perspectives) rather than as a severe boat. The following considerations concern the relationship of our findings to this premise.

Dauben and Pitzer[32] have estimated the energy difference between the boat and chair conformations of cyclohexane by considering that in the boat form the two C–C systems, at the gunwales, are of the eclipsed ethane type as compared with the chair form where these same two systems are of the staggered ethane type. The energy difference between these two conformations should, therefore,

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(26) N. L. Allinger and J. L. Coke, THIS JOURNAL, **81**, 4080 (1959).

(27) N. L. Allinger and J. L. Coke, *ibid.*, **82**, 2553 (1960).

(28) *Cf.* S. Winstein and R. B. Henderson in Elderfield's "Heterocyclic Compounds," Vol. I, John Wiley and Sons, Inc., New York, N. Y. (1950), p. 27.

(29) *Cf.* N. L. Wendler, D. Taub, S. Dobriner and D. K. Fukushima, *J. Am. Chem. Soc.*, **78**, 5027 (1956).

(30) K. Bowden, I. M. Heilbron, E. R. H. Jones and B. C. L. Weedon, *J. Chem. Soc.*, 39 (1946).

(31) (a) P. Hazebroek and L. J. Oosterhoff, *Disc. Faraday Soc.*, **10**, 87 (1951); (b) K. E. Howlett, *J. Chem. Soc.*, 4353 (1957); (c) N. L. Allinger, THIS JOURNAL, **81**, 5727 (1959).

(32) W. G. Dauben and K. S. Pitzer, ref 5, pp. 14, 15.

be approximately equal to twice the internal rotational barrier of ethane (*ca.* 3 kcal./mole) of *ca.* 6 kcal./mole. It was pointed out that this calculation neglects the non-bonded interaction of the two axial hydrogen atoms at the stern and bow of the boat.[32] Now these two hydrogen atoms are separated by only 1.8 Å. and, moreover, are directed obliquely toward each other, in that orientation where the sum of the van der Waals radii is probably not less than the minimum classical value of 2.4 Å.[33] It is estimated that this repulsive force is significant and may be responsible for an additional increment (perhaps as much as 2 kcal./mole) of instability in the boat modification.

If the difference between the experimentally determined value of about 5.5 kcal./mole and that predicted from the above analysis is truly significant, then this consideration constitutes evidence that the so-called boat conformation of cyclohexane is stabilized in the twisted form (shown in its right-handed modification in Figs. 1 and 2). We prefer the term *twist*[34] to stretched,[31a] which is non-descriptive and implies angular deformation or to *skewed*,[35] because the latter has already been well accepted to refer to a specific conformation in 4-atom systems; moreover skew does not embrace the implication of right- and left-handed forms that "twist" connotes.[36] The twist conformation is energetically attractive *a priori* because, not only is it strainless with respect to angular deformation,[31a] but it entirely eliminates the severe bow–stern axial hydrogen interaction of the boat; this H–H distance is thus increased from 1.8 to 2.5 Å.[37] Moreover, a gain in stability results in the twist form by partial relief of the two eclipsed ethane type of interactions at the gunwales. It is particularly noteworthy that parameters selected by Allinger[31c] for use in the Hazebroek–Oosterhoff type of calculation[31a] yield a value (5.1 kcal./mole) which is in excellent agreement with that found experimentally.

The foregoing is presented as confirmatory evidence that when cyclohexane or its derivatives assumes what has been commonly considered to be the boat form, these molecules in reality preferentially adopt the more stable twist conformation, provided the latter form is not precluded by angular requirements as in the [2.2.1]-bicycloheptane system. It is noteworthy that cyclohexane has a right- and left-handed twist form interconvertible through the higher energy boat conformation. In fused ring systems, like those in the present study, only one twist form may be possible because of angular restrictions.

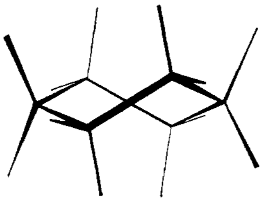

Fig. 1.

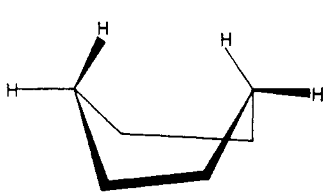

Fig. 2.

Acknowledgment.—This work was supported, in part, by grants from the National Institutes of Health, the National Science Foundation and the Wisconsin Alumni Research Foundation.

Experimental[38]

***cis*-2,3,5,8,9,10-Hexahydro-1,4-naphthoquinone (II).**[16]—A solution of 250 g. (1.54 moles) of *cis*-5,8,9,10-tetrahydro-1,4-naphthoquinone (m.p. 48–53°)[39] in 860 ml. of 95% acetic acid was treated with small portions of zinc dust (Mallinckrodt A.R.), the temperature of the exothermic reaction being maintained at 30° with an ice-bath. Addition of zinc (197 g. in all) was continued until the temperature ceased to rise upon further treatment. Then 900 ml. of acetone was added and the mixture was allowed to stir for 45 minutes. The suspension was filtered with the aid of Filter-Cel and the solvent was removed under reduced pressure on the steam-bath. The solid residue was dissolved in 860 ml. of chloroform. The resulting solution was washed with aqueous sodium bicarbonate and water, and the organic layer was dried over anhydrous magnesium sulfate. Evaporation of the solvent at reduced pressure on the steam-bath affored 246 g. (97% yield) of off-white needles, m.p. 99–101° (reported[16] 108°), suitable for the next reaction.

Δ^2-Octalin Mixture.—The Huang-Minlon modification[17] of the Wolff–Kishner reduction was employed. A solution of 100 g. (0.61 mole) of *cis*-2,3,5,8,9,10-hexahydro-1,4-naphthoquinone (m.p. 99–101°) and 111 g. of potassium hydroxide pellets in 800 ml. of triethylene glycol was swirled for 5 min.; then 140 ml. of 100% hydrazine hydrate was added and the mixture was refluxed for 1.5 hr. The temperature was gradually raised, and the distillate, which separated into two layers, was collected in a water separator, diluted with water, and extracted with ether. The ether layer was dried over anhydrous magnesium sulfate. The residue obtained on evaporation of the solvent was distilled, affording 64.0 g. (78% yield) of colorless liquid, b.p. 80° (20 mm.), $n^{25}{}_{\mathrm{D}}$ 1.4838.

***trans*-Δ^2-Octalin Dibromide.**—A solution of 140 g. of bromine in 100 ml. of chloroform was added dropwise with stirring and ice-bath cooling to a solution of 120 g. (0.88 mole) of crude Δ^2-octalin mixture in 200 ml. of chloroform. The solution was diluted with 300 ml. of chloroform, extracted with 150 ml. of 10% aqueous sodium bisulfite, washed with water, and dried over anhydrous magnesium sulfate. The solvent was removed at reduced pressure on the steam-bath and the residual material was allowed to crystallize from boiling absolute ethanol, affording 149 g. of colorless crystals, m.p. 50–80°. Two recrystallizations from absolute ethanol yielded 113.1 g. (44% yield) of colorless prisms, m.p. 84.0–84.5° (reported[18] 85°), with a characteristic sweet odor.

***trans*-Δ^2-Octalin (III).**—To a slurry of 200 g. of zinc dust (Mallinckrodt A.R.) in 900 ml. of absolute ethanol was added 113.1 g. (0.38 mole) of *trans*-Δ^2-octalin dibromide (m.p. 84.0–84.5°). The mixture was stirred at room temperature for 1.5 hr. and at 65° for 2.5 hr. Ether (400 ml.)

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[33] *Cf.* R. F. Curl, Jr., *J. Chem. Phys.*, **30**, 1529 (1959), and E. B. Wilson, Jr., and W. B. Dixon, report at the Ohio State Symposium on Molecular Structure and Molecular Spectroscopy, June, 1959.

[34] We are indebted to M. F. and C. W. Ellms for this suggestion.

[35] *Cf.* R. E. Reeves, paper presented before the Carbohydrate Division at the 132nd Meeting of the American Chemical Society, New York, N. Y., September, 1957; R. E. Reeves, *Ann. Rev. Biochem.*, **27**, 15 (1958); R. Bentley, THIS JOURNAL, **81**, 1952 (1959).

[36] Other terms that have been suggested are "screw" by Professor G. Ourisson, and "helix" which is appropriate if the model is viewed (see Fig. 2) as a screw propeller (Fr. *helice*) shape which is emphasized by passing an imaginary shaft perpendicularly through the center of the model.

[37] Thanks are due to K. L. Williamson for assistance in preparing the scale drawing shown in Fig. 2 and in making this calculation.

[38] Melting points of analytical specimens were determined in capillaries using a Hershberg apparatus with totally immersed Anschütz thermometers. Melting points of the other samples were obtained on a micro-hot-stage. Infrared spectra were determined on a Baird double beam infrared spectrometer, model B, fitted with sodium chloride prisms. Microanalyses were performed by Mrs. Sonia W. Bauer and by the Huffman Microanalytical Laboratories, Wheatridge, Colo.

[39] Prepared in 91% yield from butadiene and *p*-benzoquinone according to a procedure of E. E. van Tamelen and A. Burgstahler. We wish to thank Professor van Tamelen for making this information available to us prior to publication.

was added, the mixture was filtered with the aid of Filter-Cel, and the filter cake was washed with 300 ml. of ether. The filtrate was washed with water and saturated salt solution and was dried over calcium chloride. The solvent was removed at 30° under reduced pressure, and the residual yellow liquid was fractionally distilled through a 24″ Podbielniak column,[40] affording 50.1 g. (97% yield) of colorless liquid, b.p. 59° (8 mm.), $n^{25}\text{D}$ 1.4796 (reported, b.p. 72° (13 mm.),[41] $n^{20}\text{D}$ 1.4841.[19]). This material was shown to be homogeneous by vapor phase chromatographic analysis.

A solution of 1.00 g. (7.35 mmoles) of *trans*-Δ^2-octalin in 5 ml. of chloroform was titrated at 0° with a solution of 2.35 g. of bromine in 50.0 ml. of chloroform. The end-point was reached after 25.0 ml. of solution (containing 7.35 mmoles of bromine) had been added. The solvent was distilled affording, after recrystallization from absolute ethanol, 2.05 g. (94%) of colorless prisms, m.p. 83.5–84.5°.

Oxidation of 1.00 g. (7.4 mmoles) of *trans*-Δ^2-octalin with alkaline potassium permanganate solution afforded 0.46 g. of colorless acidic solid. Recrystallization from water yielded 0.35 g. (24% yield) of *trans*-cyclohexane-1,2-diacetic acid as colorless cubes, m.p. 167–167.5° (reported[18] 167°).

2,3-Epoxy-*trans*-decalin (IV).—The procedure for epoxidation described by Hibbert and Burt[42] was followed. To a cold (0°) solution of 11.60 g. (0.084 mole) of perbenzoic acid in 248 ml. of chloroform[43] was added cautiously 10.47 g. (0.077 mole) of *trans*-Δ^2-octalin. The solution was maintained at 6° for 5 days, then extracted with cold 10% aqueous sodium hydroxide, washed with water, and dried over anhydrous sodium sulfate. The solvent was distilled and the residual liquid was fractionally distilled through a 24″ Podbielniak column,[40] affording 10.00 g. (85% yield) of colorless liquid, b.p. 105° (21 mm.), $n^{25}\text{D}$ 1.4835 (reported[15] b.p. 91–92° (10 mm.), $n^{24}\text{D}$ 1.4872).

Diethyl 3(a)-Hydroxy-*trans*-decalin-2(a)-malonate (V).—The malonic ester condensation was carried out as described by Westheimer.[44] To an anhydrous solution of sodium ethoxide, prepared from 110 ml. of absolute ethanol and 1.73 g. (0.075 mole) of sodium, was added 12.00 g. (0.075 mole) of diethyl malonate (Abbott, malonic ester decolorized, b.p. 80° (10 mm.)). The solution was heated under reflux, and 10.00 g. (0.066 mole) of 2,3-epoxy-*trans*-decalin ($n^{25}\text{D}$ 1.4835) was added dropwise over a 30-minute interval. The solution was refluxed for 2 hr. during which a dense white precipitate formed. After cooling, the mixture was acidified with dilute sulfuric acid, 500 ml. of water was added, and the solution was extracted with ether. The ether layer was dried over anhydrous sodium sulfate. Removal of the solvent afforded 19.4 g. (94% yield) of a viscous yellow oil which partially solidified on standing.

A small portion of the crude oil was chromatographed on Florisil. The fraction eluted with benzene–ether (19:1) afforded colorless crystals, m.p. 66–68°. Evaporative distillation at 130° (0.015 mm.) followed by crystallization of the colorless oil from petroleum ether (b.p. 37°) afforded colorless plates, m.p. 60–63°.

Anal. Calcd. for $C_{17}H_{28}O_5$: C, 65.36; H, 9.03. Found: C, 65.5; H, 9.01.

3(a)-Hydroxy-*trans*-decalin-2(a)-malonic Acid.—A mixture of 19.4 g. (0.062 mole) of the aforementioned crude oily diester and 250 ml. of 1 *N* aqueous sodium hydroxide was refluxed for 4 hr. under nitrogen. The solution was cooled, washed with ether, and acidified. The precipitated colorless solid, m.p. 154–158° dec., amounted to 11.2 g. (71% yield). Attempts to recrystallize the product were unsuccessful because of facile decarboxylation. A small sample was washed with ethyl acetate affording colorless microcrystals, m.p. 166–167° dec.

3(a)-Hydroxy-*trans*-decalin-2(a)-acetic Acid (VI).—The method of decarboxylation has been described by Westheimer.[44] A solution of 5.12 g. (0.02 mole) of the crude dicarboxylic acid (m.p. 154–158° dec.) in 50 ml. of anhydrous pyridine was refluxed for 15 min. The solution was cooled, diluted with 200 ml. of ether, washed with 10% hydrochloric acid and water, and dried over anhydrous sodium sulfate. Removal of the solvent left 4.39 g. (100% yield) of colorless solid, m.p. 113–116.5°. Recrystallization from ethyl acetate afforded 3.65 g. (86% yield) of colorless needles, which appeared to exist in three polymorphic modifications, m.p. 66–71°, then resolidifying, again melting at 103–104.5°, followed by resolidification, and final melting at 116–117°. A sample was repeatedly recrystallized from ethyl acetate to give colorless needles, m.p. 107.5–108°.

Anal. Calcd. for $C_{12}H_{20}O_3$: C, 67.89; H, 9.50. Found: C, 67.8; H, 9.25.

3-Keto-*trans*-decalin-2(a)-acetic Acid (VII).—A solution of 400 mg. (4.0 mmoles) of chromium trioxide in 5.0 ml. of 80% acetic acid was added to a solution of 1.0 g. (4.7 mmoles) of 3(a)-hydroxy-*trans*-decalin-2(a)-acetic acid (m.p. 116–117°) in 5.0 ml. of glacial acetic acid over a 30-min. period with stirring and ice-bath cooling. The solution was stirred at room temperature for 24 hr. After removal of the solvent at room temperature under reduced pressure, the residual violet colored oil was diluted with water and extracted with ether. The ether solution was washed with saturated salt solution and dried over anhydrous sodium sulfate. Evaporation of the solvent left a pale violet colored oil which was crystallized from petroleum ether (b.p. 68°) affording colorless crystals, m.p. 87–95°. Recrystallization afforded 435 mg. (44% yield), m.p. 95–98°. Several recrystallizations yielded colorless needles, m.p. 97.3–98.5°, followed by resolidification, m.p. 106.2–10.7.3°.

Anal. Calcd. for $C_{12}H_{18}O_3$: C, 68.54; H, 8.63. Found: C, 68.6; H, 8.67.

3-Keto-*trans*-decalin-2(e)-acetic Acid (VIII). (a) By Isomerization of VII.—A solution of 40.0 mg. (0.19 mmole) of 3-keto-*trans*-decalin-2(a)-acetic acid (m.p. 95–98°) and 31 mg. of sodium hydroxide in 15 ml. of water was heated at reflux under nitrogen for 72 hr. The solution was cooled, acidified, and extracted with ether. The ether solution was dried over anhydrous sodium sulfate. After evaporation of the solvent, the residual oil was crystallized from petroleum ether (b.p. 68°) affording 31 mg. (77.5% yield) of colorless crystals, m.p. 70–75°. Five recrystallizations afforded colorless prisms, m.p. 75–77°, followed by resolidification and remelting at 91.5–92°.

Anal. Calcd. for $C_{12}H_{18}O_3$: C, 68.54; H, 8.63. Found: C, 68.8; H, 8.36.

The melting point of the sample was depressed to 65–85° upon admixture with 3-keto-*trans*-decalin-2(a)-acetic acid (VII).

(b) **Directly from VI.**—A modification of the oxidation procedure described by Jones[30] was used. A solution of 5.08 g. (0.024 mole) of 3(a)-hydroxy-*trans*-decalin-2(a)-acetic acid (m.p. 116–117°) in 75 ml. of acetone was treated with a solution of 2.21 g. (0.022 mole) of chromium trioxide in 25 ml. of water and 7.5 ml. of sulfuric acid with stirring and ice-bath cooling over a period of 45 min. Stirring was continued for 1.5 hr. at room temperature. The mixture was poured into water, extracted with ether, and the ether layer was concentrated. A solution of the oily residue and 2.0 g. of sodium hydroxide in 200 ml. of water was heated at reflux for 1 hr. The solution was cooled, acidified, and extracted with ether. After drying over anhydrous sodium sulfate, the ether was evaporated, affording 4.95 g. (98% yield) of colorless prisms, m.p. 68–73°, followed by resolidification and remelting at 89–91°.

3(e)-Hydroxy-*trans*-decalin-2(e)-acetic Acid (IX).—To a stirred boiling solution of 6.69 g. (0.032 mole) of 3-keto-*trans*-decalin-2(e)-acetic acid (m.p. 89–91°) in 1100 ml. of anhydrous isopropyl alcohol was added, in small portions over a 30-min. period, 78 g. of sodium metal. The mixture was heated at reflux for 3 hr.; then 300 ml. of methanol was slowly added and the clear solution poured onto 1.5 l. of ice. After acidification with concentrated sulfuric acid, the mixture was concentrated to a volume of 1.5 l. on the steam-bath under reduced pressure, then extracted with ether. The ether layers were combined, washed with water, and dried over anhydrous sodium sulfate. Evaporation of the solvent on the steam-bath afforded 6.62 g. of off-white solid, m.p. 105–140°. Recrystallization from benzene yielded 4.43 g. (66% yield) of colorless crystals, m.p. 152–154°. Five additional recrystallizations from benzene afforded fine colorless needles, m.p. 156–156.3°.

Anal. Calcd. for $C_{12}H_{20}O_3$: C, 67.89; H, 9.50. Found: C, 68.1; H, 9.47.

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(40) J. Cason and H. Rapoport, "Laboratory Text in Organic Chemistry," Prentice-Hall, Inc., New York, N. Y., 1950, p. 237.

(41) W. Hückel and H. Sawa, *Ber.*, **74**, 57 (1941).

(42) H. Hibbert and P. Burt, "Org. Syntheses," Coll. Vol. I, 494 (1941).

(43) D. Swern, Org. Reactions, Vol. VII, 378 (1953).

(44) W. E. Grigsby, J. Hind, J. Chanley and F. H. Westheimer, THIS JOURNAL, **64**, 2606 (1942).

3(e)-Hydroxy-*trans*-decalin-2(e)-acetic Acid Lactone (A).—A solution of 1.00 g. (4.72 mmoles) of 3(e)-hydroxy-*trans*-decalin-2(e)-acetic acid (m.p. 152–154°) and 0.40 g. of *p*-toluenesulfonic acid monohydrate in 600 ml. of benzene was heated at reflux with stirring under nitrogen for 10 min.; the distillate was collected in a water separator. The solution was cooled in an ice-bath, washed with sodium bicarbonate solution and water, and dried over anhydrous magnesium sulfate. The solvent was removed at room temperature under reduced pressure, affording 0.98 g. of yellow oil. Evaporative distillation at 120° (0.05 mm.), yielded 0.89 g. (97% yield) of colorless oil which crystallized upon seeding, m.p. 38–40°. Nine recrystallizations from petroleum ether (b.p. 37°) afforded colorless prisms, m.p. 41.8–42.5°.

Anal. Calcd. for $C_{12}H_{18}O_2$: C, 74.19; H, 9.34. Found: C, 73.9; H, 9.33.

Hydrolysis of Lactone A.—A solution of 147 mg. (0.76 mmole) of lactone A and 60 mg. of sodium hydroxide in 12 ml. of water and 6 ml. of methanol was heated at reflux under nitrogen for 2 hr. The solution was diluted with water, acidified, extracted with ether, and the ether layer was dried over anhydrous magnesium sulfate. Evaporation of the solvent afforded 154 mg. (95% yield) of 3(e)-hydroxy-*trans*-decalin-2(e)-acetic acid, m.p. 154–155°, undepressed on admixture with authentic acid.

Lactonization of 3(a)-Hydroxy-*trans*-decalin-2(a)-acetic Acid. (a) With N,N'-Dicyclohexylcarbodiimide.—The procedure followed was a modification of that described by Woodward.[22] A solution of 500 mg. (2.36 mmoles) of 3(a)-hydroxy-*trans*-decalin-2(a)-acetic acid (m.p. 116–117°) and 510 mg. (2.43 mmoles) of N,N'-dicyclohexylcarbodiimide[45] (b.p. 114–115° (0.3 mm.)) in 50 ml. of anhydrous pyridine was stirred at room temperature for 5 days. (After 6 hr. colorless crystals began to separate.) The solvent was removed at room temperature under reduced pressure. The oily residue was suspended in ether and washed with dilute hydrochloric acid, water, and saturated salt solution. After drying over anhydrous sodium sulfate, the solvent was removed at room temperature under a stream of nitrogen and the residue was chromatographed on 30 g. of Florisil. The fraction eluted with benzene amounted to 241 mg. (55% yield) of white crystals, m.p. 47–49°. Recrystallization from petroleum ether (b.p. 37°) afforded lactone B, m.p. 48.5–49.5°.

In a larger scale experiment the acyl urea was isolated. A solution of 5.00 g. (0.024 mole) of 3(a)-hydroxy-*trans*-decalin-2(a)-acetic acid (m.p. 116–117°) and 5.10 g. (0.024 mole) of N,N'-dicyclohexylcarbodiimide in 500 ml. of dry pyridine was stirred at room temperature for 11 days. The solvent was removed at room temperature under reduced pressure. The semi-solid residue was washed with ether, and the remaining colorless needles were dried to a constant weight of 8.66 g. (86% yield), m.p. 165–166°; $\lambda_{\max}^{\mathrm{CHCl_3}}$ 5.95, 6.12 μ. Hydrolysis of the material with methanolic potassium hydroxide regenerated the hydroxy acid in 88% yield.

(b) Acid-catalyzed Method.—A solution of 1.00 g. (4.72 mmoles) of 3(a)-hydroxy-*trans*-decalin-2(a)-acetic acid (m.p. 116–117°) and 0.40 g. of *p*-toluenesulfonic acid monohydrate in 600 ml. of xylene was heated at reflux with stirring under nitrogen for 10 min.; the distillate was collected in a water separator. The solution was cooled in an ice-bath, washed with sodium bicarbonate solution and water, and dried over anhydrous sodium sulfate. The solvent was removed at room temperature under reduced pressure, affording 1.10 g. of brown oil which was chromatographed on 50 g. of Florisil. The fractions eluted with petroleum ether–benzene (1:1), pure benzene and benzene–ether (99:1) amounted to 0.70 g. of colorless oil which crystallized upon seeding. Evaporative distillation at 100° (0.05 mm.) yielded 0.67 g. (73%) of colorless crystals, m.p. 48–49°. Twelve recrystallizations from petroleum ether (b.p. 37°) afforded pure lactone B as colorless plates, m.p. 49.6–50.3°.

Anal. Calcd. for $C_{12}H_{18}O_2$: C, 74.19; H, 9.34. Found: C, 74.2; H, 9.19.

Hydrolysis of Lactone B.—A solution of 75 mg. (0.39 mmole) of lactone B (m.p. 48.5–49.5°) and 30 mg. of sodium hydroxide in 6 ml. of water and 3 ml. of methanol was heated at reflux for 2 hr. The solution was concentrated to 5 ml., diluted with water, acidified, and extracted with ether. The ether layer was dried over anhydrous sodium sulfate. Removal of the solvent yielded 83.3 mg. (100%) of colorless crystals, m.p. 100–104°. Two recrystallizations from ethyl acetate afforded 3(a)-hydroxy-*trans*-decalin-2(a)-acetic acid, m.p. 116–117°, undepressed on admixture with authentic acid.

3(e)-Hydroxy-*trans*-decalin-2(a)-acetic Acid (X).—Hydrogenation of 50.0 mg. (0.24 mmole) of 3-keto-*trans*-decalin-2(a)-acetic acid (m.p. 96–98°) in 5 ml. of absolute ethanol over 20 mg. of platinum oxide catalyst at atmospheric pressure and room temperature afforded, after the separation of the catalyst and evaporation of the solvent, 52.6 mg. of colorless oil. Two recrystallizations from benzene at 50° yielded 12.3 mg. of colorless needles, m.p. 131–132°.

3(e)-Hydroxy-*trans*-decalin-2(a)-acetic Acid Lactone (XI).—The crude oil from the catalytic hydrogenation of 100 mg. (0.48 mmole) of 3-keto-*trans*-decalin-2(a)-acetic acid (m.p. 96–98°) was taken up in boiling benzene. Removal of the solvent under reduced pressure afforded an oil which was dissolved in ether. The ether solution was washed with dilute sodium bicarbonate solution and water, dried over anhydrous sodium sulfate, and evaporated to afford 79.6 mg. of colorless oil which partially crystallized on standing. Five recrystallizations from petroleum ether (b.p. 37°) yielded 11.6 mg. of colorless rods, m.p. 60–60.5°.

Anal. Calcd. for $C_{12}H_{18}O_2$: C, 74.19; H, 9.34. Found: C, 74.45; H, 9.57.

Hydrolysis of Lactone XI.—A solution of 175 mg. (0.90 mmole) of lactone XI and 100 mg. of potassium hydroxide pellets in 20 ml. of ethanol was heated at reflux under nitrogen for 2 hr. The solvent was removed on the steam-bath under reduced pressure, and the residue was dissolved in water, acidified, and extracted with ether. The ether layer was dried over anhydrous magnesium sulfate. Evaporation of the solvent afforded 183 mg. (96% yield) of colorless crystals, m.p. 120–126°. Recrystallization from benzene at 60° yielded 3(e)-hydroxy-*trans*-decalin-2(a)-acetic acid, m.p. 132–133°, undepressed upon admixture with authentic acid.

3(a)-Hydroxy-*trans*-decalin-2(e)-acetic Acid (XII).—Hydrogenation of 50.0 mg. (0.24 mmole) of 3-keto-*trans*-decalin-2(e)-acetic acid (m.p. 91–92°) in 5 ml. of absolute ethanol over 20 mg. of platinum oxide catalyst at atmospheric pressure and room temperature proceeded smoothly with the uptake of 1 mole-equivalent of hydrogen in 1 hr. The catalyst was separated, and the solvent was removed on the steam-bath, affording 54 mg. of colorless oil Crystallization from benzene yielded 36.9 mg. of colorless crystals, m.p. 100–109°. Three recrystallizations from warm benzene (not above 70°) afforded 15.5 mg. (30.5% yield) of colorless rhombs, m.p. 114–115°. The melting point, upon admixture with 3(a)-hydroxy-*trans*-decalin-2(a)-acetic acid, was depressed to 83–106°.

Anal. Calcd. for $C_{12}H_{20}O_3$: C, 67.89; H, 9.50. Found: C, 68.0; H, 9.35.

3(a)-Hydroxy-*trans*-decalin-2(e)-acetic Acid Lactone (XIII).—A solution of 90 mg. (0.42 mmole) of 3(a)-hydroxy-*trans*-decalin-2(e)-acetic acid (m.p. 113–115°) and 50 mg. of *p*-toluenesulfonic acid in 100 ml. of benzene was heated at reflux under nitrogen for 10 min.; the distillate was collected in a water separator. The solution was cooled, washed with dilute sodium bicarbonate and water, and dried over anhydrous magnesium sulfate. Evaporation of the solvent afforded 78.2 mg. of semi-crystalline material which was chromatographed on 5 g. of Florisil. The fractions eluted with benzene–petroleum ether (1:1) and pure benzene amounted to 36.3 mg. of crystalline material. Three recrystallizations from petroleum ether (b.p. 37°) yielded colorless prisms, m.p. 85.3–85.8°.

Anal. Calcd. for $C_{12}H_{18}O_2$: C, 74.19; H, 9.34. Found: C, 74.15; H, 9.23.

3(a)-Hydroxy-*trans*-decalyloxy-2(a)-acetic Acid (XIV).—A solution of 500 mg. (3.3 mmoles) of 2,3-epoxy-*trans*-decalin ($n^{25}\mathrm{D}$ 1.4835), 790 mg. of ethyl glycolate (K and K Laboratories, b.p. 70–71° (3 mm.)) and 1 drop of concentrated sulfuric acid in 3 ml. of chloroform was heated at reflux under nitrogen for 4 hr. The solution was cooled, diluted with ether, washed with aqueous sodium bicarbonate, water, and saturated salt solution, and dried over anhydrous magnesium sulfate. Evaporation of the solvent afforded 900 mg. of a yellow oil. A solution of the oil and 800 mg. of potassium hydroxide pellets in 40 ml. of absolute ethanol was heated at reflux under nitrogen for 1 hr. The mixture was

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[45] E. Schmidt, F. Hitzler and E. Lahde, *Ber.*, **71**, 1933 (1938).

concentrated under reduced pressure, diluted with water, washed with ether, acidified, and extracted with ether. The ether layer was dried over anhydrous magnesium sulfate. Evaporation of the solvent afforded 242 mg. of semi-crystalline material, m.p. 106–115°. Recrystallization from benzene yielded 124 mg. of colorless crystals, m.p. 121–123°. Five recrystallizations from benzene afforded 94 mg. of colorless microcrystals, m.p. 122–122.6°.

Anal. Calcd. for $C_{12}H_{20}O_4$: C, 63.13; H, 8.83. Found: C, 63.3; H, 8.80.

3(a)-Hydroxy-*trans*-decalyloxy-2(a)-acetic Acid Lactone (XV).—A solution of 200 mg. (0.88 mmole) of 3(a)-hydroxy-*trans*-decalyloxy-2(a)-acetic acid (m.p. 121–123°) and 75 mg. of *p*-toluenesulfonic acid monohydrate in 150 ml. of benzene was heated at reflux under nitrogen for 10 min.; the distillate was collected in a water separator. The solution was washed with 5% aqueous sodium bicarbonate solution and water, dried over anhydrous magnesium sulfate, and concentrated to a yellow liquid (152 mg.) at room temperature under reduced pressure. Evaporative distillation at 100° (0.1 mm.) afforded 94.5 mg. (51% yield) of colorless crystals, m.p. 46.5–50°. Nine recrystallizations from petroleum ether (b.p. 37°) yielded colorless crystals, m.p. 51.8–52.5°.

Anal. Calcd. for $C_{12}H_{18}O_3$: C, 68.54; 8.58. Found: C, 68.3; H, 8.42.

Upon standing at room temperature in a tightly closed vial, the analytical sample gradually liquified.

3-Keto-*trans*-decalyloxy-2(a)-acetic Acid (XVI).—The method described by Jones[30] was used. A solution of 81 mg. (0.81 mmole) of chromium trioxide in 1.0 ml. of water and 0.3 ml. of sulfuric acid was added dropwise with stirring and ice-bath cooling to a solution of 200 mg. (0.88 mmole) of 3(a)-hydroxy-*trans*-decalyloxy-2(a)-acetic acid (m.p. 121–123°) in 4.0 ml. of acetone over a period of 30 min. After stirring for 1.5 hr. at room temperature, the mixture was poured into 100 ml. of water. The solution was extracted with ether. The ether solution was washed with saturated salt solution, dried over anhydrous magnesium sulfate, and concentrated to a colorless oil (218 mg.). Crystallization from petroleum ether–ether afforded 124 mg. (62% yield) of colorless crystals, m.p. 68–70°. Eleven recrystallizations yielded 42 mg. of colorless prisms, m.p. 69.5–70.5°.

Anal. Calcd. for $C_{12}H_{18}O_4$: C, 63.70; H, 8.03. Found: C, 64.1; H, 8.17.

3-Keto-*trans*-decalyloxy-2(e)-acetic Acid (XVII).—A solution of 200 mg. (0.88 mmole) of crude 3-keto-*trans*-decalyloxy-2(a)-acetic acid and 100 mg. of sodium hydroxide in 20 ml. of water was heated at reflux under nitrogen for 2 hr. The solution was cooled, diluted with water, acidified, and extracted with ether. The ether layer was dried over anhydrous magnesium sulfate. Evaporation of the solvent afforded 207 mg. of yellow crystals, m.p. 95–105°. Recrystallization from petroleum ether–ether yielded 125 mg. of colorless crystals, m.p. 107–113°. Repeated recrystallization failed to improve the melting point. Attempted chromatographic purification on silicic acid was unsuccessful. Paper chromatographic analysis, using a butanol–water system with brom cresol green solution for the detection of the spots, suggested that the product was contaminated with starting material.

3(e)-Hydroxy-*trans*-decalyloxy-2(e)-acetic Acid (XIX).—To a refluxing solution of 300 mg. (1.33 mmoles) of 3-keto-*trans*-decalyloxy-2(e)-acetic acid (m.p. 107–113°) in 50 ml. of anhydrous isopropyl alcohol was added in small portions over a period of 30 min., a total of 3.5 g. of sodium metal. The mixture was heated at reflux for 3 hr., then 50 ml. of methanol was added. The solution was poured onto 250 ml. of ice, acidified, and extracted with ether. The ether layers were washed with saturated salt solution and dried over anhydrous magnesium sulfate. Evaporation of the solvent at room temperature under reduced pressure afforded 306 mg. of yellowish crystalline material. Recrystallization from benzene–methanol at 65° yielded 73.6 mg. of colorless crystals, m.p. 136–141°. Further purification was precluded by facile lactonization as indicated by the development of a band at 5.72 μ in the infrared spectrum.

3(e)-Hydroxy-*trans*-decalyloxy-2(e)-acetic Acid Lactone (XVIII).—Evaporative distillation at 100° (0.1 mm.) of the residue obtained from the concentration of the mother liquor from the preceding experiment afforded 75 mg. of colorless crystals, m.p. 92–112°, which was chromatographed on 2.7 g. of Florisil. The fraction eluted with benzene afforded 26 mg. of product, m.p. 111.5–112°. Recrystallization from petroleum ether (b.p. 68°) yielded colorless needles, m.p. 113.3–113.6°.

Anal. Calcd. for $C_{12}H_{18}O_3$: C, 68.54; H, 8.58. Found: C, 68.3; H, 8.57.

[CONTRIBUTION FROM THE DEPARTMENT OF CHEMISTRY, PURDUE UNIVERSITY, LAFAYETTE, IND.]

Transmission of Electrical Effects Through Homoallylic Systems. IV. The Solvolysis of Some Secondary Cyclopropylcarbinyl *p*-Nitrobenzoates

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The *p*-nitrobenzoate esters of methyl-, phenyl- and *p*-tolylcyclopropylcarbinol have been solvolyzed in 60 volume per cent. aqueous acetone at various temperatures. The relative first-order rates of solvolysis at 65° were found to be $k_{\text{methyl}} = 1$, $k_{\text{phenyl}} = 179$ and $k_{p\text{-tolyl}} = 2140$. These rates are contrasted with the recently reported[1b,c] rates of solvolysis of similarly substituted cholesteryl *p*-toluenesulfonates and the conclusion is drawn that the anomalously low rate of reaction of 6-phenylcholesteryl *p*-toluenesulfonate is accounted for neither by ground state energy nor by stereoelectronic considerations, but rather that it is a result of steric inhibition of resonance in the transition state.

Introduction

We recently reported the results of a series of experiments undertaken with a view toward determining the mechanisms by which electrical effects are transmitted through homoallylic systems.[1a,b,c] In particular the rates of solvolysis of some 6-substituted cholesteryl *p*-toluenesulfonates were measured in the solvent system 90 volume per cent. aqueous dioxane. The effect of 6-methyl substitution, a 75-fold rate enhancement, was interpreted as further confirmation of the generally accepted picture of electron delocalization in the cyclocholesteryl cation. However the kinetic effect of 6-aryl substitution contrasted sharply with this picture: even 6-*p*-anisylcholesteryl *p*-toluenesulfonate solvolyzed more slowly than the unsubstituted cholesteryl ester.

To explain this unusual order of reactivity, three factors were considered.[1c] First, it was suggested that the decreased reactivity of the aryl-substituted compounds results from the increased ground state stabilization of the starting esters due to the conjugation of the aryl rings with the C_5–C_6 π-electrons; it was also suggested that non-bonded steric

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[1] (a) R. A. Sneen, THIS JOURNAL, **80**, 3971 (1958); (b) **80**, 3977 (1958); (c) **80**, 3982 (1958).