The present results provide further support for a picture of conformationally dependent, classical processes functioning in carbonium ion reactivity of substituted cyclobutanes, and contribute to an increasing mass of evidence which impugns the concept of nonclassical bicyclobutonium ion intermediates.

Experimental Section

3-Methylenecyclobutanecarbonitrile was prepared from a bomb reaction of allene and acrylonitrile as described.[32] However, a run of 2 mol (80 g) of allene, 8 mol (424 g) of acrylonitrile, and 4 g of hydroquinone in the presence of 100 ml of dry benzene diluent, in a 2-l. bomb under autogenous pressure at 196° for 14 hr, produced a yield of 155 g (1.62 mol, 81%) of material with $n^{23}{}_D$ 1.4596 (lit. $n^{25}{}_D$ 1.4590). This represents a considerable improvement over the *ca.* 60% reported in the absence of diluent, and in a smaller vessel for a shorter time.[32] Conversion to 3-methylcyclobutylamine was carried out as reported.[11a] Isomers were separated by freezing the effluent vapors from a 30 ft × 0.25 in., 5% KOH–20% Carbowax 20M on Chromosorb W column maintained at 70° with a helium flow rate of *ca.* 35 ml/min. Under these conditions, the retention times of the *cis* and *trans* isomers were 13.07 and 14.53 min, respectively.

Deamination was carried out on the individual isomers and the mixture as previously described.[11a] The deamination mixture was analyzed on a 30 ft × 0.25 in., 5% CO-990 on Chromosorb W column. Components were obtained by isolation of effluent vapors from a mixed amine deamination. With the CO-990 column operated at 100° and a helium flow rate of 40 ml/min., retention times were as follows:

Table II

Product	Retention time, min
4-Penten-2-ol	7.70
Cyclopropylmethylcarbinol	9.63
trans-(2-Methylcyclopropyl)carbinol	12.61
cis-3-Methylcyclobutanol	12.70
trans-3-Methylcyclobutanol	13.46
cis-(2-Methylcyclopropyl)carbinol	15.00

Inadequate separation of *trans*-(2-methylcyclopropyl)carbinol and *cis*-3-methylcyclobutanol resulted in isolation of mixtures. However, content could be assayed by nmr integration and comparison with authentic material.

Authentic 4-penten-2-ol was synthesized from allylmagnesium bromide and acetaldehyde. Its retention time was found to differ widely from its isomers 1-penten-3-ol and 3-penten-2-ol under these conditions. Cyclopropylmethylcarbinol was prepared by lithium aluminum hydride reduction of commercial cyclopropyl methyl ketone. *cis*- and *trans*-(2-methylcyclopropyl)carbinol were prepared by a Simmons–Smith reaction[33] with commercial crotyl alcohol, whose *cis/trans* ratio was about 3:1, and were isolated by freezing of effluent vapors from the CO-990 column. Isomeric configuration was assigned on the bssis of retention time (*cis* longer) and nmr, as has been discussed[34] and also observed for the homologous 2-isopropylcyclopropylcarbinols.[21] The methylene protons were at higher field for the *trans* isomer, and were seen as a ABX multiplet for the *cis* carbinol, and an A_2X doublet for the *trans*. 3-Methylcyclobutanol was prepared as described,[11a] and the isomers were separated by preparative vpc on the CO-990 column. Configuration was assigned by analogy with the 3-isopropylcyclobutanols.[25] The proton geminal to hydroxy was centered at 3.9 ppm for the *cis* and 4.4 ppm for the *trans* isomer.

Registry No.—*cis*-3-Methylcyclobutylamine, 20826-76-0; *trans*-3-methylcyclobutylamine, 20826-77-1.

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[32] J. D. Roberts and C. M. Sharts, *Org. Reactions*, **12**, 32 (1962).

[33] L. Fieser and M. Fieser, "Reagents for Organic Synthesis," John Wiley & Sons, Inc., New York, N. Y., 1967, p 1019.

[34] G. W. Van Dine, Ph.D. Thesis, Princeton University, Princeton, N. J., 1967, p 152.

Ring-Cleavage Reactions of 2-Bicyclo[2.1.1]hexyl Grignard Reagents[1]

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Ring-cleavage reactions of 2-bicyclo[2.1.1]hexyl Grignard reagents have been investigated. Preparation of the chloride or bromide from β-5,5-dimethylbicyclo[2.1.1]hexan-2-ol (**1**) leads to a mixture of halides including α- and β-2-halo-5,5-dimethylbicyclo[2.1.1]hexanes (**2** and **3**) and 2-halo-3,3-dimethylbicyclo[2.1.1]hexane (**4**) as major products. The Grignard reagents from these halides rearrange on heating to the Grignard reagent derivable from 4-halomethyl-3,3-dimethylcyclopentene (**5**). In the preparation of the halide, **5** is also a minor product, which is postulated to form by nucleophilic attack of halide ion on an intermediate ester or carbonium ion. During formation of the Grignard reagent, an alternative cleavage occurs yielding eventually 4-isopropylcyclopentene and 4-isopropenylcyclopentene. A radical process is believed responsible for these latter products. The Grignard reagent from 2-chlorobicyclo[2.1.1]hexane rearranges cleanly to the reagent derivable from 4-chloromethylcyclopentene. The ring cleavages observed are all slower than the analogous cleavage of the Grignard reagents from α-cyclobutylethyl halides, despite substantially greater relief of ring strain in the bicyclic system. These results are in agreement with predictions from a concerted four-center mechanism for the ring-cleavage reactions. However, hybridization effects, the *gem*-dimethyl effect, and overlap control, the magnitude of which are difficult to assess, may contribute to the slowness of the observed cleavages.

A kinetic and mechanistic study of the ring cleavage of cyclobutylmethyl organomagnesium compounds has been reported previously.[3,4] A concerted four-center process was considered to be more consistent with observed solvent, α-deuterium, and methyl substituent effects than were alternative radical and carbanionic mechanisms. The proposed mechanism, in which transfer of the magnesium is synchronous with bonding

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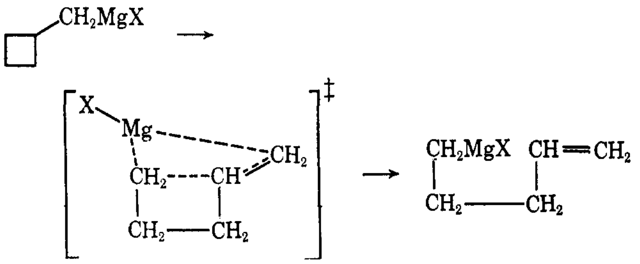
[1] (a) Acknowledgment is made to the donors of The Petroleum Research Fund, administered by the American Chemical Society, for support of this research, and to the National Science Foundation and the Shell Oil Co. for summer and academic year fellowships, respectively, for R. J. T. (b) Presented in part at the 151st National Meeting of the American Chemical Society, Pittsburgh, Pa., March 1966, Abstracts, p 19-K.

[2] (a) To whom inquiries should be addressed: University of Wisconsin-Milwaukee, Milwaukee, Wis. 53201. (b) Taken in part from the Ph.D. Thesis of R. J. Theissen, University of Minnesota, 1966. (c) National Science Foundation Undergraduate Research Participant, University of Wisconsin-Milwaukee, 1967.

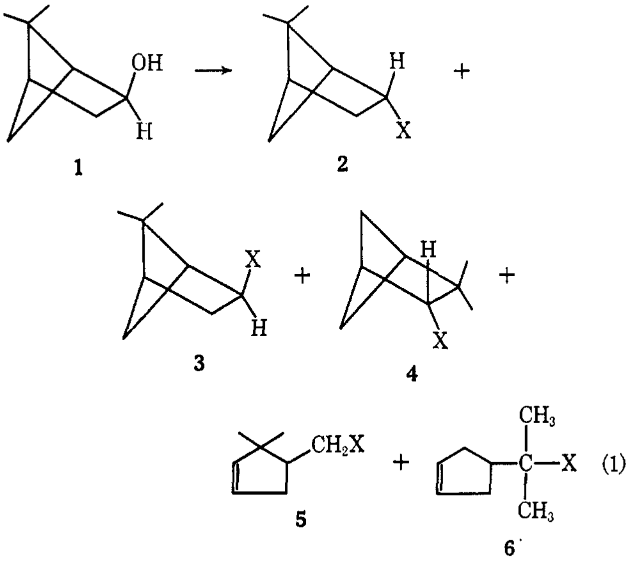
[3] E. A. Hill and J. A. Davidson, *J. Amer. Chem. Soc.*, **86**, 4663 (1964).

[4] Analogous cleavages of other cyclobutylmethyl and cyclopropylmethyl organometallic compounds are known: M. S. Silver, P. R. Shafer, J. E. Nordlander, C. Ruchardt, and J. D. Roberts, *ibid.*, **82**, 2646 (1960); P. T. Lansbury, *ibid.*, **85**, 1886 (1963); H. G. Richey, Jr., and E. A. Hill, *J. Org. Chem.*, **29**, 421 (1964).

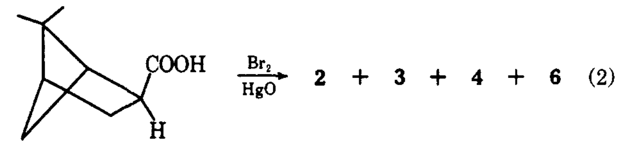


changes in the carbon skeleton, has a further consequence. The rate of ring cleavage should be quite sensitive to geometric restrictions on the conformation of the starting and transition states, which might be achieved by incorporating the cyclobutylalkyl system into a rigid bicyclic skeleton. In the present paper, we report a study of the preparation and cleavage of Grignard reagents derived from one such bicyclic skeleton, 2-substituted bicyclo[2.1.1]hexyl. Most of the work now reported deals with compounds with 5,5- or 3,3-dimethyl substitution, although some work is included on the unsubstituted 2-bicyclo[2.1.1]hexyl Grignard reagent.

Preparation of Halides.—The bicyclo[2.1.1]hexyl skeleton was synthesized by previously published routes. 5,5-Dimethylbicyclo[2.1.1]hexan-2-ol (**1**) was prepared from *β*-pinene by the synthesis developed by Meinwald and Gassman.[5] The chloride and bromide were obtained by treating **1** with thionyl chloride and the triphenylphosphine–bromine reagent,[6] respectively (eq 1). The bromide was also made in low yield from 5,5-dimethylbicyclo[2.1.1]hexane-2-carboxylic acid (**7**) by the modified Hunsdiecker procedure of Cristol and Firth[7] (eq 2).



a, X = Cl
b, X = Br



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In all cases, the product was shown by nmr and gas chromatography to be a mixture of up to five isomeric halides. Unfortunately, separation by gas chromatography was incomplete, and, furthermore, isomerization was found to occur during chromatography. Therefore, it was necessary to carry the halide mixtures through the Grignard studies. For this reason, care was taken to characterize the halide mixtures as fully as possible by partial gas chromatographic separation and nmr.[8] Approximate product distributions for the three halide preparations are listed in Table I which is shown on p 3064.

Assignments of structure were based primarily on the methyl and CHX resonances, which are also in Table I. For the former, assignments were facilitated by published data[9-13] and spectra of compounds with known structure.[14] The CHX resonances of the *α* and *β* isomers of 5,5-dimethylbicyclo[2.1.1]hexan-2-ol and the corresponding halides are similar in position and overlap in mixtures. The CHX spectrum of the *α*-bromide could be observed with minimum interference and may be interpreted as a first-order multiplet with apparent coupling constants of 7.1, 2.5, 1.6, and 1.6 Hz. The most obvious interpretation would assign the first two coupling constants to the *cis*- and *trans*-vicinal couplings and the latter two to the near bridgehead hydrogen (J_{cd}) and remote *exo* hydrogen ($J_{bd'}$). Long-range couplings of the latter type fit approximately to a "W" arrangement of intervening bonds and have been suggested previously.[13] Observation of the CHBr resonance with simultaneous irradiation in the vicinity of δ (ppm) 1.9 and 2.48 eliminated the 2.5- and 7.1-Hz coupling, respectively. By double irradiation at low

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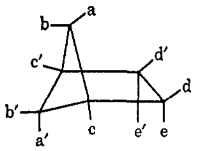
(5) (a) J. Meinwald and P. G. Gassman, *J. Amer. Chem. Soc.*, **82**, 2857 (1960); (b) *ibid.*, **82**, 5445 (1960).

(6) G. A. Wiley, R. L. Hershkowitz, B. M. Rein, and B. C. Chung, *ibid.*, **86**, 964 (1964).

(7) S. J. Cristol and W. C. Firth, Jr., *J. Org. Chem.*, **26**, 280 (1961).

(8) For discussion of nmr spectra, we will follow the lettering scheme of Wiberg, Lowry, and Nist,[9] in slightly modified form as shown. In keeping



with nomenclature suggested by Meinwald and Gassman,[5] isomeric positions on the ethylene bridge of the 5,5-dimethyl isomers are designated *α* or *β* if they are *cis* to the methylene or isopropylidine bridges, respectively. A substituent on the one-carbon bridges is *endo* in the a or a′ positions, and *exo* in b or b′.

(9) K. B. Wiberg, B. R. Lowry, and B. J. Nist, *J. Amer. Chem. Soc.*, **84**, 1594 (1962).

(10) T. Gibson and W. F. Erman, *J. Org. Chem.*, **31**, 3028 (1966).

(11) R. C. Cookson, J. Hudec, S. A. Knight, and B. R. D. Whitear, *Tetrahedron*, **19**, 1995 (1963).

(12) (a) J. Meinwald and A. Lewis, *J. Amer. Chem. Soc.*, **83**, 2769 (1961); (b) K. Ebisu, L. B. Batty, M. Higaki, and H. O. Larson, *ibid.*, **88**, 1995 (1966); (c) R. S. H. Liu and G. S. Hammond, *ibid.*, **86**, 1892 (1964); (d) R. Srinivasan and F. I. Sonntag, *ibid.*, **89**, 407 (1967); (e) J. Meinwald and J. K. Crandall, *ibid.*, **88**, 1292 (1966).

(13) A. Cairncross and E. P. Blanchard, Jr., *ibid.*, **88**, 496 (1966).

(14) Some characteristic features are summarized.

Compd	δ (*endo*-5-CH_3)	δ (*exo*-5-CH_3)	δ (*endo*-6-H)
12	0.75	1.25	0.72
α **1**	0.73	1.22	
β **1**	1.07	1.29	0.73
β **1** benzoate	1.11	1.28	0.74
7	0.79	1.33	0.89

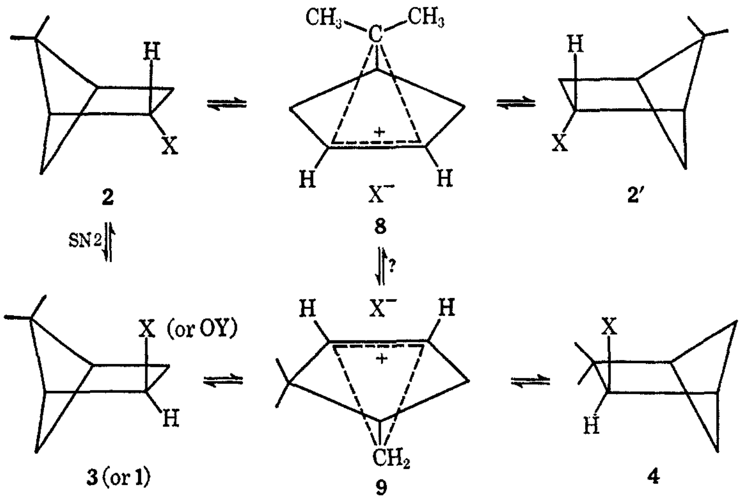
The *endo*-6 hydrogen of *α* **1**, and the *endo*-5 and *endo*-6 hydrogens of 3,3-dimethylbicyclo[2..11]hexane were apparently shifted downfield by a *syn* substituent on the two-carbon bridge, and were not seen. The *endo*-5-methyl group of **7** is apparently shifted upfield by the magnetic anisotropy of the carboxy group. Examples of a previously reported [R. S. Liu, *Tetrahedron Lett.*, 2159 (1966)] long-range coupling, $J_{cc'}$, of 8 Hz was observed in compounds **4a** and **13**.

power levels,[15a] the sign of the coupling constant between the resonances at δ 1.9 and 2.48 was shown to be opposite their coupling to the CHBr proton.[16] The α-chloride was apparently similar, although only part of it could be seen clearly. For the β isomers, the spectral appearance was substantially different and could not be cleanly interpreted as a first-order pattern. Some simplification which resulted from double irradiation indicated that the CHCl proton was probably coupled to more than one proton in the vicinity of δ 2.1 to 2.2. For the rearranged 2-halo-3,3-dimethylbicyclo[2.1.1]hexanes **4**, the CHX absorption was a triplet with J = 1.5 Hz. One of the coupled protons is undoubtedly the adjacent bridgehead hydrogen. The other most probably results from bd′ coupling.

In addition to the bicyclic isomers, olefinic nmr absorption indicated that some ring cleavage had occurred during the halide preparations. The 4-halomethyl-3,3-dimethylcyclopentenes were isolated by gas chromatography in reasonably pure form and characterized by their nmr spectra. The methyls of the *gem*-dimethyl group are nonequivalent, owing to *cis* and *trans* relationship to the halomethyl group. The CH$_2$X appears at higher field than CHX resonances of the bicyclic compounds and exhibits a coupling pattern which may be analyzed as the AB portion of an ABX spectrum.[15b] Parameters obtained at 100 MHz are shown in Table II. Nonequivalence of the methylene protons is reasonable, since the halomethyl group is bonded to an asymmetric carbon atom, and additionally, the adjacent *gem*-dimethyl group might be expected to produce some rotational restriction. To help to confirm the structure of the primary halide, a Grignard reagent was prepared from a sample of the bromide which had been partially separated by gas chromatography. The bromide used was about 50% **4b** and 50% **5b**, based on integration of the nmr spectrum. Hydrolysis of the Grignard reagent yielded a mixture of hydrocarbons which was 50% 3,3,4-trimethylcyclopentene and 50% 2,2-dimethylbicyclo[2.1.1]hexane.

Additional weak olefinic signals were present in distilled samples of the halides, but did not appear in the gas chromatographed fractions. It is likely that tertiary halide **6** might be formed during synthesis of the halides, but not survive gas chromatography. The analogous alcohol has been isolated in solvolytic studies.[17] If the tertiary halide is held responsible for the additional signals, a reevaluation of the product distributions in Table I would show it to comprise 0.7% of the chloride product and 1.5 and 6% of the product in the two bromide preparations. Substantial amounts of the corresponding hydrocarbons, 4-isopropylcyclopentene and 4-isopropenylcyclopentene, were isolated from Grignard reactions, but, in large measure, they were apparently derived from the other halides.

The variation in composition of the halide mixtures is of some interest. Had the thionyl chloride and triphenylphospine–bromine reactions proceeded with clean SN2 inversion of configuration, pure **2** would have been formed (eq 3). Wagner–Meerwein rearrangement of this halide by a stereospecific nonclassical carbonium ion-pair mechanism leads only to racemization. The other bicyclic halides **3** and **4** are related to each other by such a stereospecific rearrangement, but a "crossover" is required for interconversion with **2**.[18] An "SNi" carbonium ion process in competition with SN2 would explain the bicyclic isomers. The larger amount of simple inversion product **2** in the triphenylphosphine–bromine reaction is consistent with the demonstrated tendency[6] of that reagent to react by direct displacement and with the greater nucleophilicity of bromide. Formation of isomer **4** could occur by rearrangement in the "SNi" ion pair or by Wagner–Meerwein rearrangement of **3** to **4**. The increased proportion of **4** in the bromide is consistent with the latter possibility, because of the greater lability of alkyl bromides. In the Hunsdiecker reaction, the probable free-radical intermediate would not be expected to rearrange. The absence of **3b** and presence of **4b** in that reaction is most satisfactorily explained by mercuric salt catalysis of the Wagner–Meerwein rearrangement of **3** to **4**.



(3)

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(15) (a) J. W. Emsley, J. Feeney, and L. H. Sutcliffe, "High Resolution Nuclear Magnetic Resonance Spectroscopy," Pergamon Press, London, 1966: (a) p 468; (b) pp 357–364.

(16) A similar result has been reported for norbornanes and norbornenes: J. I. Musher, *Mol. Phys.*, **6**, 93 (1963); F. A. L. Anet, H. H. Lee, and J. L. Sudmeier, *J. Amer. Chem. Soc.*, **87**, 4431 (1967).

(17) J. Meinwald, P. G. Gassman, and J. J. Hurst, *ibid.*, **84**, 3722 (1962); J. Meinwald and P. G. Gassman, *ibid.*, **85**, 57 (1963).

(18) In eq 3, the nonclassical formalism is used for convenience and in recognition of the solvolysis results of J. Meinwald, P. G. Gassman, and J. J. Hurst.[17] Formation of all products *via* rearranging classical ions might also be considered. A "crossover" between the two nonclassical systems **8** and **9** is suggested in the solvolysis studies[17] and by our finding that **2b** and **3b** both appear to be converted into **4** during gas chromatography.

Table I

Composition and Nmr Spectra of Products in 2-Halodimethylbicyclo[2.1.1]hexane Preparations

Component	% of product Cl[a]	% of product Br[b]	% of product Br[c]	Nmr, δ, ppm Methyl Cl	Nmr, δ, ppm Methyl Br	Nmr, δ, ppm CHX Cl	Nmr, δ, ppm CHX Br
2	10	44	40	0.76 1.27	0.78 1.31	4.38	4.43
3[d]	47	8	0	1.12 1.30	1.16 1.32	4.30	4.29
4[e]	39	33	60	1.12 1.14	1.17 1.20	3.98	4.09
5[f,g]	4	15	0	0.90 1.14	0.89 1.16	3.49	3.37

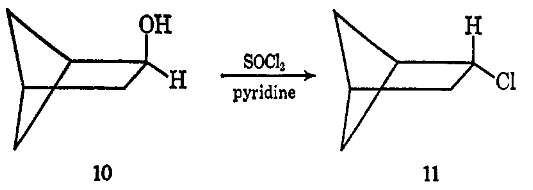
[a] From alcohol and $SOCl_2$–C_5H_5N. [b] From alcohol and $P(C_6H_5)_3$–Br_2. [c] From acid and HgO–Br_2. [d] Nmr doublet at δ 0.82 from *endo*-6 hydrogen of chloride. Corresponding absorption in bromide was obscured by methyl group of mixture. [e] Additional prominent nmr absorptions: δ 1.6 (m, 4), 2.05 (pair of triplets, 1, *J* 8.0, 2.5, and 2.5 Hz), 2.50 (broadened doublet, 1, *J* = 8.0 Hz) in chloride. [f] Olefinic absorption at δ 5.47 (chloride) and 5.49 (bromide). [g] Additional olefinic absorptions at δ 5.59, 5.71, and 5.8 in the three reactions might be assigned to halides **6a** and **6b**.

Table II

Parameter	Hz Chloride	Hz Bromide
$\lvert J_{AB} \rvert$	10.5	9.4
$\lvert J_{AX} \rvert$	8.6	9.4
$\lvert J_{BX} \rvert$	6.0	5.2
$\lvert \nu_A - \nu_B \rvert$	17.7	18.7

The primary ring-opened halide **5** is an unexpected reaction product. It seems unlikely that either a classical or a nonclassical ion would be likely to cleave directly to a primary carbonium ion, and indeed no such products were detected in solvolysis and deamination studies.[17] The most probable explanation would seem to be that the phosphorus or chlorosulfite ester intermediate either undergoes a fragmentation concerted with nucleophilic attack on the primary carbon by chloride or bromide, or, more likely, the bridging methylene of nonclassical cation **9** is attacked by halide. In either case, steric hindrance to more normal substitution might enhance this unusual reaction pathway. In any event, nucleophilic participation by halide seems necessary. Absence of the primary halide from the Hunsdiecker reaction is consistent with the expectation that cleavage to a primary radical would not occur. Either radical or cationic cleavage to yield the tertiary halide **6** would be reasonable.

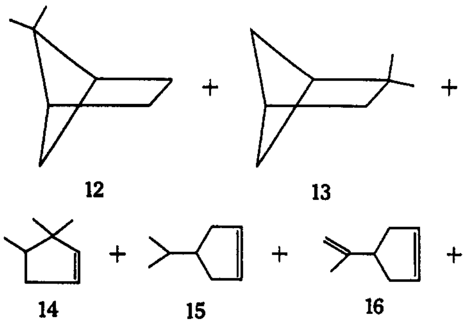
In addition to the methyl-substituted bicyclohexyl chlorides, the unsubstituted 2-chlorobicyclo[2.1.1]hexane (**11**)[19] was prepared from the corresponding alcohol (**10**). In this instance, the conversion into halide was quite clean (eq 4).



(4)

Formation and Cleavage of Grignard Reagents.—Grignard reagents were prepared in ether and in tetrahydrofuran from the chloride and bromide mixtures derived from **1** (eq 5). After reaction of the halide with magnesium, solvent and any hydrocarbons generated during formation of the reagent were pumped to a cold trap under high vacuum, and new solvent was added. Hydrolysis of the residual Grignard reagent yielded a mixture of four hydrocarbons (eq 6), which were separated by preparative gas chromatography and identified by ir and nmr spectra. The hydrocarbons found were 5,5-dimethylbicyclo[2.1.1]hexane (**12**), 2,2-dimethylbicyclo[2.1.1]hexane (**13**), 3,3,4-trimethylcyclopentene (**14**), and 4-isopropylcyclopentene (**15**). The hydrocarbons in the solvent pumped from the preparation of the Grignard reagent contained, in addition, 4-isopropenylcyclopentene (**16**) and small amounts of some unidentified components of longer retention time.

"bicyclohexyl halide mixture" $\xrightarrow[\text{ether or tetrahydrofuran}]{\text{Mg}}$



Grignard reagent (5)

$$\text{Grignard reagent} \xrightarrow{H_2O} \mathbf{12} + \mathbf{13} + \mathbf{14} + \mathbf{15} \quad (6)$$

The Grignard reagent from the chloride was formed in a yield of 60–80%, based on acid titer and semiquantitative analysis of the hydrocarbon fractions. However, the Grignard reagent from the bromide was apparently formed in only about 15% yield. The major side reaction appears to be a disproportionation, in which isopropenylcyclopentene is the major product formed by hydrogen loss. In both preparations, the amount of halide eventually appearing with isopropyl- or isopropenylcyclopentene skeleton far exceeds the 1–3% of this skeleton in the original halide mixture. For instance, in the Grignard reagent from the bromide mixture, the hydrocarbons pumped from the Grignard reagent (about 75% of the total product) contained 37% of this skeleton. While the unrearranged 5,5-dimethylbicyclo[2.1.1]hexyl bromides had comprised 51% of the halide mixture, the corresponding hydrocarbon made up only 24% of the hydrocarbons pumped from the Grignard, and 47% of the hydrocarbons from hydrolysis of the Grignard reagent. It appears likely that a free radical **17** generated during reaction of the

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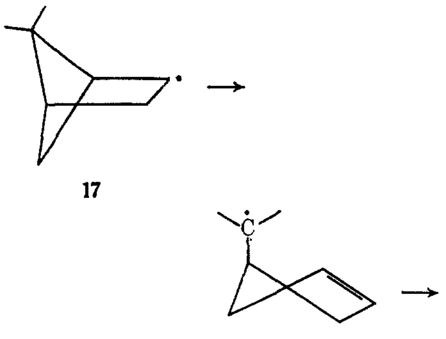
(19) Preparation of the same chloride by chlorination of the hydrocarbon has been reported previously.[12d] Nmr spectra agree. Nmr data on **10** are in good agreement with other generalizations of bicyclo[2.1.1]hexane spectra. The spectrum was run at 100 MHz and decoupled to help clarify the spin–spin coupling pattern. The ring proton of the CHOH group is a broad doublet. By double irradiation, it was shown to be coupled to multiplets at δ 1.94 (*J* = 7.5 Hz) and 1.24 (*J* = 2.0 Hz), which were in turn coupled with each other (*J* = 11.5 Hz), as expected for the methylene group at C_3. There was weak coupling to the bridgehead (δ 2.39) and possibly to a proton of the three-hydrogen multiplet at δ 1.34–1.70, which presumably includes the two *exo* protons and one of the *endo* protons. The other *endo* proton appears as a quartet at δ 0.90, with coupling constants of about 7 and 9 Hz to protons within the same three-proton multiplet and is apparently coupled to no other protons in the molecule.

halide with magnesium cleaves to tertiary radical **18**, which leads eventually to much of the disproportionation product (eq 7). Alternatively, it is possible that



17

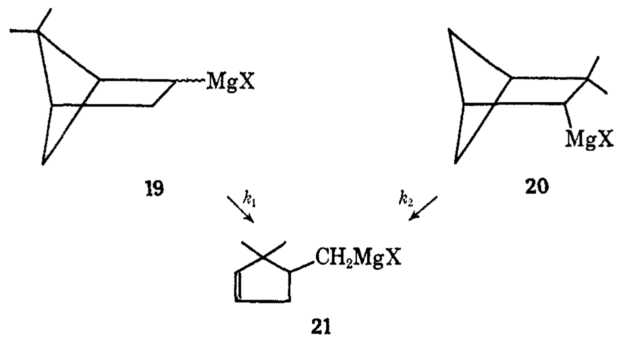
18

→ **15** + **16** (7)

some cationic ring cleavage of the bromide may occur under the influence of Lewis-acidic magnesium compounds. To test the possibility, a small sample of bromide mixture containing no **6b** was refluxed for 0.5 hr in 0.8 *M* ethereal ethylmagnesium bromide solution. The recovered bromide was very slightly altered in composition. A new weak olefinic absorption appeared at δ 5.59, which could correspond to no more than 4% **6b**. (This resonance differs somewhat in position from that observed in the halide mixtures previously.) A new methyl signal of undetermined origin was also observed at δ 1.26.

As discussed earlier, small amounts of the bromide mixture were partially separated by preparative gas chromatography. Small-scale Grignard reagents were made from fractions containing (1) 50% **5** and 50% **4**; (2) 15% **5**, 46% **4**, and 39% **2** and **3**; (3) 4% **5**, 19% **4**, and 77% **2** and **3**. In fraction 1, the only products isolated from immediate hydrolysis of the mixture were the corresponding hydrocarbons **14** and **13**, but, in the other two reactions, 10 and 16%, respectively, of the total hydrocarbons were of the isopropenyl- or isopropylcyclopentene skeleton, while other hydrocarbons compared roughly with the amounts of the corresponding halides in the mixtures.

When the Grignard reagent mixture was heated in either ether or tetrahydrofuran for several hours at 100–125°, the hydrocarbon mixture formed on hydrolysis changed in composition, with the trimethylcyclopentene increasing at the expense of the bicyclic hydrocarbons. The isopropylcyclopentene (present in significant amount only in the Grignard reagent from the chloride) underwent little or no change. There was very little (<10%) loss of organometallic owing to attack on solvent or hydrolysis by adventitious proton sources. The principal processes occurring on heating are thus ring cleavage of the two bicyclic Grignard reagents. From qualitative inspection of chromatograms, it is apparent that $k_2 > k_1$.

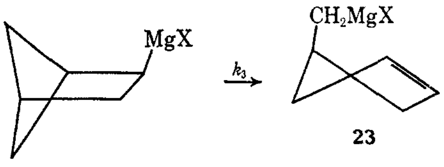


19 **20**

21

Nmr spectra of Grignard reagent mixtures confirmed the nature of the reaction which was occurring. The original reagent from the chloride in ether showed absorption at δ 0.33, with apparent coupling constants of 2.6, 7.2, and 7.2 Hz, and at 0.01, about 4 Hz in width, with a hint of splitting with a coupling constant of about 2 Hz. These are reasonably assigned to Grignard reagents **19** and **20**, respectively. (The α isomer of **19** would be preferred on steric grounds.) The apparently identical 7.2-Hz vicinal coupling constants in the spectrum of **19** could be attributed to a "deceptively simple" situation in which this is the average of *cis* and *trans* coupling;[20] the long-range coupling found with the halide isomers appears to be small (<1 Hz) in both Grignard reagents. The olefinic region of the original Grignard spectrum had two minor peaks, presumably due to a small amount of Grignard reagent **21** and olefins **14**, **15**, and **16**, which were not pumped off before taking the nmr sample. The spectrum in tetrahydrofuran was similar, but with the α-H multiplets at δ 0.10 and −0.15. On heating, a higher field multiplet appeared at δ −0.48 (−0.66 in THF), which could be analyzed as the AB portion of the ABX spectrum of the CH_2MgX group in **21**. Parameters derived were $|J_{AB}| = 11.5$ Hz, $|J_{AX}| = 11.0$ Hz, $|J_{BX}| = 4.5$ Hz, and $|\Delta\nu_{AB}| = 19.5$ Hz, showing a reasonable similarity to the spectra reported for halides **5**. Simultaneously, a strong olefinic singlet appeared at δ 5.53. In the tetrahydrofuran spectrum two major peaks remained in the methyl region at δ 0.69 and 0.90 after heating. The rate of change of the nmr patterns was roughly comparable with that derived from gas chromatographic analysis of the hydrolyzed Grignard reagent.

2-Chlorobicyclo[2.1.1]hexane was converted into a Grignard reagent without complication and in high yield. Immediate hydrolysis yielded a single hydrocarbon (>99.5%) identified spectroscopically as bicyclo[2.1.1]hexane. Hydrolysis after 18 hr at 90° produced a new hydrocarbon (95% yield), identified as 4-methylcyclopentene. The nmr spectrum of the initial ethereal Grignard solution showed a multiplet at δ 0.01 with apparent coupling constants of 2.6, 7.8, and 7.8 Hz, similar to that observed for the 5,5-dimethyl homolog. Less well-defined absorptions apparently also attributable to Grignard reagent **22** were at δ 0.9, 1.8, and 2.6. On heating, new high-field doublet absorption appeared at δ −0.22 ($J = 8.1$ Hz) and olefinic absorption at 5.59, attributed to primary Grignard **23**. Absorption from **22** decreased in intensity.



22 **23**

Rates of ring-cleavage reactions of the dimethylbicyclohexyl Grignard reagents were determined from gas chromatographs of hydrocarbons obtained on hydrolysis of heated samples of the reagents. For comparison, rates of ring cleavage were also determined for α-cyclo-

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(20) R. J. Abraham and H. J. Bernstein, *Can. J. Chem.*, **39**, 216 (1961).

butylethylmagnesium bromide and chloride. Values of rate constants extrapolated to 100° are summarized in Table III. Also listed is a rough estimate of the rate constant for the 2-bicyclohexyl Grignard estimated from nmr spectra.

Discussion

From earlier kinetic studies, it was concluded that the most acceptable mechanism for ring cleavage of the cyclobutylmethyl Grignard reagent is a concerted four-center process. On the basis of the small effect of α-deuterium or α-methyl substitution and insensitivity to solvent polarity, alternative free-radical and carbanion mechanisms were considered less likely.[3] In the present study, the preference for kinetically controlled cleavage of the 5,5-dimethylbicyclo[2.1.1]hexyl Grignard reagent to a primary rather than a tertiary organometallic likewise argues against a radical mechanism and suggests that the carbon to which the magnesium migrates has appreciable organometallic character in the transition state.

An expected consequence of a cyclic mechanism is sensitivity to geometric restriction in a rigid bicyclic system. It may be calculated for the 2-bicyclo[2.1.1]hexyl skeleton[21] that the magnesium and the carbon to which it will become attached are separated by 3.3 Å, as opposed to a minimum 2.9 Å in a simple cyclobutylmethyl derivative.[22] In the bicyclic compound, the dihedral angle between the carbon–magnesium bond and the cleaving carbon–carbon bond is 73°; in the cyclobutylmethyl system, free rotation allows any dihedral angle. It thus seems reasonable that the rigidity of the bicyclic system might make it more difficult to attain optimum transition state geometry.

On the other hand, the bicyclo[2.1.1]hexyl skeleton should be substantially more strained than a simple cyclobutyl ring. It is reasonable that a part of this additional strain should be relieved in the transition state, resulting in a rate acceleration. For instance, Srinivasan has found that thermal cleavage of bicyclo[2.1.1]hexane to 1,5-hexadiene has an activation energy 6.8 kcal lower than that for analogous cleavages of simple disubstituted cyclobutanes.[23] It is apparent also that cationic and probably radical cleavages are facilitated by the high ring strain. Unfortunately, no thermochemical data appear to be available for bicyclo[2.1.1]hexane. Therefore, an attempt was made to estimate the strain of this molecule on the basis of the geometry calculated by Wilcox.[21] While there are substantial uncertainties in such an estimate, it appears likely that bicyclo[2.1.1]hexane is between 10 and 16 kcal more highly strained than cyclobutane.[24] Coupled with 4 kcal of ring strain in the product,[33] cleavage of the 2-bicyclo[2.1.1]hexyl Grignard reagent should be 6 to 12 kcal more exothermic than cleavage of the α-cyclobutylethyl Grignard.

It is then significant to find that the methyl-substituted bicyclohexyl Grignard reagents cleave much less rapidly than the simple cyclobutylethyl Grignard and that the unsubstituted bicyclohexyl reagent is also slower. The observed result is thus consistent with a sizable rate deceleration owing to geometric restrictions on a cyclic transition state.

A closely related factor which should result in a decrease in cleavage rate by any mechanism (including carbanion or radical) is steric restriction of π-orbital

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(21) Calculations were made on the geometrical model of C. F. Wilcox, Jr., *J. Amer. Chem. Soc.*, **82**, 414 (1960).

(22) Calculations were based on the geometry of bromocyclobutane, as determined by W. G. Rothchild and B. P. Dailey, *J. Chem. Phys.*, **36**, 2931 (1962).

(23) R. Srinivasan and A. A. Levi, *ibid.*, **85**, 3363 (1963).

(24) One approach is to calculate contributions to the strain energy from angle bending, torsion, and van der Waals repulsions. This approach is complicated by the known fact that the simple quadratic dependence of energy upon angle distortion is invalid for large distortions. Wiberg[25] and Allinger[26] have independently suggested the use of an empirical sigmoid bond angle–strain energy relationship, which presumably also incorporates any contributions from 1,3 carbon–carbon van der Waals interactions as bond angles are decreased and any bond-stretching necessary to accommodate such repulsions in a strained ring. These curves were normalized to fit cyclobutane; so it is likely that they should provide reasonable strain energies for the angles of the cyclobutane ring in bicyclo[2.1.1]hexane. However, they differ substantially in the vicinity of 100°, leading to total bond-bending strain energies of 32.0 (Wiberg) and 23.9 (Allinger) kcal/mol. A similar discrepancy is noted for calculations on norbornane.[27] (Some objection might be raised to using a markedly different potential function for energy calculations from that used in predicting the geometry, but Wilcox[21] noted that variation of the parameters had remarkably little effect on calculated geometry.) Torsional energy (ignoring the possibility of a decrease in torsional strain due to exocyclic bond spreading in small-ring systems) was calculated in the conventional manner to contribute 6.6 kcal/mol. Average torsional angles at the bridgehead were used. van der Waals repulsions, aside from those possibly implicit in bond bending and torsional contributions, were presumed small. The resulting estimate of total strain energy is then 38.6 or 30.5 kcal/mol (*vs.* the experimental value of 26 kcal for cyclobutane[28]). The latter estimate is probably low.[27] A calculation using the customary quadratic relation for bond bending yields a strain estimate of at least 65 kcal/mol.

An alternate approach to torsional and van der Waals strain has been presented by Simmons.[29] In this treatment, torsional energy is treated as a manifestation of hydrogen–hydrogen van der Waals repulsions, using a "hard" potential function. This procedure appears to be invalid in the present instance, as it predicts torsional and H–H repulsion strain energy in cyclohexane to be no less than in norbornane or bicyclohexane.

An additional estimate of strain energy for bicyclo[2.1.1]hexane treats the molecule as a modified cyclobutane. The increased folding (42°) of the cyclobutane ring due to bridging is estimated to increase strain by 1.2 kcal/mol over that of cyclobutane.[25] Torsional and bond-angle strain in the two-carbon bridge should contribute an additional 2.8 and 3.3 (Wiberg) or 1.1 (Allinger) kcal/mol. Finally, distortion of the two bonds on the cyclobutane ring to the proper angle to bond to the two-carbon bridge requires a decrease in a total of four C–C–C angles to 97.2°. This should contribute about 10 (Wiberg) or 5 (Allinger) kcal/mol more. Estimates of total strain energy add up to 43 (Wiberg) or 36 (Allinger) kcal/mol.

(25) K. B. Wiberg and G. M. Lampman, *J. Amer. Chem. Soc.*, **88**, 4429 (1966).

(26) N. L. Allinger, J. A. Hirsch, M. A. Miller, I. Tyminski, and F. A. Van Catledge, *ibid.*, **90**, 199 (1968).

(27) Norbornane appears to be a reasonable proving ground for strain energy calculations in a bicyclic system, since there exists in the literature a strain energy value of 18.5 kcal/mol derived from the heat of combustion.[30] However, the exact magnitude of this strain energy rests on an assumed heat of fusion of 4 kcal/mol, which was presented with no justification, and might be somewhat in error. The situation is further confused by an estimated heat of vaporization of only 2.2 kcal, used by Allinger.[26] A more reasonable estimate would seem to be closer to 8.5 kcal, based on Trouton's rule. With the probably erroneous heat of vaporization, use of the methods of Franklin or Klages[31] to estimate gas phase heats of formation for the unstrained molecule leads to a strain energy of only 12 kcal/mol. Allinger and coworkers[26] calculated the contribution of "strain terms" to norbornane as 12.01 kcal/mol. It is not certain whether calculations on norbornane were used to help establish their empirical strain energy–bond angle curve, but it does appear likely that their curve may not be soundly based vicinity of 10–15° bond angle distortions. Calculations similar to those described for bicyclo[2.1.1]hexane lead to total strain energies of 22.75 and 13.85 kcal/mol, based on bond-bending strain curves of Wiberg and Allinger. The result provides no clear choice between the two. Another calculation by Allinger's method has been reported by Wilcox and compared with his electron diffraction results.[32]

(28) S. Kaarsemaker and J. Coops, *Rec. Trav. Chim.*, **71**, 261 (1952).

(29) H. E. Simmons and J. K. Williams, *J. Amer. Chem. Soc.*, **86**, 261 (1964).

(30) A. Bedford, A. E. Beezer, C. T. Mortimer, and H. D. Springall, *J. Chem. Soc.*, 3823 (1963).

(31) G. J. Janz, "Thermodynamic Properties of Organic Compounds," Academic Press, Inc., New York, N. Y., 1967, pp 58–85.

(32) J. F. Chiang, C. F. Wilcox, Jr., and S. H. Bauer, *J. Amer. Chem. Soc.*, **90**, 3149 (1968).

(33) (a) R. B. Turner, "Kekule Symposium," Butterworth and Co., Ltd., London, 1959, p 67; (b) R. B. Turner, P. Goebel, W. von E. Doering, and J. F. Coburn, Jr., *Tetrahedron Lett.*, 997 (1965).

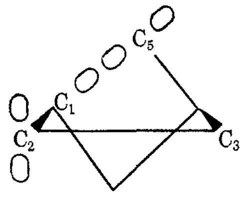
TABLE III

RATES OF RING CLEAVAGE OF 2-BICYCLO[2.1.1]HEXYL GRIGNARD REAGENTS IN ETHER[a]

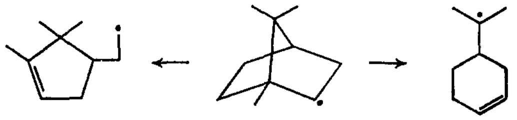
Grignard	X	Concn, M[b]	T, °C	$k \times 10^7$ [c]	$\Delta H^{\ddagger}$ [c]	$\Delta S^{\ddagger}$	k_{rel} (100°)
19[d]	Cl	0.16	102.7	7.64 ± 0.39	32.1 ± 1.3	−1.4	0.0016
		0.16	118.7	49.6 ± 4.2			
		0.16	125.7	96.6 ± 5.8			
19	Br	0.03[e]	102.7	31.7 ± 1.9	30.6 ± 1.1	−1.2	0.0070
		0.03	114.6	122 ± 6			
		0.046	114.6	134 ± 6			
		0.03	125.7	367 ± 9			
20[f]	Cl	0.16	102.7	44.0 ± 3.2	33.4 ± 2.0	5.3	0.0085
		0.16	118.7	269 ± 21			
		0.16	125.7	653 ± 75			
20	Br	0.03[e]	102.7	322 ± 32	28.2 ± 1.9	−4.6	0.0681
		0.03	114.6	970 ± 83			
		0.04	114.6	1100 ± 51			
		0.03	125.7	2960 ± 140			
22[g]	Cl	1.2	88.0	100			0.1
Cyclobutylethyl	Cl	0.145	66.0	169 ± 15	25.7	−5.8	1.68
			80.0	803 ± 92			
Cyclobutylethyl	Br	0.06	66.0	53.1 ± 0.9	31.9 ± 0.7	11.1	1.00
			80.0	355 ± 4			
			94.0	1880 ± 45			

[a] Water content of solvent 1.2×10^{-3} M or less. [b] Metal-bound alkyl group concentration as determined by acid titration or gas chromatography. [c] 50% confidence limits. [d] 5,5-Dimethylbicyclo[2.1.1]hexane-2-magnesium halide. [e] Low concentration of reagent due to large amounts of disproportionation. [f] 3,3-Dimethylbicyclo[2.1.1]hexane-2-magnesium halide. [g] Bicyclo[2.1.1]hexane-2-magnesium halide.

overlap in the forming double bond. As the bond between carbon atoms 1 and 5 begins to break, the hybrid orbital on carbon atom 1 evolves into a p orbital, and π bonding between this orbital and the orbital on carbon atom 2 develops. Most probably, the transition state occurs at some intermediate stage in this transformation. However, at such an intermediate stage, the geometry of the molecule prevents parallel orientation of the axes of the orbitals on C_1 and C_2, diminishing



their overlap and hence the stabilization which the transition state may derive from their bonding. Expressed somewhat differently, the forming π bond is twisted, so that the relief of strain in the transition state is less than in a more mobile system of comparable initial strain. There seems to be little basis in experiment for evaluating the magnitude of this effect, but experiments are currently under way in these laboratories to determine its importance in free-radical cleavage reactions. It might be noted that, in the rearrangements of the bornyl radical studied by Berson, cleavage to the primary radical, which might be geometrically preferred, does compete with cleavage to the tertiary radical, although the latter predominates.[34]



Several other factors, with a potential influence on the rate, make the above interpretation less certain. The two-carbon bridge of the bicyclohexyl system possesses substantial angle strain, with a bond angle of 100°.[22] It is expected that a carbon atom in a strained ring would use increased s character in its other bonds, which should lead to stabilization of a carbon–metal bond. To the extent that equilibrium data of Applequist[35] and Dessy[36] may be taken to reflect the stability of polar carbon–metal bonds, this prediction is verified. Stabilization of the starting state by such an effect should produce a decrease in rate, but it is premature to attempt an evaluation of the magnitude of this effect.

An additional factor may be important with the methyl-substituted systems. The "*gem*-dimethyl effect" [37] is expected to stabilize the strained-ring system relative to the transition state for its cleavage. This effect may account for much of the difference in rate between the methylated and unmethylated bicyclo[2.1.1]hexylmagnesium chlorides. In addition, it is possible that the attachment of an alkyl group (the two-carbon bridge) to the 3 position on the cyclobutane ring may have a sizable rate effect. No information is available now to evaluate alkyl group effects at that position, but a 2-alkyl group slows the rate of ring cleavage of cyclobutylmethylmagnesium chloride by a factor of about 0.3,[38] slightly more than the statistical factor of 0.5 (since ring cleavage occurs mainly to the side away from the methyl group).

Another factor, which is particularly important with the dimethylbicyclohexylmagnesium bromide is the large amount of magnesium halide produced by disproportionation in the Grignard preparation. It had

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[34] J. A. Berson, C. J. Olsen, and J. S. Walia, *J. Amer. Chem. Soc.*, **84**, 3337 (1962).

[35] D. E. Applequist and D. F. O'Brien, *ibid.*, **85**, 743 (1963).

[36] R. E. Dessy, W. Kitching, T. Psarras, R. Salinger, A. Chen, and T. Chivers, *ibid.*, **88**, 460 (1966).

[37] See T. C. Bruice and W. C. Bradbury, *ibid.*, **90**, 3808 (1968); F. G. Bordwell, C. E. Osborne, and R. D. Chapman, *ibid.*, **81**, 2698 (1959), and references therein. Heats of formation calculated by Allinger and coworkers[26] for methyl-substituted cycloalkanes predict that alkyl group substitution on a cyclobutane ring produces a substantially greater degree of stabilization than the corresponding substitution in a cyclopentane or cyclohexane.

[38] E. A. Hill and R. A. Doughty, unpublished data.

been found previously that addition of magnesium chloride to cyclobutylmethylmagnesium chloride decreased the rate of ring cleavage. In an attempt to remove the excess of magnesium bromide, one preparation of the bromo Grignard was treated with a slight excess of dioxane. However, the net effect appeared to be to decrease the Grignard concentration (0.05 to 0.02 *M*), while still leaving an excess of bromide in solution (0.05 *M*). The rate of ring cleavage *decreased* by a factor of about 5. A curious difference may be noted in the bicyclic system, in that the bromo Grignard reacts more rapidly than the chloro Grignard while the opposite is true with both cyclobutylmethyl and α-cyclobutylethyl reagents. With the unsubstituted bicyclohexyl Grignard, formation of the Grignard reagent appeared to occur very cleanly, and so no complications are present owing to an excess of magnesium chloride.

Experimental Section

Infrared spectra were obtained on Beckman IR-5 and IR-8 spectrometers and on a Unicam SP500. Nuclear Magnetic resonance spectra were obtained with Varian A-60 and HA-100 spectrometers at ambient temperature with tetramethylsilane as internal standard. (Nmr spectra of Grignard solutions were compared with the high field solvent signal, which, in turn, was referenced to tetramethylsilane in several Grignard solutions.) Microanalyses were performed at the University of Minnesota by Mrs. O. Hamerston and T. S. Prokopov. Boiling points are uncorrected; melting points are calibrated. Gas chromatograms were run on an Aerograph Model A-90-P gas chromatograph, using the following columns: A, 17% Apiezon J on Chromosorb P, 10 ft × $^1/_2$ in.; B, 25% Carbowax 400 on Chromosorb P, 10 ft × $^1/_4$ in.; C, 25% Ucon Polar on Chromosorb P, 10 ft × $^1/_4$ in. and 10 ft × $^1/_2$ in.; D, 20% Carbowax 20M on Chromosorb P, 10 ft × $^1/_4$ in.; E, 25% tricresyl phosphate on Chromosorb P, 10 ft × $^1/_4$ in.; F, 20% Dow Hi-Vac grease on Chromosorb W, 10 ft × $^1/_4$ in.

β-5,5-Dimethylbicyclo[2.1.1]hexan-2-ol (1) was prepared by lithium aluminum hydride reduction of the corresponding ketone as described by Meinwald and Gassman:[5] bp 91–92° (25 mm); n^{24}_{D} 1.4758 [lit.[5] bp 90–92° (24 mm); n^{23}_{D} 1.4757]; ir (neat) 3370 (OH), 1013 cm^{-1} (CO); nmr (CCl_4) δ 0.73 (*d*, 1, *J* = 8 Hz, *endo* C_6H), 1.07 (s, 3, *endo* C_5CH_3), 1.29 (s, 3, *exo* C_5CH_3), 1.5–2.3 (m, 5), 3.30 (s, broad, 1, OH), 4.33 (q, broad, 1, *J* = 7.5, 3.5 Hz, CHOH). Its benzoate was obtained as an oil: ir (neat) 1715 cm^{-1} (C=O); nmr (CCl_4) δ 0.84 (d, 1, *J* = 8 Hz), 1.11 (s, 3, CH_3), 1.28 (s, 3, CH_3), 1.5–2.5 (m, 5), 5.34 (m, 1, CHOH), 7.44 (m, 3, aryl), 8.07 (m, 2, aryl).

Reduction of 5,5-dimethylbicyclo[2.1.1]hexan-2-one with sodium and alcohol was carried out as described previously.[5] The nmr spectrum of the mixture so obtained showed methyl bands of the β isomer at δ 1.08 and 1.28, as well as new stronger methyl groups at 0.75 and 1.25 due to the α epimer. Only one complex multiplet was observed in the CHOH region at δ 4.32.

Reaction of 5,5-Dimethylbicyclo[2.1.1]hexan-2-ol with Thionyl Chloride.—Over a period of 0.5 hr, 9.95 g (0.083 mol) of thionyl chloride was added to a stirred mixture of 10.5 g (0.083 mol) of 5,5-dimethylbicyclo[2.1.1]hexan-2-ol and 6.6 g (0.083 mol) of dry pyridine cooled to 0°. The reaction mixture was stirred for 2 hr at 90–100°. Salt that crystallized on cooling was removed by filtration and washed with ether. The organic phase was washed with dilute hydrochloric acid and sodium bicarbonate solutions and water, dried ($MgSO_4$), and distilled to yield crude chloride. After passage in pentane solution over a column of alumina to remove traces of alcohol, 6.6 g (55%) of chloride product was obtained by distillation: bp 72–73° (30 mm); n^{24}_{D} 1.4760; ir (neat) 2970, 1468, 1391 and 1373 [$C(CH_3)_2$], 1290, 1265, 915, 720 cm^{-1}.

Anal. Calcd for $C_8H_{13}Cl$: C, 66.43; H, 9.05. Found: C, 66.72; H, 9.31.

The nmr spectrum suggested a mixture, and gas chromatography (column C) showed three partially overlapping peaks with relative areas 5, 42, and 53% in order of increasing retention time. The three peaks were partially separated on a preparative scale (154°), and components in the fractions were identified by nmr absorptions. Nmr spectra of the chromatographic fractions indicated the following compositions: (1) 90% 4-chloromethyl-3,3-dimethylcyclopentene (**5a**) and 10% 2-chloro-3,3-dimethylbicyclo[2.1.1]hexane (**4a**); (2) 5% **5a** and 95% **4a**; (3) 10% **4a**, 22% α-2-chloro-5,5-dimethylbicyclo[2.1.1]hexane (**2a**), and 68% β-2-chloro-5,5-dimethylbicyclo[2.1.1]hexane (**3a**). Prominent nmr features are summarized in Table I.

An attempted rechromatogram of the third fraction brought about an increase in the percentage of **4a**, apparently primarily at the expense of **3a**. Other evidence of instability of the products to chromatographic conditions was to be found in minor, ill-formed early peaks in the repeated chromatograms.

The nmr of the total product mixture contained an additional weak resonance at δ 5.59, tentatively assigned to **6a**. The product distribution as derived from the nmr spectrum is listed in Table I.

Reaction of 5,5-Dimethylbicyclo[2.1.1]hexan-2-ol with Triphenylphosphine and Bromine.—Over a period of 25 min, 8.8 g (0.055 mol) of bromine was added to a solution of 6.9 g (0.055 mol) of 5,5-dimethylbicyclo[2.1.1]hexan-2-ol and 15.45 g (0.059 mol) of triphenylphosphine in 40 ml of dry dimethylformamide at 50–55°. After stirring at 55° for 2 hr, the mixture was distilled at 0.8 mm, up to a temperature of 85°. The distillate was diluted with 50 ml of saturated aqueous sodium chloride and extracted with three 25-ml portions of 30–60° petroleum ether. The solution was dried (Na_2SO_4), passed through a short column of alumina, and distilled, yielding 5.85 g (57%) of bromide: bp 68–70° (9 mm); n^{21}_{D} 1.5011; ir (neat) 2970, 1462, 1390 and 1370 [$C(CH_3)_2$], 1230, 901, 685 cm^{-1}.

Anal. Calcd for $C_8H_{13}Br$: C, 50.81; H, 6.93. Found: C, 50.55; H, 6.81.

The nmr spectrum indicated a mixture, and gas chromatography (column D, 140°) showed three overlapping peaks, the last of which had a pronounced shoulder. Relative areas of four components were estimated as 14, 34, 44, and 8%, in order of increasing retention time. A preparative partial separation was carried out, and the three fractions collected were characterized by their nmr spectra. The following compositions were indicated: (1) 50% 4-bromomethyl-3,3-dimethylcyclopentene (**5b**) and 50% 2-bromo-3,3-dimethylbicyclo[2.1.1]hexane (**4b**); (2) 17% **5b**, 45% **4b**, 28% α-2-bromo-5,5-dimethylbicyclo[2.1.1]hexane (**2b**), and 10% β-2-bromo-5,5-dimethylbicyclo[2.1.1]hexane (**3b**); (3) 4% **5b**, 20% **4b**, 55% **2b**, and 21% **3b**. Rechromatography of fraction 1 yielded **5b** in about 90% purity. Prominent nmr features are summarized in Table I. An additional nmr absorption at δ 5.71 in the product mixture was tentatively assigned to the olefinic hydrogens of **6b**.

The integral of the original chloride mixture in the vinyl, CHX, and methyl regions was consistent with a distribution of products **2b**:**3b**:**4b**:**5b**:**6b** of 43:7.5:33:15:1.5. The estimate is approximate, since the result is sensitive to small errors in some of the integrals.

Reaction of β-5,5-Dimethylbicyclo[2.1.1]hexane-2-carboxylic Acid with Bromine and Mercuric Oxide.—Over a period of 25 min, 8.65 g (0.054 mol) of bromine was added to a stirred suspension of 8.30 g (0.054 mol) of β-5,5-dimethylbicyclo[2.1.1]-hexane-2-carboxylic acid and 6.30 g (0.028 mol) of red mercuric oxide in 50 ml of carbon tetrachloride. The reaction was sightly exothermic. After the reaction mixture was heated at 80° for 40 min, cooled, and filtered, the solvent was distilled. The residue was dissolved in ether and extracted with dilute base. Upon acidification of the basic solution, a 48% recovery of starting acid was realized. The ether layer was dried and fractionated, yielding 0.55 g (5%), bp 67–68° (9 mm). The infrared and nmr spectra were similar to those of the product from the previous preparation except that the absorptions ascribed to 4-bromomethyl-3,3-dimethylcyclopentene (**5b**) were missing. From the integration, the mixture appeared to have the composition **2b**:**4b**:**6b** of 38:56:6.

The residue from distillation of the bromide had a strong infrared carbonyl band at 1730 cm^{-1} (neat) suggesting that ester formation had been the predominant reaction path. In an attempted decarboxylation of the carboxylic acid with lead tetraacetate only recovered acid (84%) was obtained.

5,5-Dimethylbicyclo[2.1.1]hexane.—A solution of 5,5-dimethylbicyclo[2.1.1]hexan-2-one (2.0 g, 0.016 mol), 85% potassium hydroxide (2.0 g), and 95% hydrazine (2.5 g, 0.078 mol) in 15 ml of triethylene glycol was stirred in an open flask at 150–160° for 1 hr and then refluxed at 190–200° for 3 hr. Distillation yielded a clear liquid (1.2 g, 68%), which was taken up in pentane, washed with water, dried, and separated by gas chromatography (column A). It contained three components in relative amounts of 0.5, 90.5, and 9%. The first of these appeared from its infrared spectrum to be saturated, but was not characterized further owing to the small amount. The second component was 5,5-dimethylbicyclo[2.1.1]hexane: $n^{25}\text{D}$ 1.4451; ir (neat) 2960 (CH), 1479 (w), 1479 (s), 1460 (s), 1387 and 1370 [s, $C(CH_3)_2$], 1300 (m), 1274 (s), 1259 (s), 1194 (m), 1185 (m), 1161 (m), 1115 (m), 1083 (m), 920 (m), 821 cm^{-1} (m); nmr (neat), methyl singlets at δ 0.75 and 1.25, an "A_2B_2" pattern centered at 1.61 (ethylene bridge), broad singlet at 2.08 (bridgehead hydrogens), additional absorption which is partially covered, apparently centered ~0.8 and 2.0 accounting for the remaining two hydrogens.

Anal. Calcd for C_8H_{14}: C, 87.20; H, 12.80. Found: C, 87.23; H, 13.03.

The third fraction was composed of two unsaturated materials present in similar quantities (as shown by further chromatography on column B): ir (neat) 3075 (=CH), 2960, 2870, 1770 (w, $=CH_2$ overtones), 1642 (C=C), 1450, 1380 (CH_3), 986, 958, 888, cm^{-1}; nmr (CCl_4) δ 1.02 (t, J = 7.5 Hz, CH_3), 1.03 (broad singlet), 1.73 (broad singlet), 1.9 (multiplet), 4.69 (broad singlet, $=CH_2$), 5.1–6.4 (multiplet, =CH). These components were not identified further, but are believed to have arisen by pyrolytic cleavage of some component or intermediate in the reaction.

2-Chlorobicyclo[2.1.1]hexane.—Over a period of 30 min, 12.1 g (0.102 mol) of thionyl chloride was added to a solution of 10.0 g (0.102 mol) of bicyclo[2.1.1]hexan-2-ol and 8.0 g (0.102 mol) of dry pyridine maintained at 0°. The reaction mixture was then stirred for 2 hr at 90–100° and overnight at 25°. Pentane (20 ml) was added and the organic solution was filtered from the solid pyridinium salts. The filtrate was washed with dilute hydrochloric acid and saturated sodium bicarbonate, dried ($MgSO_4$), and distilled through a 6-in glass helix packed column, bp 37° (25 mm) [lit.[19] 134–136° (760 mm)]. A trace of alcohol was removed by passage through alumina. The product was greater than 99% pure by gas chromatography: ir (neat) 2900, 1445, 1300, 1280, 1260, 1205, 1147, 1003, 925, 913, 850, 815, and 700 cm^{-1}.

Grignard Reagent from "2-Chlorodimethylbicyclo[2.1.1]hexane."—Sublimed magnesium (0.15 g, 6.14 mg-atoms) was placed in a throughly dried flask with a sealed condenser and flame dried under nitrogen. To the flask was added 0.75 g (5.19 mmol) of chloride mixture in 3.5 ml of dried ether (distilled from lithium aluminum hydride in a stream of prepurified nitrogen). A very small crystal of iodine and 0.01 g of methyl iodine were required to initiate the Grignard reagent formation. After a reflux time of 45 min, a sample was transferred to an nmr tube and sealed. The solvent from the remainder of the solution was pumped under high vacuum to a cold trap (<10 μ for 45 min). The residual Grignard reagent wss dissolved in new dry ether (24 ml), and the resulting clear solution was transferred by syringe under a stream of nitrogen to a set of 36 ampoules, which were sealed under less than an atmosphere of nitrogen for use in kinetics studies. The Grignard concentration was 0.16 M (75%) by acid titration. Several similar preparations of Grignard reagent in ether or tetrahydrofuran were made which varied somewhat in final concentration, yield of reagent (60–80% by acid titration and chromatographic analysis of hydrocarbons), and the efforts needed to initiate reagent formation.

The hydrocarbons removed with the solvent and the hydrocarbons produced by hydrolysis of the Grignard reagent were separatedly analyzed by gas chromatography (column C, 78°, 200 cc/min). Results are presented in Table IV. The components shown were collected and identified as follows, in order of increasing retention time.

(1) 3,3,4-Trimethylcyclopentene (**14**) was obtained with the following spectra: ir (CS_2) 3060 (=CH), 2900, 1650 and 1612 (C=C), 1390, 1377, 1365, 1211, 1100, 1072, 947, 902, 754, 751 (vs, =CH) cm^{-1}; nmr (15% in CS_2) δ 0.81 (s, 3, CH_3), 0.95 (d, 3, J = 7 Hz, CH_3), 1.03 (s, 3, CH_3), 1.7–2.5 (complex multiplet, 3), 5.48 (broadened singlet, 2, =CH); mass spectrum (7 eV) m/e (rel intensity), 110 (7), 96 (8), 95 (100), 93 (6), 79 (5), 77 (7), 66 (26), 55 (17), 53 (9), 44 (6), 41 (16), 39 (11). The spectra require a trimethylcyclopentene with a nonequivalent *gem*-dimethyl group. The 3,3,4 isomer is most consistent with the positions of aliphatic proton resonances and is the only isomer derivable in straightforward fashion from the bicyclic system.

(2) 2,2-Dimethylbicyclo[2.1.1]hexane (**13**) was obtained: ir (neat and gas, 20 mm) 2960 (vs), 1460 (s), 1390 and 1373 [$C(CH_3)_2$], 1306, 1238, 1200, 1068, 938, 848, 800 cm^{-1}; nmr (CCl_4) δ 1.08 [s, 6, $C(CH_3)_2$], 1.37 (m, 6), 2.19 (AB pattern, 2, J = 7 Hz, $\Delta\nu$ = 0.37 ppm, with additional coupling). The bicyclic skeleton is required by the lack of olefinic absorption in the nmr and ir. The single unsplit methyl peak and the coupled bridgehead protons at δ 2.19 allow only the 2,2-dimethyl isomer.

TABLE IV

HYDROCARBONS FROM DIMETHYLBICYCLO[2.1.1]HEXYL-2-MAGNESIUM HALIDE PREPARATIONS

	% of C_8 hydrocarbons			
Component[a]	Solvent from chloride[b]	Grignard from chloride	Solvent from bromide	Grignard from bromide
14	3	8	9	23
13	13	26	29	30
12	14	58	24	47
15	24	5	8	
16	37	3	30	

[a] In order of retention time, 25% Ucon Polar on Chromosorb P.
[b] Two minor components between **15 and 16** were present in about 3% each, but were not identified owing to small quantities.

(3) 5,5-Dimethylbicyclo[2.1.1]hexane (**12**) was obtained with ir and nmr identical with those of independently synthesized material.

(4) 4-Isopropylcyclopentene (**15**) was obtained: ir (neat and gas) 3060 (=CH), 2960, 1620 (C=C), 1459, 1391 and 1373 [$C(CH_3)_2$], 1300, 1260, 1180, 937, 686 cm^{-1} (*cis* CH=CH); nmr (CCl_4) δ 0.89 (unsymmetrical doublet, 6, J = 6 Hz, CH_3), 1.4–2.5 (m, 6), 5.60 (broadened singlet, 2, =CH). The infrared spectrum is in agreement with a published spectrum[39] and, in addition, the 4-isopropyl isomer is preferred by the similarity of the aliphatic methylene resonance at about δ 2.1 to that of 4-methylcyclopentene. Two minor unidentified components followed in the hydrocarbon pumped from the chloro-Grignard preparation.

(5) 4-Isopropenylcyclopentene (**16**) was obtained: ir (CS_2) 3060 (=CH), 2940, 1643 and 1617 (C=C), 1378, 890 ($=CH_2$), 675 cm^{-1} (*cis* CH=CH); nmr (CS_2) δ 1.69 (s, 3 $=CCH_3$), 2.0–3.0 (m, 5), 4.60 and 4.68 (2, $=CH_2$), 5.63 (s, 2, CH=CH). The isopropenyl group is indicated by an unsymmetrically disubstituted double bond and unsplit allylic methyl group in the ir and nmr spectra. Orientation relative to the double bond in the cyclopentene ring is indicated by the absence of methylene absorption above δ 2.0.

Sealed ampoules of the Grignard solution were heated in an oil bath and analyzed in the following manner. The ampoules were broken open under a nitrogen atmosphere, the solvent and volatile materials were pumped to a cold trap (30 min at <5 μ), nitrogen was readmitted to the system, and the residual Grignard reagent was hydrolyzed with ice-cold 3 M H_2SO_4 after addition of ~0.5 ml of ether. The hydrocarbons in the ether solution were analyzed gas chromatographically. It was possible from such analyses to determine separate rate constants for disappearance of the bicyclic components **12** and **13**.

Grignard Reagent from "2-Bromodimethylbicyclo[2.1.1]hexane" Mixture.—A reaction flask containing 0.316 g (13 mg-atoms) of sublimed magnesium was flame dried under high vacuum, and about 5 ml of ether (over lithium aluminum hydride) was distilled into the flask on a vacuum line. Under a stream of dry nitrogen, 1.5 g (7.93 mmol) of bromide mixture was added by syringe. The flask was warmed to initiate reaction and refluxed for 50 min under nitrogen. After removal of an nmr sample, solvent and volatiles were pumped to a cold trap under vacuum (<5 μ). Fresh ether (40 ml) was distilled into the flask, and the resulting clear solution was transferred by syringe to ampoules and sealed under nitrogen. Titration for base and bromide ion gave concentrations of 0.03 and 0.18 M, respectively. Analysis of the Grignard solutions was carried out in a manner similar to that for the chloride. Compositions of the hydrocarbon mixtures are shown in Table IV. In another preparation of Grignard reagent, base concentration was 0.05 M and bromide concentration 0.2 M. An amount of dioxane equivalent to the bromide was added, the sample was sealed, shaken for 3 days, and centrifuged, and the clear supernatant solution was withdrawn. Base and bromide concentrations were 0.02 and 0.05 M, respectively.

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(39) W. Hückel and R. Bross, *Ann.*, **664**, 1 (1963).

Grignard Reagent from 2-Chlorobicyclo[2.1.1]hexane.—Sublimed magnesium (0.156 g, 6.5 mg-atoms) was placed in a dried flask with a sealed condenser and flamed out under nitrogen. To this was added 0.69 g (5.9 mmol) of 2-chlorobicyclo[2.1.1]-hexane in 4 ml of ether (distilled from lithium aluminum hydride). About 0.01 g of methyl iodide was used to initiate formation of the Grignard, and reflux was continued for 3 hr. Most of the reagent was transferred by syringe to two ampoules and an nmr tube and sealed under nitrogen, and the remaining reagent was hydrolyzed with water. Gas chromatography (column A) showed one hydrocarbon component comprising at least 99.5% of the total, which was isolated by preparative chromatography: ir (gas) 2930 (vs), 1460, 1292, 1203, 1123, 1078, 1018, 898, 829 cm^{-1}; nmr identical with reported spectra of bicyclo[2.1.1]-hexane.[9,40]

The sealed tubes were heated for 18 hr at 90°, opened, hydrolyzed, and analyzed in a similar fashion. The major component (~95%) was isolated by preparative gas chromatography: ir identical with the published spectrum[41] of 4-methylcyclopentene; nmr (CCl$_4$) δ 1.10 (d, 3, CH$_3$), 1.95 (m, 2) 2.45 (m, 3), 5.58 (s, 2, olefinic).

α-Cyclobutylethyl chloride was prepared by adding α-cyclobutylethanol (5.0 g, 0.050 mol) to a solution of preformed triphenylphosphine dichloride[42] (0.055 mol) in dry dimethylformamide (50 ml) at 35–40°. Work-up as in previous halide preparations gave a 25% yield of chloride: bp 127–128°; n^{23}D 1.4408 (lit.[3] bp 122–127.5°); ir (neat) 2970 (vs), 2860 (m), 1450 (s), 1380 (m), 1252 (s,) 1050 (m), 670 cm^{-1}; nmr (neat) δ 1.34 (d, 3, J = 6.6 Hz), 3.87 (m, 1, coupling constants of 6.6 Hz to three hydrogens and 7.6 Hz to a lone hydrogen, CHCl). A small amount (*ca.* 11%) of isomeric impurity was probably responsible for a broad absorption at δ 4.24. Gas chromatography showed two components (about 12%) in addition to the major product. In a previous sysnthesis using thionyl chloride, about 56% of the product consisted of rearranged isomers with a cyclopentane ring.[3]

α-Cyclobutylethyl Bromide.—Bromine (12.95 g, 0.08 mol) was added to a stirred solution of α-cyclobutylethanol (8.0 g, 0.080 mol) and triphenylphosphine (22.0 g, 0.084 mol) in dry dimethylformamide (50 ml) at 55°. Work-up as in the case of α-cyclobutylethyl chloride gave the product bromide (5.2 g, 40%): bp 62–64° (30 mm); n^{27}D 1.4730; ir (neat) 1380 (s), 1240 (s), 1181 (s), 1161 (s), 1040 (m) cm^{-1}; nmr (neat) δ 1.54 (d, 3, J = 6.7 Hz), 1.84 (m, 7), 4.00 (doublet of quartets, 1, J = 8.0, 6.7 Hz, CHBr). In addition, three broad resonances at *ca.* δ 3.50, 3.65, and 4.40 from isomeric impurities amounted to about 0.1 proton. Gas chromatography showed three minor components in addition to the major product.

Anal. Calcd for C$_6$H$_{11}$Br: C, 44.19; H, 6.80. Found: C, 44.17; H, 6.94.

Grignard reagents from α-cyclobutylethyl bromide and chloride were prepared in ether in a manner similar to that described for previous Grignard preparations. Immediate hydrolysis of the Grignard reagent from the chloride produced a mixture of hydrocarbons consisting of 68% ethylcyclobutane, 19% 2-hexene (almost exclusively *cis*), and 13% methylcyclopentane. After the mixture was heated, hydrolysis of the Grignard reagent yielded hydrocarbon mixtures with an equal mixture of *cis*- and *trans*-2-hexenes increasing at the expense of the ethylcyclobutane. The methylcyclopentane remained as a constant fraction of the total. Similar results were obtained from the bromide.

Registry No.—**2a,** 20826-69-1; **2b,** 20826-70-4; **3a,** 20826-71-5; **3b,** 20826-72-6; **4a,** 20826-95-3; **4b,** 20826-96-4; **5a,** 20826-97-5; **5b,** 20826-98-6; **13,** 20858-75-7; **14,** 20826-99-7; **16,** 20827-00-3; **19** (X = Cl), 20827-01-4; **19** (X = Br), 20827-02-5; **20** (X = Cl), 20858-76-8; **20** (X = Br), 20827-03-6; **22** (X = Cl), 20827-04-7; cyclobutylethyl-2-magnesium chloride, 20858-77-9; cyclobutylethyl-2-magnesium bromide, 20826-73-7; 5,5-dimethylbicyclo[2.1.1]hexane, 20826-74-8; α-cyclobutylethyl bromide, 20826-75-9.

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[40] R. Srinivasan, *J. Amer. Chem. Soc.*, **83**, 4923 (1961).

[41] K. Kochloefl, V. Bazant, and F. Šorm, *Collect. Czech. Chem. Commun.*, **22**, 1895 (1957).

[42] D. G. Coe, R. S. Landauer, and H. W. Rydon, *J. Chem. Soc.*, 2281 (1954).

The Stereochemistry of Methylation of Lithium Enolates of 2-Methyl-4-*t*-butylcyclohexanone[1a]

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The reaction of the lithium enolate of 4-*t*-butylcyclohexanone and the three lithium enolates derived from *cis*- and *trans*-2-methyl-4-*t*-butylcyclohexanone with methyl iodide or methyl-d_3 iodide in 1,2-dimethoxyethane has been investigated. In all cases, mixtures of stereoisomeric methylation products were obtained. The results have been interpreted by considering that the geometry of the transition state for the alkylation reaction closely resembles the reactants.

Alkylation reactions of a number of systems involving trapping of specific lithium enolates of unsymmetrical ketones have demonstrated that these species, in contrast to other alkali metal enolates, undergo slow proton-transfer reactions with derived alkylation products.[2] This unique property makes lithium enolates particularly valuable in studies on the stereochemistry of alkylation of simple enolate systems, since kinetically formed alkylation products having epimerizable centers α to the carbonyl group should be isolable under appropriate conditions.

We have studied the stereochemistry of methylation of the lithium enolate **2** derived from 4-*t*-butycyclohexanone (**1**). In addition, we have determined the stereochemistry of methylation of the enolates **3**, **4**, and **5**, derived from *cis*- and *trans*-2-methyl-4-*t*-butylcyclohexanone, **6** and **7**, respectively, by treating enolate mixtures composed largely of each of these species with methyl iodide or methyl-d_3 iodide in 1,2-dimethoxyethane (DME). Enolate **2** was formed by titration of a solution of trityl lithium in DME at room temperature with **1** until the equivalence point was reached, and then excess methyl iodide was added rapidly. Vpc

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[2] (a) G. Stork, P. Rosen, and N. L. Goldman, *J. Amer. Chem. Soc.*, **83**, 2965 (1961); G. Stork, P. Rosen, N. L. Goldman, R. V. Coombs, and J. Tsuji, *ibid.*, **87**, 275 (1965); (b) H. O. House and B. M. Trost, *J. Org. Chem.*, **30**, 2502 (1965); (c) D. Caine, *ibid.*, **29**, 1868 (1964); (d) D. Caine B. J. L. Huff, *Tetrahedron Lett.*, 4695 (1966).