not nearly so critical for formation of the amine complex as for that of the aromatic hydrocarbon. It is conceivable that the amino group of *p*-toluidine rather than the entire π-electron cloud of the aromatic nucleus may serve effectively as a center of donor activity. A much less intimate arrangement of the complex components may, therefore, be required than when hexamethylbenzene is the donor.

It has been suggested[26,33] that 2:1 and 1:2, as well as 1:1 complexes, may form to some extent in solutions of aromatic amines and polynitrobenzenes.[34] Although this matter was not thoroughly investigated in the present series of measurements on the *p*-toluidine complexes, there was no positive evidence for the formation of other than 1:1 type aggregates. In the spectrophotometric studies of both the bipicryl and 1,3,5-trinitrobenzene complexes the *p*-toluidine concentrations were varied from 0.1–0.8 *M* (the acceptor concentrations were of the order of 10^{-3} *M*). When the resultant data were interpreted graphically according to equation 1, very satisfactory linear plots were obtained.

It is interesting to observe that the low donor strength of hexaethylbenzene as compared to that of hexamethylbenzene is again manifested when 1,3,5-trinitrobenzene is the donor. The spectrum of the nitro compound in chloroform is so little enhanced by hexaethylbenzene that it is questionable whether *any* significant donor–acceptor interactions occur in solutions of the two substances.

Acknowledgment.—The authors are indebted to the National Science Foundation for a grant in support of this research.

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[33] S. D. Ross and M. Labes, THIS JOURNAL, **79**, 76 (1957).

[34] See, however, R. Foster and D. Ll. Hammick, *J. Chem. Soc.*, 2685 (1954).

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

Kinetic Isotope Effects in the Acetolyses of Deuterated Cyclopentyl Tosylates[1,2]

BY A. STREITWIESER, JR., R. H. JAGOW, R. C. FAHEY AND S. SUZUKI

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The acetolysis rates of the tosylates of cyclopentanol, cyclopentanol-1-*d*,*cis*- and *trans*-cyclopentanol-2-*d* and cyclopentanol-2,2,5,5-d_4 are described. All of the deuterated compounds solvolyze significantly more slowly than does cyclopentyl tosylate itself. An analysis of the α-deuterium case based on statistical mechanics indicates that the isotope effect is due predominantly to the change of a tetrahedral C–H bending vibration to an "out-of-plane" deformation in the transition state. The β-deuterium isotope effect is ascribed to the change of a tetrahedral C–H bending mode to a vibration in the transition state along a molecular orbital resulting from increased hyperconjugation in the electron deficient system. An argument is advanced for discounting any important specific solvation of the β-hydrogens in the solvolyzing molecule.

The isotope effect in solvolytic reactions derived from the substitution of β-hydrogens by deuterium in a substrate molecule was first exploited by Shiner[3] and by Lewis[4] and was demonstrated by them to be a valuable new tool in understanding such reactions.[5] In the present work, we wished to determine the isotope effect derived from an α-deuterium atom and the effect of stereochemical configuration of a β-deuterium, independent of conformational differences. For these purposes, we prepared the tosylates of cyclopentanol-1-*d* (I), *cis*- and *trans*-cyclopentanol-2-*d* (*cis*-II and *trans*-II, respectively) and of cyclopentanol-2,2,5,5-d_4 (III) and determined the solvolysis rates in acetic acid.

Preparation of Deuterated Cyclopentanols.—The opening of epoxide rings with lithium aluminum hydride has been amply demonstrated to be a completely *trans* opening.[6] Consequently, the structure *trans*-cyclopentanol-2-*d* was confidently assigned to the alcohol obtained in good yield from the reaction of cyclopentene oxide with lithium aluminum deuteride. The density of the alcohol indicated 1.0 deuterium/molecule. This material was converted in the usual way to the tosylate (*trans*-II-OTs) which was treated with tetramethylammonium acetate in pure, dry acetone solution. The product, obtained in 76% yield, was assigned the structure of *cis*-cyclopentyl-2-*d* acetate (*cis*-II-OAc) since the reaction conditions were chosen to favor an S$_N$2 reaction. Hydrolysis gave *cis*-II. The infrared spectra in the 4–11 μ region of *cis*- and *trans*-II and of the corresponding acetates are compared in Table I. The spectra show a number of differences, particularly in the 9–11 μ region. The *cis* and *trans* compounds are not only clearly different and distinguishable, but are not mutually contaminated to any observable extent.

Cyclopentanone-2,2,5,5-d_4 (IV-d_4) was prepared by repeated exchanges of cyclopentanone (IV) with weakly basic D_2O. The infrared spectra of the two ketones showed interesting features. In IV-d_4, the C–D stretching doublet at 2135 and 2230 cm.$^{-1}$ was much less intense than the C–H doublet in IV at 2880 and 2965 cm.$^{-1}$ which is little changed in IV-d_4. Clearly, the intensities of the α-C–H stretching modes are much less than those of the β-C–H, in agreement with Francis[7] that a carbonyl

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[1] This work was communicated in part by A. Streitwieser, Jr., R. H. Jagow and S. Suzuki, THIS JOURNAL, **77**, 6713 (1955), and by A. Streitwieser, Jr., and R. C. Fahey, *Chemistry & Industry*, 1417 (1957).

[2] This research was supported in part by a grant from the Petroleum Research Fund of the American Chemical Society.

[3] (a) V. J. Shiner, Jr., THIS JOURNAL, **75**, 2925 (1953); (b) **76**, 1603 (1954).

[4] E. S. Lewis and C. E. Boozer, *ibid.*, **76**, 791 (1954).

[5] For reviews see (a) K. B. Wiberg, *Chem. Revs.*, **55**, 713 (1955), and (b) A. Streitwieser, Jr., *ibid.*, **56**, 571 (1956).

[6] For example, see P. A. Plattner, H. Heuser and M. Feurer, *Helv. chim. Acta*, **32**, 587 (1949); L. W. Trevoy and W. G. Brown, THIS JOURNAL, **71**, 1675 (1949); W. G. Dauben, R. C. Tweit and R. L. McLean, *ibid.*, **77**, 48 (1955).

[7] S. A. Francis, *J. Chem. Phys.*, **19**, 942 (1951).

TABLE I

INFRARED SPECTRA

Cyclopentanol	I	*trans*-II	*cis*-II	III	Cyclopentyl acetate	*trans*-II acetate	*cis*-II acetate
Wave length of absorption bands in microns[a]							
3.0b	3.0b	3.0b	3.0b	3.0b	3.37	3.37	3.37
3.39	3.37	3.39	3.39	3.39	3.50	3.50	3.50
3.48sh	3.48	3.49	3.49	3.49		4.58w	4.54w
	4.63sh	4.62	4.56	4.49	5.77	5.77	5.77
	4.69			4.72	6.945	6.945	6.945
6.87	6.88b	6.87b	6.88b	6.9b	7.285	7.285	7.285
6.96					7.385	7.36sh	7.36sh
7.46	7.58	7.47	7.48	7.51	8.00	8.0	8.0
7.66		7.66	7.69	7.72	8.57	8.61	8.63
8.55	8.38	8.63	8.61	8.85		9.10	8.91
9.35	8.97	9.11	8.98	9.3b	9.5sh	9.55sh	9.55
	9.12	9.47	9.30		9.795	9.8b	9.78
9.67	9.64	9.69	9.64		10.28	10.30	10.43
						10.94	10.62
10.07	9.86	10.10	9.92	9.98	11.12	11.12	11.12
10.72	10.54		10.56	10.24	11.93w	11.71	12.02
	10.87						
11.19	11.29w	11.21	11.23	11.37			
11.96		11.68	11.91				
	12.4b	12.57	12.56	12.45			

[a] Spectra were taken on liquid films with a Baird AB2 infrared spectrometer using sodium chloride optics; b means broad; sh indicates shoulder and w means weak.

group greatly decreases the intensities of α-C-H stretching bands. A doublet at 1457 and 1474 cm.$^{-1}$ in IV is unchanged in intensity or position in IV-d_4 and is assigned to the β-methylene deformation. In hydrocarbons, a methylene deformation usually occurs at about 1465 cm.$^{-1}$.[8] A more intense band at 1409 cm.$^{-1}$ in IV has vanished in IV-d_4 and is assigned to α-methylene deformation. Francis[7] and Jones, *et al.*,[9] assign 1410–1415 cm.$^{-1}$ to a methylene group alpha to a ketonic carbonyl group. The band near 1360 cm.$^{-1}$, attributed by both sets of authors to the same structural feature, is not present in cyclopentanone.

Reduction of IV-d_4 with lithium aluminum hydride at −80° gave a good yield of III having 4.1 ± 0.1 deuterium atoms per molecule (by density). Some comment on this reduction is necessitated by the report of Brown[10] that the reaction of cyclopentanone with lithium aluminum hydride gives initially an insoluble complex and that refluxing in ether[11] or preferably tetrahydrofuran[10] is required to give a good yield. We find that the reduction proceeds smoothly at Dry Ice temperature with no evidence of complex formation and with no apparent loss of deuterium. Probably at room temperature a significant amount of the enolate salt is formed which requires more vigorous treatment for reduction. At low temperatures, however, enolate salt formation is clearly not important.

Correspondingly, cyclopentanone is reduced at −80° with lithium aluminum deuteride to yield an alcohol having 1.0 ± 0.1 deuterium atom per molecule (density) and which is not *cis*-II or *trans*-II (compare infrared spectra in Table I); the structure of cyclopentanol-1-*d* (I) is assigned. The tosylates of each of the cyclopentanols were prepared in the usual way with tosyl chloride in pyridine.

Results and Discussion

The kinetics of the solvolyses of solutions of the tosylates in dry acetic acid containing roughly equivalent amounts of sodium acetate were determined at 50°. Each determination was run at least in duplicate. The reproducibility was generally about 1%. The rate constants measured are listed in Table II.

TABLE II

ACETOLYSES OF DEUTERATED CYCLOPENTYL TOSYLATES AT 50.0°

Alkyl tosylate	[ROTs]	[NaOAc]	10^5k, sec.$^{-1}$	k_H/k_D	$\Delta\Delta F^{\ddagger}$ per deuterium, cal./mole
Cyclopentyl[a]	0.1017	0.1170	4.19	1.00	..
	.0955	.1170	4.26		
Cyclopentyl-1-*d*	.0313	.1221	3.78[b]	1.15	90
	.0591	.1221	3.66		
	.0918	.1221	3.70		
trans-Cyclopentyl-2-*d*	.0948	.1170	3.65	1.16	110
	.0884	.1170	3.63		
cis-Cyclopentyl-2-*d*	.0965	.1170	3.50	1.22	127
	.0736	.1170	3.43		
Cyclopentyl-2,2,5,5-d_4	.0935	.1170	2.06	2.06	116
	.0900	.1170	2.05		

[a] Previous results: 4.28 × 10^{-5} sec.$^{-1}$, KOAc = 0.113 *M*, (J. D. Roberts and V. C. Chambers, THIS JOURNAL, **73**, 5034 (1951)); 3.84 × 10^{-5} sec.$^{-1}$, no acetate ion added (S. Winstein, B. K. Morse, E. Grunwald, H. W. Jones, J. Corse, D. Trifan and H. Marshall, *ibid.*, **74**, 1127 (1952)); 3.82 × 10^{-5} sec.$^{-1}$, no acetate ion added (H. C. Brown and G. Ham, *ibid.*, **78**, 2735 (1956)). [b] At 50.1°. Extrapolates to 3.72 × 10^{-5} sec.$^{-1}$ at 50.0°.

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[8] S. A. Francis, *J. Chem. Phys.*, **18**, 861 (1950).

[9] R. N. Jones, A. R. H. Cole and B. Nolin, THIS JOURNAL, **74**, 5662 (1952).

[10] W. G. Brown, "Organic Reactions," Vol. VI, John Wiley and Sons, Inc., New York, N. Y., 1951, p. 475.

[11] J. D. Roberts and C. W. Sauer, THIS JOURNAL, **71**, 3928 (1949).

In all cases, the deuterated compounds solvolyze significantly more slowly than does cyclopentyl tosylate itself.

α-**Deuterium Effect.**—Electronic wave functions are virtually identical for isotopically substituted molecules.[12] Hence, in the absence of any significant change in the average electron distribution due to anharmonicity (*vide infra*), the source of deuterium isotope effects must be sought almost wholly in the rotational and vibrational partition functions.

From absolute rate theory and statistical mechanics, assuming only the usual approximations that the partition function is the product of translational, vibrational and rotational, etc., partition functions and the neglect of anharmonicity, Bigeleisen[13] has derived an equation for the isotope effect on rate which is given as equation 1 in a rearranged form applicable to the present discussion.

$$\frac{k_H}{k_D} = \frac{\kappa_H}{\kappa_D}\left(\frac{m_D^{\ddagger}}{m_H^{\ddagger}}\right)^{1/2} \times \frac{\dfrac{\sigma_H}{\sigma_H^{\ddagger}}}{\dfrac{\sigma_D}{\sigma_D^{\ddagger}}} \times \frac{\Pi_i \dfrac{u_{Hi}^{\ddagger}}{u_{Hi}}\, e^{(u_{Hi} - u_{Hi}^{\ddagger})/2}(1 - e^{-u_{Hi}})(1 - e^{-u_{Hi}^{\ddagger}})^{-1}}{\Pi_i \dfrac{u_{Di}^{\ddagger}}{u_{Di}}\, e^{(u_{Di} - u_{Di}^{\ddagger})/2}(1 - e^{-u_{Di}})(1 - e^{-u_{Di}^{\ddagger}})^{-1}} \qquad (1)$$

In this equation, κ is the transmission coefficient, $m\ddagger$ is the effective mass for the reaction coördinate, σ is the symmetry number, $u_i = h\nu_i/kT$, the product being taken over all of the fundamental frequencies, with repetition of degenerate frequencies. Subscripts H and D refer to the hydrogen and deuterium compounds, respectively. The ratio of the transmission coefficients may be taken as unity. Because of the relatively small contribution to the effective mass of the hydrogen being substituted by deuterium, the mass term may also be taken as close to unity.[14] The symmetry numbers are the same in the ground state and the transition state in this case, hence the symmetry number term is also unity.

Deuterium substitution will change significantly only those vibration frequencies which involve the vibration of the substituted hydrogen in an important way[15]; hence, most of the fundamental frequencies will hardly be altered by the deuterium substitution. For these frequencies, the ratios, u_H/u_D and $(1 - e^{-u_H})/(1 - e^{-u_D})$ will be unity. The vibrations most affected by the change from cyclopentyl tosylate to cyclopentyl-1-*d* tosylate will be the stretching and bending frequencies of the tertiary C–H bond. Since these frequencies are greater than ~ 1000 cm.$^{-1}$, at temperatures near room temperature, $e^{-u} \cong 0$; thus all of the $(1 - e^{-u})$ terms cancel. For such frequencies also, equation 2[16] is generally a good approximation.

$$\nu_D = \frac{\nu_H}{1.35} \qquad (2)$$

Substitution of u_D by the use of equation 2 reduces equation 1 to equation 3, in which the product is taken over the three tertiary C–H stretching and bending fundamentals.[17] In equation 3 only the effects due to changes in zero-point energy remain from the original equation 1. In the related system of substitution on a benzene ring, Melander[18] concluded that zero-point energy effects were dominant.

$$\frac{k_H}{k_D} \cong \Pi_i e^{\left(1 - \frac{1}{1.35}\right)(u_{Hi} - u_{Hi}^{\ddagger})/2} \qquad (3)$$

Insertion of the values for the universal constants gives equation 4 or, equivalently, 5.

$$\frac{k_H}{k_D} \cong \Pi_i e^{\frac{0.187}{T}(\nu_{Hi} - \nu_{Hi}^{\ddagger})} \qquad (4)$$

$$\frac{k_H}{k_D} \cong e^{\frac{0.187}{T}\sum_i(\nu_{Hi} - \nu_{Hi}^{\ddagger})} \qquad (5)$$

There is no problem in assigning reasonably good values to the tertiary C–H frequencies: 2890 cm.$^{-1}$ [19] for C–H stretching and about 1340 cm.$^{-1}$ [19] for the two approximately degenerate bending vibrations. The problem arises in assigning frequencies to the three fundamental vibrations in the transition state. In the cyclopentyl cation, the fundamentals may be approximated as C–H stretching, in-plane bending and out-of-plane bending modes. As a model for a C–H bond attached to a carbonium ion, we have used an aldehyde C–H; the carbon atom involved in both cases is sp^2 hybridized, and the carbonyl carbon may be expected to have at least some net positive charge (however, *vide infra*.) The assignments for such a bond may be taken as ~2800 cm.$^{-1}$ (stretching),[20] 1350 cm.$^{-1}$ (in-plane bending)[21] and ~800 cm.$^{-1}$ (out-of-plane bending.)[21,22] The changes may be represented

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[12] *Cf.* (a) G. Herzberg, "Molecular Spectra and Molecular Structure," Vol. I, D. Van Nostrand Co., Inc., New York, N. Y., 1950, p. 162; (b) Vol. II, p. 227.

[13] J. Bigeleisen, *J. Chem. Phys.*, **17**, 675 (1949).

[14] The argument suggested by Professor Kenneth S. Pitzer is as follows: Superimposed on the complicated motions and vibrations of all of the constituent atoms of the reacting system are the relatively more simple motions which comprise the reaction coördinate; $m\ddagger$ is the effective mass along the reaction coördinate required to express the kinetic energy along this coördinate and is generally a complicated function of the system. Important motions in the reaction of cyclopentyl tosylate are the stretching of the C–X (X = OTs) bond and the forward movement of the *α*-H from a tetrahedral to a more trigonal position. The mass of the hydrogen is so small compared to that of the other moving atoms that its contribution to this kinetic energy is small; hence, to our approximation, replacement by deuterium would be expected to make a negligible change in $m\ddagger$.

Some idea of the magnitude of this term may be obtained by regarding the C–D group as acting as a unit; *i.e.*, as if the C^{12} was converted to C^{13}. An isotope effect of about 4% is found for the decarboxylation of malonic acid containing C^{13} (P. E. Yankwich and H. S. Weber, This Journal, **77**, 4513 (1955)) only part of which is attributable to the effective mass term. We might reasonably expect, then, that this term would amount to only a few per cent. with our system

[15] Reference 12b, p. 228.

[16] In the harmonic oscillator approximation, the group to which the hydrogen (or deuterium) is attached is relatively so large that it makes but a negligible contribution to the reduced mass of the bond (infinite mass approximation) and the ratio, ν_H/ν_D, should equal $\sqrt{2}$. Because the attached mass is not infinite and perhaps also because of anharmonicity, the ratio is actually somewhat smaller and is generally about 1.35 (see the many examples in ref. 12b).

[17] The neglect of other fundamentals should not be serious. The isotope effect is small, and many frequencies would not change appreciably in the transition state. Even combined changes of the order of 100 cm.$^{-1}$ would only change k_H/k_D by a few per cent.

[18] L. Melander, *Arkiv Kemi*, **2**, 211 (1950).

[19] L. J. Bellamy, "The Infra-red Spectra of Complex Molecules," Methuen and Co., Ltd., London, 1954, p. 13.

[20] A. Pozetsky and N. D. Coggeshall, *Anal. Chem.*, **23**, 1611 (1951).

[21] Assignment in acetaldehyde, K. S. Pitzer and W. Weltner, Jr., This Journal, **71**, 2842 (1949).

[22] Reference 19, p. 136.

as 2900 → ~2800, 1340 → ~1350 and 1340 → ~800. The decrease in the stretching frequency of ~100 cm.$^{-1}$ would result in $k_H/k_D = 1.06$. One bending vibration is essentially unchanged; the reduction in the second of ~550 cm.$^{-1}$ is equivalent to k_H/k_D of 1.38. Consequently, it appears that the most important factor involved in the α-deuterium effect is the isotopic inhibition of the out-of-plane bending vibration (Fig. 1A) of the cation which is looser (weaker) than the corresponding vibration in the ground state. This analysis is essentially unchanged if an olefinic C–H bond is used as our model instead of the aldehydic C–H.[23,24]

The observed k_H/k_D is only 1.15. Acetolysis of secondary alkyl tosylates is unassisted by backside solvent participation[5b] in the transition state. However, although the backside of the reacting carbon is clear, the tosylate group is still reasonably close to the forming carbonium ion; its presence probably impedes the C–H wagging motion (Fig. 1B). A change, ν_H-$\nu_H{}^{\ddagger}$, of ~300 cm.$^{-1}$ would be consistent with the observed effect. In this connection, it is pertinent that in the direct displacement of isopropyl bromide by sodium ethoxide, Shiner[25] found $k_H/k_D = 1.00$ for the α-deutero compound. In this case, the transition state would contain entering and leaving groups (Fig. 1C) and the wagging motion would be impeded even more; it might not be surprising if this motion were about the same as a tetrahedral C–H bending. If these suggestions should be substantiated by further work, the α-deuterium isotope effect may provide a new tool for determining the structural degree of solvent or neighboring-group assistance provided at the transition state of solvolytic displacement reactions.

In addition to the possible effect of the approximations discussed above, an additional reservation must be considered. We have assumed throughout that anharmonicity makes a negligible difference in the average electronic distribution in C–H and C–D bonds. Halevi and Nussim[26] have reported that acetic-d_3 acid, phenylacetic-α,α-d_2 acid and benzyl-α,α-d_2-ammonium ion are 10–13% less acidic than the undeuterated compounds.

Their explanation is based on the reported 0.009 Å. difference in C–H and C–D bond lengths[27]—a shorter C–D bond implies greater electron density about the carbon atom and weaker acid properties. However, these acidity changes seem to be entirely explicable by changes in the vibration partition functions. The methyl group stretching and bending frequencies in acetic acid are lowered sufficiently in acetate ion[28] to account for the observed isotope effect. Similarly, an increase in the basicity of methylamine by C–D substitution is consistent with the Raman spectra of methylamine and methylammonium ion.[29] Anharmonicity differences certainly exist between hydrogen and deuterium compounds but they are probably too small to account for observed reactivity differences.

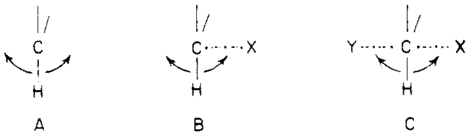

Fig. 1.—"Out-of-plane" C–H bending motions in various transition states.

The analysis as we have given it applies directly to the isotope effect on activation energy which we have equated to free energy of activation as a further implicit assumption. In the absence of temperature coefficient data no further comment on this approximation seems desirable.

β-Deuterium Effect.—The isotope effect observed in the acetolysis of III-OTs ($k_H/k_D = 2.06$) corresponds to a $\Delta\Delta F^{\ddagger}$ per deuterium of 116 cal./mole which is comparable to the magnitude of the effects observed by Lewis[4,30] and by Shiner.[3,31] This effect of β-deuterium atoms in decreasing solvolysis rates has been ascribed generally to bond weakening by hyperconjugation.[3,4,5b,31,32] The suggestion has been made that "elimination driving forces"[3] may be important; *i.e.*, that the β-hydrogens are hydrogen-bonded to specific solvent molecules.[3,33–35] This view has been criticized by Lewis.[4] If such specific solvation were important it could well be subject to the same stereochemical influences as E_2 elimination; *i.e.*, the *trans*-hydrogen should be more effectively involved[34]; hence, this hydrogen should be weakened more and substitution by deuterium should produce a greater isotope effect.[25]

The cyclopentane system was chosen to minimize the effects of conformational differences. Although the puckering of a cyclopentane ring[36] results in the important differences characteristic of axial and equatorial positions, such effects are probably much less pronounced in the cyclopentyl cation. The ring structure of this cation should resemble closely the ring structure of cyclopentanone in which the α-positions seem to be approximately equivalent.[37] To the extent that the transition

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[23] Use of olefinic C–H stretching at 3000 cm.$^{-1}$ leads to k_H/k_D of 0.95. The effect is still small and, moreover, is in the wrong direction.

[24] The presence of a net positive charge on a trigonal carbon apparently does little to the vibration frequencies of attached bonds. For example, the vibration frequencies of the tropylium cation are very similar to those of benzene (W. G. Fateley and E. R. Lippincott, THIS JOURNAL, **77**, 249 (1955).

[25] V. J. Shiner, Jr., THIS JOURNAL, **74**, 5285 (1952).

[26] E. A. Halevi and M. Nussim, *Bull. Res. Council Israel*, **5A**, 263 (1956); **6A**, 167 (1957); *Tetrahedron*, **1**, 174 (1957); Absts. *16th Intl. Cong. Pure Appl. Chem.*, *II*, 27 (1957).

[27] Reported for the methyl halides by S. L. Miller, L. C. Aamodt, G. Dousmanis, C. H. Townes and J. Kraitchman, *J. Chem. Phys.*, **20**, 1112 (1952). This difference may arise from a neglect of vibration-rotation interaction; a much smaller effective difference is reported for ethylene oxide (W. D. Gwinn, *Faraday Soc. Disc.*, **19**, 43 (1955)).

[28] E. T. Edsall, *J. Chem. Phys.*, **4**, 1 (1936).

[29] E. T. Edsall, *ibid.*, **5**, 225 (1937); E. T. Edsall and H. Scheinberg, *ibid.*, **8**, 520 (1940).

[30] E. S. Lewis and G. M. Coppinger, THIS JOURNAL, **76**, 4495 (1954).

[31] V. J. Shiner, Jr., *ibid.*, **78**, 2653 (1956).

[32] C. E. Boozer and E. S. Lewis, *ibid.*, **76**, 794 (1954).

[33] V. J. Shiner, Jr., and C. J. Verbanic, *ibid.*, **79**, 373 (1957).

[34] G. Baddeley, *Ann. Repts. on Progr. Chem.* (*Chem. Soc. London*), **51**, 169 (1954).

[35] W. M. Schubert and W. A. Sweeney, *J. Org. Chem.*, **21**, 119 (1956).

[36] J. E. Kilpatrick, K. S. Pitzer and R. Spitzer, THIS JOURNAL, **69**, 2483 (1947).

[37] This indication results from dipole moment studies of halocyclopentanones (W. D. Kumler and A. C. Huitric, THIS JOURNAL, **78**, 3369 (1956)).

state for acetolysis of cyclopentyl tosylate resembles the free cation, *conformational* distinctions between a *cis*- and *trans*-α-D should become reduced and any important stereochemical distinction should become manifest. The results in Table II, however, show that substitution of either the *cis*- or the *trans*-hydrogen by deuterium gives essentially the same rate reduction. The small difference in isotope effect between the two, which is in the wrong direction for the solvation argument, may be due to a slight conformational difference resulting from ring puckering. Consequently, if specific solvation of β-hydrogens is subject to the same stereochemical preferences as E_2 elimination, such solvation is not important in solvolytic displacement reactions.

Hyperconjugation remains the best explanation of the accumulating mass of stereochemical, conformational and structural data on the β-deuterium isotope effect in solvolyses. Overlap of the C–H bond orbital with the electron-deficient *p*-orbital of the developing carbonium ion causes a weakening of the bond and lowering of the bond frequencies. Although previously only the stretching frequencies have been specifically considered to be so altered,[3a,4] our discussion of the α-deuterium isotope effect suggests that weakening of the bending modes may be at least as important (*vide infra*). The hypothesis demands that the magnitude of the bond weakening should depend on the amount of positive charge to be distributed and on the extent of the orbital overlap. Overlap is greatest when the C–H bond is parallel to the direction of the carbonium *p*-orbital and least when the C–H bond is in the nodal plane of the carbonium ion. The recent results of Shiner[31] and of Saunders[38] provide important evidence for the dependence of the isotope effect on the angular relation between the C–H bond and the developing carbonium ion.

If the $\sim$20% effect associated with one β-deuterium were divided among three fundamental vibrations, from equation 4 the average change in frequency between ground state and transition state would be about 100 cm.$^{-1}$; the change is greater if fewer modes of vibration are affected. In neutral molecules, variations of this magnitude in the characteristic C–H modes for similar types of C–H bond are not observed. The constancy of characteristic vibrations is the foundation of the use of infrared for structure determinations. Even the $\sim$50 cm.$^{-1}$ reduction in the deformation frequency of a methylene group when adjacent to a carbonyl group[8] (*vide supra*) probably is not due to hyperconjugation with a presumed electron-deficient carbon of a carbonyl group—the 1436 cm.$^{-1}$ methyl deformation in acetic acid is lowered to 1412 cm.$^{-1}$ in acetate ion.[28] If hyperconjugation to an electron-deficient carbon were responsible for the "low" 1436 cm.$^{-1}$ band, the presence of a negative change in acetate ion would be expected to raise this frequency.

Hence, it would appear that in ground states of neutral molecules either hyperconjugation is not an important bonding force or such hyperconjugation does not involve weakening of bonds *unless significant net electron-deficiency is involved.*

The increase in carbonium ion stability in the series: methyl, ethyl, isopropyl, *t*-butyl, is frequently associated with an increase in hyperconjugation along this series. We wish to point out that the demonstration that hyperconjugation is responsible for the β-deuterium isotope effect does not mean that hyperconjugation is necessarily the dominant bonding force in these carbonium ions. Inductive effects, regardless of their importance as bonding forces, generally have a relatively small effect on fundamental vibration frequencies; for example, the methyl bending and stretching frequencies in methylamine and in acetic acid are changed *relatively* little in methylammonium and acetate ions, respectively.[28,29,39] The similarity of the stretching and bending frequencies of methane (2900 and 1400 cm.$^{-1}$, respectively) and of ammonium ion (3000 and 1400 cm.$^{-1}$, respectively) may be taken as further examples.[40,41]

This interpretation implies that infrared spectra can be used as a criterion for the amount of positive charge distributed by hyperconjugation. The relative constancy of the characteristic frequencies of α-C–H bonds suggests that a carbonyl group has rather little net positive charge,[42] but this criterion is not a sensitive one. In the positively charged transition state for the acid-catalyzed hydrolysis of ketals the central carbon atom surely possesses a much larger amount of net positive charge than in a neutral carbonyl group; yet, the isotope effect for the hydrolysis of acetone diethyl ketal, $k_H/k_D = 1.15$,[43] corresponds to an average change of only $\sim$13 cm.$^{-1}$ per α-C–H bond vibration. ($\sim$40 cm.$^{-1}$ if only one bending mode per methyl group is involved).

Consequently, in molecular orbital terms, these considerations require that even appreciable overlap of a C–H σ-bond with a carbon 2p-orbital in

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(38) W. H. Saunders, Jr., S. Asperger and D. H. Edison, *Chemistry & Industry*, 1417 (1957).

(39) It should be emphasized that the difference is one of degree. The changes in vibration frequency in these examples are enough to give an isotope effect on acidity of about 3–4% per deuterium atom (*vide supra*). This effect is in the opposite direction and is almost an order of magnitude smaller than the β-deuterium isotope effect observed in a number of solvolytic displacement reactions in which a lesser charge and a smaller inductive effect presumably is involved.

(40) The analogy cannot be pressed too far, however. The stretching and bending frequencies in borohydride ion are significantly *lower*, 2300 and 1100 cm.$^{-1}$, respectively (W. C. Price, *J. Chem. Phys.*, **17**, 1044 (1949); L. A. Woodward and H. L. Roberts, *J. Chem. Soc.*, 1170 (1956)).

(41) We wish to thank Professor William D. Gwinn for pointing out the following argument: If a harmonic oscillator potential is modified by a constant potential or one linear in the distance, r, the potential function is changed only by a simple transformation. Its shape, which determines spectral characteristics, is unchanged unless r^2 and higher terms are involved. Since $1/r$ can be expressed as a power series in r, the first and most important terms in the series would not change the shape of the potential function. Electrostatic interaction such as is involved in inductive effects contains a coulombic $1/r$ term; thus, to a first approximation, such interaction would not affect vibration frequencies.

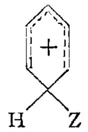
The changes that do occur often tend to cancel; for example, in the methyl halides the C–H stretching frequencies increase and the bending frequencies decrease along the series: F, Cl, Br, I (ref. 12b, p. 315).

(42) On the basis of this argument, the choice of an aldehydic hydrogen as a model for a hydrogen on a carbonium ion (*vide supra*) may be criticized. However, different choices of models (*e.g.*, a vinyl hydrogen) do not materially affect the conclusions of the origin of the α-deuterium isotope effect.[23]

(43) V. J. Shiner, Jr., and S. Cross, This Journal, **79**, 3599 (1957).

which little or no electron deficiency is involved would not significantly change the C–H bond strength; such overlap with an electron-deficient *p*-orbital, however, must be associated with a corresponding weakening of the C–H bond, the weakening being greater the greater the amount of overlap and the greater the net positive charge being distributed. The molecular orbital formulation suggests also a reason why hyperconjugative distribution of positive charge results in a lowering of vibration frequency although simple inductive effects do not to a first approximation. The π-overlap between the empty p-orbital and appropriately oriented C–H σ-orbitals results in a set of molecular orbitals the most stable of which is a totally bonding orbital. Figure 2 is a representation of such a molecular orbital in a cation of the type $RCH_2C^{\oplus}$ (V) in which the $-CH_2R$ group is so oriented that the C–R bond is in the nodal plane of the carbonium ion. A methylene bending vibration of the ground state becomes a C–H deformation in V in which the hydrogens move *along the molecular orbital.* For such a vibration the restoring force (hence, the vibration frequency) would be expected to be significantly lowered. We suggest that the β-deuterium isotope effect results predominantly from this sort of change in a bending mode.

Finally, these results may be applied to some deuterium isotope effects in aromatic substitution. A number of studies[19,44] have shown that there is no isotope effect in substitution on a deuterated aromatic ring when the formation of the σ-complex VI is rate-determining. In the transition state for the formation of VI the C–H bond being substituted may be expected to vary from near sp^2 to near sp^3



VI

depending on the nature and reactivity of Z. The progressive increase in p-character of the bond will cause a progressive increase in the frequency of what was the out-of-plane bending motion and a progressive increase in hyperconjugation. In the deuterium compound, the former effect would result in a relative rate increase and the latter effect would result in a relative rate decrease. The two effects are opposite in direction and about *equal in magnitude*, hence, no significant net isotope effect is expected regardless of the detailed geometry of the transition state leading to VI.

Experimental

trans-Cyclopentanol-2-*d*.—Twenty-seven and one-half grams of cyclopentene oxide was reduced with 4 g. of lithium aluminum deuteride in ether in the usual way. Distillation of the product gave 21.0 g. (74%) of *trans*-II, b.p. 139°, d^{25} 0.9546 (corresponding to 1.0 atom of deuterium per molecule).[45]

trans-Cyclopentyl-2-*d* *p*-Toluenesulfonate.—A mixture of 19 g. of *trans*-II and 84 g. of *p*-toluenesulfonyl chloride in 210 ml. of anhydrous pyridine was stirred in an ice–salt-bath for 1.5 hours and kept in a refrigerator for 5 hours. After the addition of 21 ml. of water with cooling, the mixture was poured into cold dilute hydrochloric acid and extracted with pentane. The washed and dried pentane extract was cooled in a Dry Ice–acetone-bath. The crystalline tosylate which precipitated was filtered and recrystallized from pentane; yield 45 g. (85%), m.p. 28–29°.

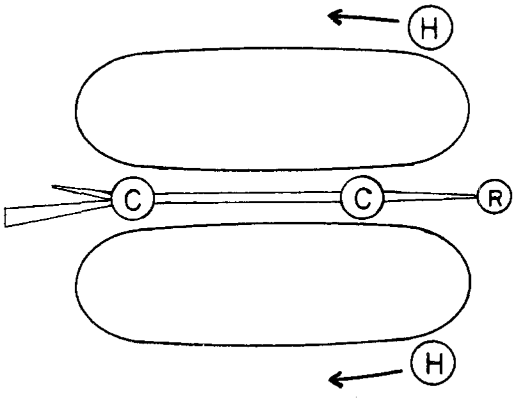


Fig. 2.—Illustrating a C–H deformation along a molecular orbital formed by combination of a carbon 2p orbital and two C–H bond orbitals.

Acetone.—The acetone used as a solvent in the next preparation was purified *via* the sodium iodide complex. A mixture of 1,100 ml. of commercial acetone and 300 g. of sodium iodide was shaken and cooled in an ice–salt-bath. The yellow needles of the complex were filtered and dried in air. The crystals decompose slowly while drying. Slow heating of the dried crystals in a flask protected from moisture yielded 400 ml. of pure acetone.

cis-Cyclopentyl-2-*d* Acetate.—A solution of 30 g. of *trans*-II-OTs and 62 g. of dry tetramethylammonium acetate in 150 ml. of purified acetone was gently refluxed for 20 hours and allowed to stir an additional 20 hours at room temperature. The contents of the flask were vacuum distilled; acetone was removed from the distillate by evacuation at room temperature. The crude residue was washed with sodium bicarbonate and with water and was distilled, collecting 12.5 g. (76%), b.p. 152°.

Twelve grams of the acetate was saponified with dilute sodium hydroxide yielding 6.8 g. (78%) of *cis*-cyclopentanol-2-*d*, b.p. 139°. Five grams of this alcohol was converted to the tosylate using the procedure described above.

Cyclopentanone-2,2,5,5-d_4.—A mixture of 10 ml. of cyclopentanone and 5 ml. of deuterium oxide containing 0.1 g. of potassium carbonate and 0.5 g. of sodium chloride was refluxed overnight. After cooling, the cyclopentanone was withdrawn with a syringe and transferred to a fresh deuterium oxide solution. The spent deuterium oxide mixture was refluxed with another 10 ml. of cyclopentanone. A total of 6 portions of cyclopentanone was carried through this fractional exchange procedure. The head portion was exchanged a total of 6 times with fresh deuterium oxide mixture. The final exchange of each of the succeeding portions was carried out with a fresh deuterium oxide mixture. The combined exchanged cyclopentanone was dried with sodium sulfate and distilled, collecting 10 g. of distillate, b.p. 128°. A large pot residue remained consisting presumably of condensed material. The low yield of exchanged cyclopentanone obtained indicates that the exchange procedure is somewhat too vigorous. The product was redistilled collecting 8.7 g., b.p. 127°, d^{25} 0.9892 (corresponding to 4.04 ± 0.12 atoms of deuterium per molecule).[45]

Cyclopentanol-2,2,5,5-d_4.—A solution of 8.4 g. of cyclopentanone-2,2,5,5-d_4 in ether was added dropwise to 4 g. of lithium aluminum hydride in ether with stirring in a Dry Ice–acetone-bath over a period of 1.5 hours. After stirring for an additional 3 hours the mixture was allowed to warm to 0°. The salts were decomposed with dilute sulfuric acid at 0° and the ether solution was separated, washed and dried. Distillation of the ether left a crude product which was taken up in pentane, dried and distilled. Distillation of the residue gave 7.0 g. (82%) of alcohol, b.p. 140–141°, d^{25} 0.9890 (corresponding to 4.08 ± 0.12 atoms of deuterium

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(44) P. B. D. de la Mare, T. M. Dunn and J. T. Harvey, *J. Chem. Soc.*, 923 (1957); T. G. Boner, F. Bowyer and G. Williams, *ibid.*, 2650 (1953); W. M. Lauer and W. E. Noland, THIS JOURNAL, **75**, 3689 (1953); H. Zollinger, *Helv. Chim. Acta*, **38**, 1597, 1617 (1955).

(45) A. McLean and R. Adams, THIS JOURNAL, **58**, 804 (1936).

TABLE III

ACETOLYSIS OF *cis*-CYCLOPENTYL-2-*d* TOSYLATE

Temp. 50.0°; [ROTs] = 0.0965; [NaOAc] = 0.1170; calcd. infinity titer, 1.762 ml.; found, 1.779 ml.

Time, min.	Titer, ml.	10^5k, sec.$^{-1a}$
0	7.609	. .
108.9	6.066	3.46
209.2	4.859	3.55
315.3	3.920	3.50
384.5	3.395	3.50
488.0	2.723	3.52
555.8	2.356	3.52
616.7	2.082	3.50
		3.51 ± 0.02[a]

[a] Using equation for a first-order reaction. The least squares $k = 3.502 \times 10^{-5}$ sec.$^{-1}$.

per molecule).[45] The tosylate was prepared as above, m.p. 28–29°.

Cyclopentanol-1-*d*.—Cyclopentanone was reduced with lithium aluminum deuteride using the procedure detailed above for the reduction of IV-d_4; yield 3 g. (37%) of alcohol, b.p. 140.5–141.5°, d^{25} 0.9547 (corresponding to 1.07 deuterium atoms per molecule).[45] The tosylate prepared as above had m.p. 25.5–26°.

Kinetics.—Anhydrous acetic acid was prepared by treating reagent grade acetic acid, which had been analyzed for water by the Karl Fischer method, with an amount of acetic anhydride calculated to give a 1% excess. Freshly fused sodium acetate and dried *p*-toluenesulfonic acid were used to make up stock solutions in acetic acid. In most of the runs about 2 g. of the tosylate was dissolved in sodium acetate stock solution in a calibrated 100-ml. volumetric flask. The flask was placed in a thermostat at 50.00 ± 0.05° and aliquots were removed periodically with a calibrated 5-ml. automatic pipet and titrated potentiometrically with stock *p*-toluenesulfonic acid solution in acetic acid. The procedure for the cyclopentyl-1-*d* tosylate runs was similar except that the solution was placed in sealed tubes which were periodically withdrawn and titrated. Infinity titers generally agreed with the calculated titers within 1–2%. A typical run is shown in Table III; a summary of rate constants calculated by the method of least squares is presented in Table II.

Acknowledgment.—We are indebted to Professors W. D. Gwinn, K. S. Pitzer, H. S. Johnston, G. C. Pimentel and W. E. Doering for discussions and suggestions which greatly assisted the formulation of some of the concepts and arguments presented in this paper. We thank Professor William H. Saunders, Jr., for exchange of information in advance of publication.

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[CONTRIBUTION FROM THE DEPARTMENT OF CHEMISTRY, UNIVERSITY OF SOUTHERN CALIFORNIA]

Heterocyclic Compounds. VI. Reduction of 3-(3,4-Methylenedioxyphenyl)-4-nitro-1-phenyl-1-butanone[1]

BY MILTON C. KLOETZEL AND JACK L. PINKUS

RECEIVED NOVEMBER 11, 1957

Reduction of 3-(3,4-methylenedioxyphenyl)-4-nitro-1-phenyl-1-butanone (I) by catalytic hydrogenation over platinum black or Raney nickel, or by zinc dust and aqueous ammonium chloride, yields 4-(3,4-methylenedioxyphenyl)-2-phenyl-Δ^1-pyrroline (VI). Chemical and physical evidence clearly supports a Δ^1-pyrroline structure for VI.

Pyrrolidines and Δ^1-pyrrolines have become increasingly recognized as characteristic reduction products from aliphatic γ-nitro ketones.[2–11] However, despite the fact that aromatic nitroketones frequently have been reduced to N-oxygenated derivatives of indole or quinoline,[12] oxygen-containing reduction products from aliphatic γ-nitro ketones have remained elusive.

Kohler and Drake[2] reported the only products from catalytic hydrogenation of 3-(3,4-methylenedioxyphenyl)-4-nitro-1-phenyl-1-butanone (I), over platinum black, to be amino ketone II, pyrrolidine III and an hydroxylated pyrroline to which they ascribed structure IV or V. Prior to our reduction studies[13] this was the only instance in which an oxygenated pyrrole nucleus had been obtained by reduction of an aliphatic γ-nitro ketone.[15] For this reason it appeared of interest to include nitro ketone I in a series of nitro ketones whose behavior upon reduction we have been studying.

In our hands, reduction of I by hydrogen over platinum black or Raney nickel, or by zinc dust and aqueous ammonium chloride, yielded only 4-(3,4-methylenedioxyphenyl)-2-phenyl-Δ^1-pyrroline (VI). We obtained none of the products (II-V) reported by Kohler and Drake.[2]

Pyrroline VI was characterized by formation of a crystalline picrate, hydrochloride[16] and oxalate.

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(1) Partially abstracted from a portion of the Ph.D. dissertation of Jack L. Pinkus.

(2) E. P. Kohler and N. L. Drake, THIS JOURNAL, **45**, 2144 (1923).

(3) A. Sonn, *Ber.*, **68**, 148 (1935); **72**, 2150 (1939).

(4) J. Dhont and J. P. Wibaut, *Rec. trav. chim.*, **63**, 81 (1944).

(5) M. C. Kloetzel, THIS JOURNAL, **69**, 2271 (1947).

(6) P. M. Maginnity and J. B. Cloke, *ibid.*, **73**, 49 (1951).

(7) F. G. Bordwell and M. Knell, *ibid.*, **73**, 2354 (1951).

(8) L. I. Smith and E. R. Rogier, *ibid.*, **73**, 3837 (1951).

(9) B. Witkop, *ibid.*, **76**, 5597 (1954).

(10) M. L. Stein and A. Burger, *ibid.*, **79**, 154 (1957).

(11) M. C. Kloetzel, J. L. Pinkus and R. M. Washburn, *ibid.*, **79**, 4222 (1957).

(12) A. Reissert, *Ber.*, **30**, 1030 (1897); S. Gabriel and W. Gerhard, *ibid.*, **54**, 1067 (1921); K. L. McCluskey, THIS JOURNAL, **44**, 1573 (1922); S. Gabriel and R. Wolter, *Ber.*, **56**, 2445 (1923); J. Meisenheimer and E. Stotz, *ibid.*, **58**, 2334 (1925).

(13) Stein and Burger[10] recently reported the preparation of an oxygen-containing base by reduction of an aliphatic nitro ketone but did not ascribe to it a structure. Shortly thereafter, Brown, Clark and Todd[14] reported the synthesis of two alicyclic nitrones by reductive cyclization of aliphatic nitro carbonyl compounds.

(14) R. F. C. Brown, V. M. Clark and A. Todd, *Proc. Chem. Soc.*, 97 (1957).

(15) Inconclusive evidence for a second instance was presented in the same report and has been discussed in one of our previous papers.[11]

(16) The salt isolated by Kohler and Drake[2] and designated by them as the hydrochloride of III displayed melting point characteristics similar to those of our hydrochloride of VI. Since carbon and hydrogen analytical data do not permit positive differentiation between these compounds, it cannot be stated with certainty whether these salts are in fact identical. Kohler and Drake did not isolate the free base III.