[CONTRIBUTION FROM THE DEPARTMENT OF CHEMISTRY, MASSACHUSETTS INSTITUTE OF TECHNOLOGY]

Small-Ring Compounds. VII. Physical and Chemical Properties of Cyclopropyl, Cyclobutyl, Cyclopentyl and Cyclohexyl Derivatives

BY JOHN D. ROBERTS AND VAUGHAN C. CHAMBERS

The physical and chemical properties of some cycloalkyl derivatives have been determined as a function of ring size. The properties which have been studied include: ionization constants and reaction rate constants with diphenyldiazomethane of cycloalkanecarboxylic acids; ionization constants of cycloalkylamines and cycloalkyldimethylamines; dipole moments of cycloalkyl bromides; and intensities of infrared C–H stretching frequencies of cycloalkyl chlorides and bromides. On the whole, the properties showed reasonably smooth gradations with ring size which could be correlated qualitatively with current structural theories of small-ring compounds.

It has long been recognized that cyclopropyl and cyclobutyl compounds have some of the characteristics of unsaturated substances and that a series of ethylene (cycloethane), cyclopropane, cyclobutane, cyclopentane and cyclohexane derivatives might be expected to exhibit a relatively smooth graduation of physical and chemical properties ranging from those typical of unsaturated compounds to those characteristic of saturated aliphatic substances.[1] However, despite an accumulation of evidence indicating the similarity of cyclopropane rings to carbon–carbon double bonds,[2] there appears to be insufficient quantitative data to establish the generality of the occurrence of a smooth gradation of properties over the *whole* series of ring sizes. The most notable evidence for a graded series includes: the ease of ring opening by hydrogen, hydrogen bromide and bromine[1]: the heats of combustion of the cycloalkanes,[3] particularly when expressed per CH_2 group[3a]; molecular refractivity[4,5] and diamagnetic susceptibility[6] data; and the Raman frequencies of the totally symmetrical C–H stretching vibrations of the cycloalkanes.[7] In contrast, the ionization constants for the sequence of cycloalkanecarboxylic acids are reported[8] to attain a maximum with cyclobutanecarboxylic acid. This behavior, however, is not general since the ionization constants of the cycloalkane-1,1-dicarboxylic acids fit a simple graded sequence.[9]

In the present research, the variation of physical and chemical properties of cycloalkyl derivatives with ring size was investigated further, with particular attention to properties which might yield information as to the electrical effects of cycloalkyl groups. At the outset, the apparent ionization constants K_A in 50% water–50% ethanol (by volume) and second-order reaction rate constants k_2 with diphenyldiazomethane in absolute ethanol of the cycloalkane-carboxylic acids were determined by the methods described earlier.[10] These reactions have been used in studies of the electrical effect of substituent groups[10] and it has been shown[10a] that with *m*- and *p*-substituted benzoic acids there is direct parallelism between K_A and k_2. The experimental data with cycloalkanecarboxylic acids are given in Table I. The parallelism between K_A and k_2 noted previously with benzoic acids is also exhibited by cycloalkanecarboxylic acids and log k_2 varies linearly with log K_A (Fig. 1). The transitions in K_A and k_2 with ring size are neither large nor particularly smooth and, although cyclopropane- and cyclobutanecarboxylic acids are clearly intermediate between acrylic acid and the large-ring acids, (compare results of Zelinsky and Isgaryschew[8]) they have very similar K_A and k_2 values.

TABLE I

APPARENT IONIZATION CONSTANTS K_A IN 50% WATER–50% ETHANOL (BY VOLUME) AT 25° AND SECOND-ORDER RATE CONSTANTS k_2 FOR REACTION WITH DIPHENYLDIAZOMETHANE IN ABSOLUTE ETHANOL AT 30° OF CYCLOALKANECARBOXYLIC ACIDS $\overline{(\mathrm{CH_2})_{n-1}\mathrm{C}}\mathrm{HCOOH}$.

	Ionization data		Rate constant data		
Ring size, n	Half-point scale reading[a]	$K_A \times 10^{7\,b}$	Concn., mole/l.	Half-life, min.	k_2, l./mole/min.
2	5.53	2.96	0.0514	10.0, 9.9	1.36
3	6.20, 6.21	0.62	.0503	26.7, 26.0	0.522
4	6.21, 6.21	.62	.0505	27.7, 27.3	.502
5	6.49, 6.48	.33	.0502	38.4, 38.3	.362
6	6.49, 6.49	.32	.0510	35.5, 35.5	.385

[a] Readings on *p*H scale of *p*H meter (calibrated for aqueous buffer solutions) at half-neutralization point using glass and saturated calomel electrodes without correction for liquid junction potentials. [b] Calculated assuming that the activity coefficients of the carboxylic acid and its anion were unity and that the readings on the *p*H meter scale were equal to the logarithm of the reciprocal of the hydrogen ion concentration.

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[1] *Cf.* R. C. Fuson in H. Gilman, "Organic Chemistry, An Advanced Treatise," 2nd ed., Vol. I, John Wiley and Sons, Inc., New York, N. Y., 1943, Chap. II, for discussion of earlier speculations and evidence on the properties of small-ring compounds.

[2] *Cf.* J. D. Roberts and R. H. Mazur, THIS JOURNAL, **73**, 2509 (1951), for references.

[3] (a) W. Hückel, *Ber.*, **53**, 1277 (1920), "Theoretische Grundlagen der organischen Chemie," Akademische Verlagagesellschaft m. b. H., Leipzig, 1934, Vol. I, pp. 58–62. (b) *Cf.* G. L. Humphrey and R. Spitzer, *J. Chem. Phys.*, **18**, 902 (1950), and J. Coops and S. J. Kaarsemaker, *Rec. trav. chim.*, **69**, 1364 (1950), for recent work on cyclobutane and methylcyclobutane.

[4] G. J. Östling, *J. Chem. Soc.*, **101**, 457 (1912).

[5] G. H. Jeffery and A. I. Vogel, *ibid.*, 1804 (1948).

[6] J. Farquharson and M. V. C. Sastri, *Trans. Faraday Soc.*, **33**, 1474 (1937).

[7] Values of $\Delta\nu$ for ethylene, cyclopropane, cyclobutane, cyclopentane and cyclohexane of 3019, 3029, 2938, 2853 cm.$^{-1}$, respectively, were obtained from the following: G. Herzberg, "Infrared and Raman Spectra," D. Van Nostrand Co., Inc., New York, N. Y., 1945, pp. 326; T. P. Wilson, *J. Chem. Phys.*, **11**, 369 (1943); E. J. Rosenbaum and H. F. Jacobson, THIS JOURNAL, **63**, 2841 (1941); and K. W. F. Kohlrausch and H. Wittek, *Z. physik. Chem.*, **B48**, 177 (1941).

[8] E. Zelinsky and N. Isgaryschew, *J. Russ. Phys. Chem. Soc.*, **40**, 1379 (1908); *Chem. Zent.*, **80**, I, 531 (1909).

[9] A. I. Vogel, *J. Chem. Soc.*, 1487 (1929).

[10] (a) J. D. Roberts, E. A. McElhill and R. Armstrong, THIS JOURNAL, **71**, 2923 (1949); (b) J. D. Roberts and E. A. McElhill, *ibid.*, **72**, 628 (1950); (c) J. D. Roberts, R. L. Webb and E. A. McElhill, *ibid.*, **72**, 408 (1950); (d) J. D. Roberts, R. A. Clement and J. J. Drysdale, *ibid.*, **73**, 2181 (1951).

The apparent ionization constants K_B of the cycloalkylamines and cycloalkyldimethylamines in 50% water–50% ethanol (by volume) exhibit relatively large differences (*cf.* data of Table II) and decrease reasonably smoothly with decreasing ring size.

TABLE II

APPARENT IONIZATION CONSTANTS K_B IN 50% WATER–50% ETHANOL (BY VOLUME) AT 25° OF CYCLOALKYLAMINES AND CYCLOALKYLDIMETHYLAMINES $(\overline{\underline{CH_2)_{n-1}C}}HNR_2$

Ring size, *n*	R	Half-point scale reading[a]	Av. $K_B \times 10^6$[b]
3	H	8.66, 8.66	4.6
4	H	9.34, 9.34	22
5	H	9.92, 9.98	89
6	H	9.81, 9.85	68
3	CH_3	7.69, 7.70	0.50
4	CH_3	8.76, 8.78	5.9
5	CH_3	8.93, 8.94	8.6
6	CH_3	9.18, 9.14	15

[a] See footnote *a* to Table I. [b] See footnote *b* to Table I.

It was reported previously[11] that the dipole moment of cyclopropyl chloride (1.76 D) is considerably smaller than that of cyclopentyl chloride (2.08 D). It has now been found that the cycloalkyl bromides show similar differences in dipole moments (Table III) and that the moments decrease steadily with decreasing ring size.

TABLE III

MOLAR REFRACTIONS, POLARIZATIONS AND DIPOLE MOMENTS OF CYCLOALKYL BROMIDES, $(\overline{\underline{CH_2)_{n-1}C}}HBr$.

Ring size, *n*	MR_D	P_∞ (25°)	μ, Debyes
3	21.90	80.2	1.69
4	26.86	116.2	2.09
5	30.87	126.3	2.16[a]
6	35.65	144.2	2.31[b]

[a] Rogers and Roberts[11] obtained 2.20 *D*. [b] J. W. Williams, THIS JOURNAL, **52**, 1831(1930), reports 2.3 *D* and O. Hassel and E. Naeshagen, *Z. physik. Chem.*, **B15**, 373 (1932), give 2.1 *D*.

In the course of this and other investigations, infrared spectra of several complete series of cycloalkyl derivatives have been obtained under comparable conditions in a single infrared spectrometer. It was noted that the intensity of absorption at 3.24–3.52 μ due to C–H stretching was always markedly less for the small-ring compounds. This behavior is shown in Figs. 2 and 3 for the chlorides and bromides and was evaluated quantitatively in the following way. A plot of extinction coefficient[12] against wave length was made and integrated graphically from 3.24–3.52 μ. The integrated values were divided by the number of hydrogen atoms in the molecule and thus integrated extinction coefficients per C–H bond *B* were obtained (*cf.* Table IV). *B* decreases relatively smoothly with decreasing ring size. Since *B* is determined by the magnitude of the transition dipoles of the bonds absorbing radiant energy, it is likely that the electrical character of the C–H bonds of cycloalkyl rings is a relatively continuous function of ring size.

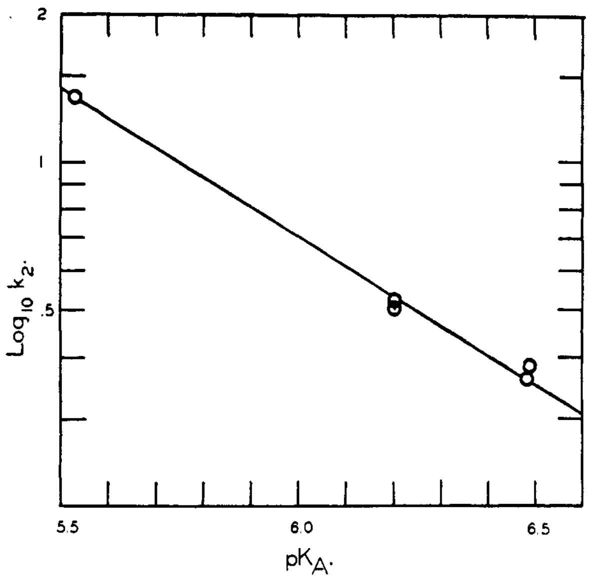

Fig. 1.—Comparison of second-order rate constants, k_2, in the reaction of cycloalkanecarboxylic acids with diphenyldiazomethane with the corresponding acidity constants.

TABLE IV

INFRARED ABSORPTIONS AND INTEGRATED EXTINCTION COEFFICIENTS *B* OF C–H BONDS OF CYCLOALKYL HALIDES, $(\overline{\underline{CH_2)_{n-1}C}}HX$

Ring size, *n*	X	λ_1, μ	E_1[a]	λ_2, μ	E_2[a]	B[b]
3	Br	3.25	10	3.35	22	0.5
4	Br	3.37	87	3.52	31	1.8
5	Br	3.40	112	3.52	61	2.0
6	Br	3.42	127	3.52	96	1.7
3	Cl	3.24	11	3.33	25	0.5
4	Cl	3.34	117	3.50	31	2.3
5	Cl	3.39	160	3.49	75	2.6
6	Cl	3.43	186	3.52	120	2.5

[a] l./mole/cm. [b] Integrated extinction coefficient over 3.24 to 3.52 μ divided by the number of C–H bonds per molecule.

Discussion

The present results show that the electrical effects of cycloalkyl groups depend markedly on ring size. Judging from the acid ionization and reactivity data, a general electron-attracting effect, cyclopropyl > cyclobutyl > cyclopentyl ~ cyclohexyl, is of some importance. An electron-attracting influence of this type can be inferred from the suggestion of Walsh[13] that the exterior bonds of small-ring compounds have more *s* character and the ring atoms a greater electronegativity than those of macrocyclic compounds. The dipole moment and base constant values may be explained by such an electron-attracting power of the ring

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(11) M. T. Rogers and J. D. Roberts, THIS JOURNAL, **68**, 843 (1946); *cf.* also M. T. Rogers, *ibid.*, **69**, 2544 (1947).

(12) It is recognized that experimentally determined infrared extinction coefficients are of uncertain significance. However, in the present work it was shown that variations of sample thickness and of sample dilution did not change the extinction coefficients by more than 20%.

(13) A. D. Walsh, *Trans. Faraday Soc.*, **45**, 179 (1949). *Cf.* also C. A. Coulson and W. E. Moffitt, *Phil. Mag.*, [7], **40**, 1 (1949).

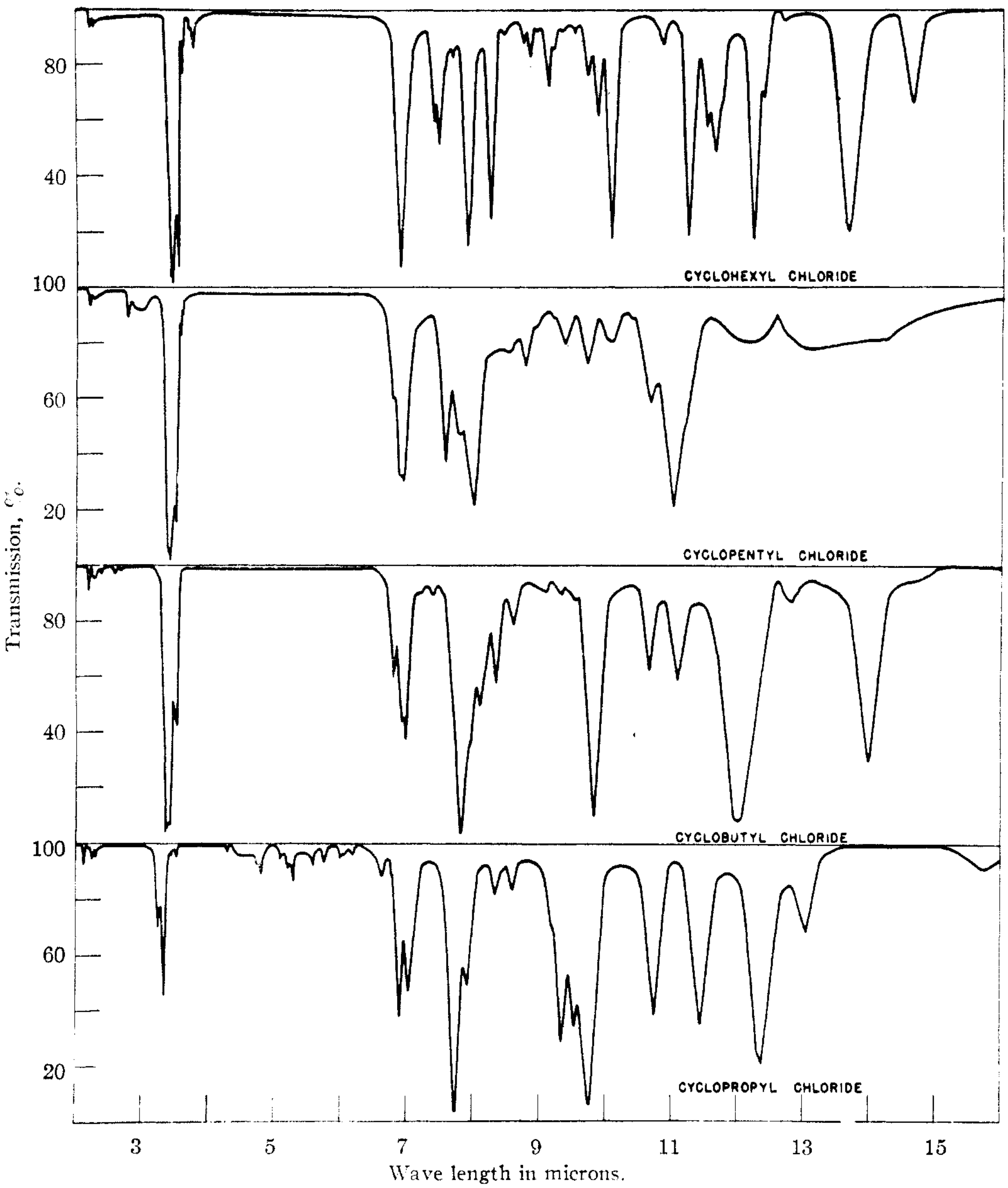
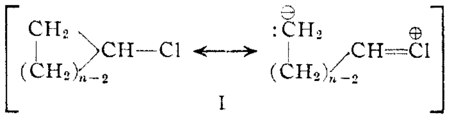


Fig. 2.—Infrared spectra.

atoms[13] and/or delocalization of unshared electron pairs on halogen or nitrogen as postulated by Rogers and Roberts.[11] The delocalization may be expressed by resonance forms such as I and II and is entirely analogous to the type of delocalization customarily evoked to account for differences in dipole moments and base strengths of phenyl and cyclohexyl halides and amines.[14]



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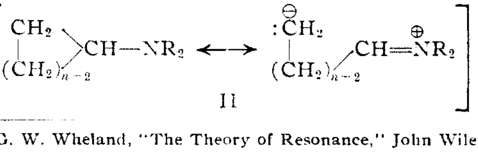

II

As pointed out earlier,[11] the degree of delocalization should be expected to decrease with increasing n and become essentially constant with $n \geqq 5$.

Acknowledgment.—We thank Dr. R. C. Lord, Jr., for suggestions regarding the evaluation of the infrared spectra. One of us (V.C.C.) is indebted to the Swarthmore Chapter of the Society of Sigma Xi for a fellowship.

Experimental

Materials.—The physical properties of the cycloalkyl derivatives used in the various experiments are summarized in Table V.

Apparent ionization constants and reactivities toward diphenyldiazomethane of the cycloalkanecarboxylic acids were determined as described previously.[10a] The data are given in Table I.

Apparent Ionization Constants of Cycloalkylamines and Cycloalkyldimethylamines.—The amines were redistilled just before use. Samples (about 0.07 g.) of the amines were dissolved in 100 ml. of 50% ethanol–50% water (by volume) and titrated with 0.19 N hydrochloric acid. The

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(14) G. W. Wheland, "The Theory of Resonance," John Wiley and Sons, Inc., New York, N. Y., 1944, pp. 130–132, 177–178.

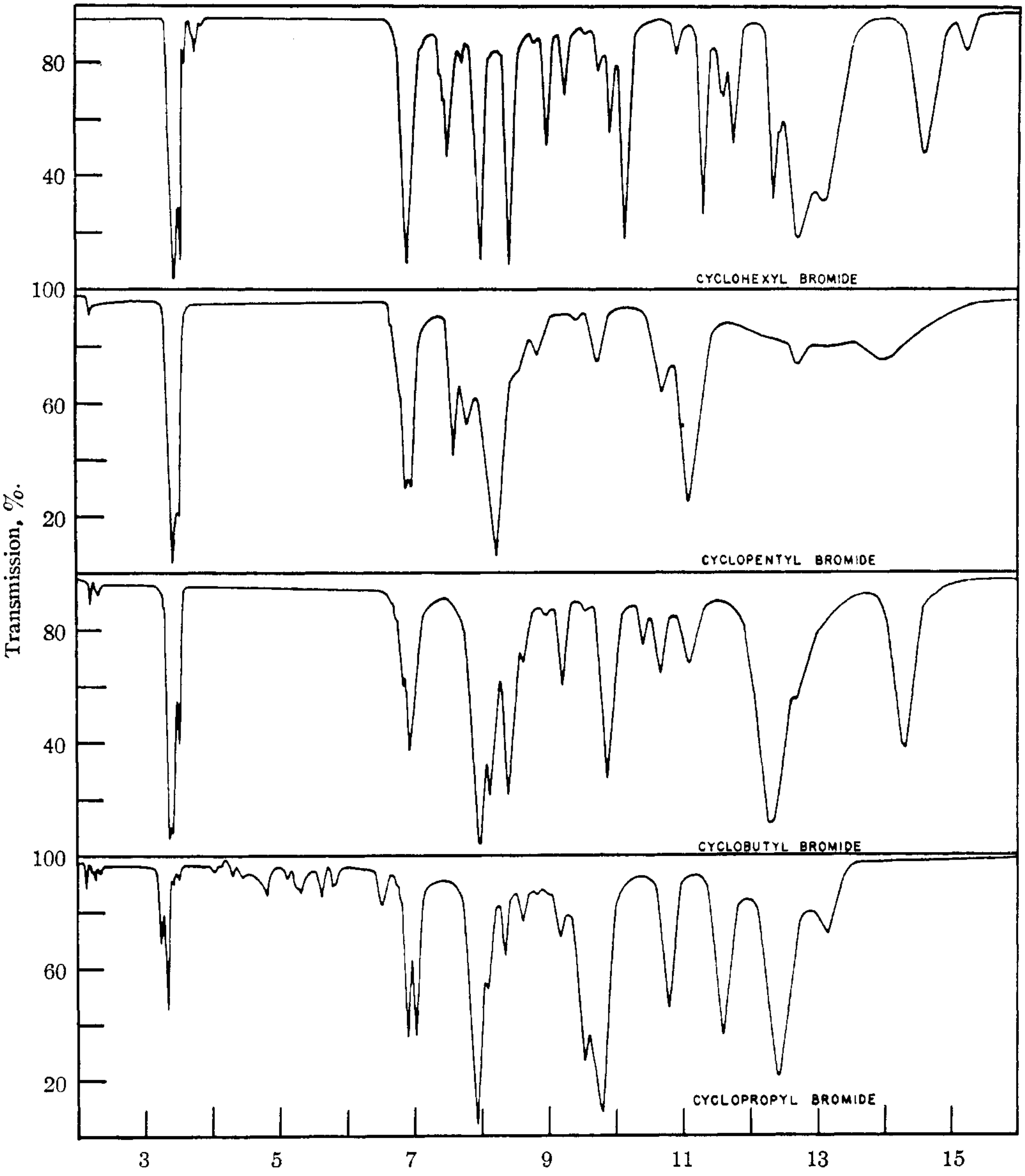

Fig. 3.—Infrared spectra.

titrations were carried out in a nitrogen atmosphere at 25.0 ± 0.1° and the change in water content of the solution resulting from the addition of aqueous hydrochloric acid was compensated by addition of ethanol. The change of acidity during the titration was followed as described earlier.[10a] The data are presented in Table II.

TABLE V

PHYSICAL PROPERTIES OF CYCLOALKYL DERIVATIVES, $(\overline{\underline{CH_2)_{n-1}C}}HX$

Ring size, *n*	x	B.p., °C.	Mm.	$n^{25}D$	d^{25}_4
3	Br[a]	69		1.4572	1.5052
4	Br[b]	108		1.4768	1.4197
5	Br[c]	56	48	1.4863	1.3867
6	Br[d]	79.6	50	1.4932	1.3299
3	Cl[e]	43		1.4079	0.990
4	Cl[f]	83		1.4332	.991
5	Cl[g]	113		1.4490	.982
6	Cl[d]	40.3	21	1.4601	.994
2	COOH[h]	70	50	1.4180	...
3	COOH[f]	105	48	1.4359	...
4	COOH[i]	93	16	1.4413	...
5	COOH[j]	91	8	1.4514	...
6	COOH[k]	110	8	....	...
3	NH_2[a]	49.7		....	...
4	NH_2[f]	82.2		....	...
5	NH_2[l]	108.0		....	...
6	NH_2[d]	133.7		....	...
3	$N(CH_3)_2$[m]	59.0		....	...
4	$N(CH_3)_2$[n]	100.9		....	...
5	$N(CH_3)_2$[o,p]	65	84	1.4379	...
6	$N(CH_3)_2$[o]	75	47	1.4517	...

[a] J. D. Roberts and V. C. Chambers, THIS JOURNAL, **73**, 3176 (1951). [b] Prepared by a modification of the procedure of J. Cason and R. L. Way, *J. Org. Chem.*, **14**, 31 (1949). [c] From cyclopentanol and phosphorus tribromide. [d] Purified commercial material. [e] J. D. Roberts and P. H. Dirstine, THIS JOURNAL, **67**, 1281 (1945). [f] Roberts and Mazur.[2] [g] From cyclopentanol, hydrochloric acid and zinc chloride. [h] Kindly supplied by Dr. A. C. Cope and redis-

tilled before use. [i] J. Cason and C. F. Allen, *J. Org. Chem.*, **14**, 1036 (1949). [j] From the carbonation of cyclopentylmagnesium bromide. [k] From the hydrogenation of benzoic acid; m.p. 31.0–31.6°. [l] From the hydrogenation of cyclopentanone oxime. [m] M. J. Schlatter, THIS JOURNAL, **63**, 1733 (1941). [n] J. D. Roberts and C. W. Sauer, *ibid.*, **71**, 3925 (1949). [o] Prepared by alkylation of the corresponding cycloalkylamine by a procedure similar to that employed by Roberts and Sauer[n] for cyclobutyldimethylamine. To ensure removal of all primary and secondary amines, the crude product was treated with benzoyl chloride and sodium hydroxide. [p] Picrate, yellow platelets from ethanol, m.p. 177–178° (dec.). *Anal.* Calcd. for $C_{13}H_{12}O_7H_4$: C, 45.61; H, 5.26. Found: C, 45.91; H, 5.44.

TABLE VI

DIELECTRIC CONSTANTS, DENSITIES AND POLARIZATIONS IN BENZENE AT 25°

f_2	ϵ	d	P_2
	Cyclopropyl bromide		
0.00000	(2.2725)	0.87278	(P_1 = 26.66)
.00510	2.290	.87562	75.1
.00999	2.310	.87837	78.7
.01959	2.348	.88386	79.8
.02908	2.386	.88915	79.8
.03844	2.423	.89437	79.6
.04776	2.462	.89990	79.5
	Cyclobutyl bromide		
0.00469	2.300	0.87550	114.1
.00900	2.326	.87792	115.6
.01753	2.376	.88275	113.8
.02604	2.428	.88752	113.9
.03537	2.483	.89304	112.0
.05033	2.574	.90177	111.0
	Cyclopentyl bromide		
0.00406	2.300	0.87524	128.9
.01374	2.361	.88107	125.1
.02429	2.428	.88746	123.6
.03529	2.498	.89420	122.1
.04848	2.583	.90221	120.9
.06033	2.658	.90941	119.5
	Cyclohexyl bromide		
0.00410	2.303	0.87516	147.5
.01458	2.378	.88170	141.3
.02977	2.485	.89084	138.1
.03725	2.535	.89547	135.9
.04519	2.592	.90022	135.1
.05471	2.656	.90587	133.4

Dipole moments were determined by the method described previously.[15] The data are given in Tables III and VI.

Infrared spectra of the cycloalkyl chlorides and bromides were taken with a Baird Recording Infrared Spectrophotometer. The samples were run successively in an 0.025 mm. rock salt cell without solvent and with a rock salt slab in the comparison cell compartment. The curves so obtained are given in Figs. 2 and 3. For the calculation of extinction coefficients, the curves were corrected for the difference in transmission between cell and salt block and Beer's law was assumed. The extinction coefficients at the absorption peaks are given in Table IV. The integrated extinction coefficients per C–H bond were obtained as described earlier.

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(15) J. D. Roberts, R. Armstrong, R. F. Trimble, Jr., and M. Burg, THIS JOURNAL, **71**, 843 (1949).

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[CONTRIBUTION FROM THE DEPARTMENT OF CHEMISTRY, MASSACHUSETTS INSTITUTE OF TECHNOLOGY, AND CONVERSE MEMORIAL LABORATORY, HARVARD UNIVERSITY]

Small-Ring Compounds. VIII. Some Nucleophilic Displacement Reactions of Cyclopropyl, Cyclobutyl, Cyclopentyl and Cyclohexyl *p*-Toluenesulfonates and Halides

BY JOHN D. ROBERTS[1] AND VAUGHAN C. CHAMBERS

A study has been made of the rates and products of some nucleophilic displacement reactions of cyclopropyl, cyclobutyl, cyclopentyl and cyclohexyl *p*-toluenesulfonates and halides. The solvolysis reactivity sequence of the *p*-toluenesulfonates in dry acetic acid was found to be cyclopentyl ~ cyclobutyl > cyclohexyl ≫ cyclopropyl. The hydrolysis rate sequence for the corresponding chlorides in 50% ethanol–50% water solution was similar except that the cyclobutyl derivative was more reactive than the cyclopentyl derivative. In acetolysis and hydrolysis, the cyclopropyl and cyclobutyl compounds react with rearrangement but without elimination. The cyclopentyl and cyclohexyl derivatives give no detectable rearrangement products but do yield considerable cyclopentene and cyclohexene, respectively. The reactivity sequence of the bromides toward sodium iodide in acetone was found to be cyclopentyl > cyclobutyl > cyclohexyl ≫ cyclopropyl. The significance of the experimental results lies primarily in the lack of any simple correlation of reactivity with ring size in contrast to expectations based on other properties of small-ring compounds.

Despite the very considerable work on the synthesis and reactions of small-ring compounds in the seventy years following the synthesis of cyclopropane by Freund,[2] very little information is available on the nucleophilic displacement reactions of cyclopropyl and cyclobutyl derivatives. Gustavson[3] early noted that cyclopropyl chloride was comparable in reactivity to 1-chloropropene toward alcoholic potassium hydroxide but made no mention of other nucleophilic reagents. Perkin[4] reported that a chloride obtained from "cyclobutanol" and phosphorus pentachloride reacted abnormally slowly with potassium iodide in acetone. However, the purity of Perkin's chloride is questionable since rearrangement products could be expected, not only in his preparation of cyclobutanol,[5,6] but in the reaction of the latter substance with phosphorus pentachloride.[6] No other work on nucleophilic displacement reactivities or reactions of cyclopropyl or cyclobutyl derivatives appears to have been published except for some research on cyclobutyl chloride[6] which will be referred to later

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(1) National Research Fellow in Chemistry, Harvard University, 1945–1946. Present address, Department of Chemistry, Massachusetts Institute of Technology, Cambridge, Mass.

(2) A. Freund, *Monatsh.*, **3**, 625 (1882).

(3) G. Gustavson, *J. prakt. Chem.*, [2] **43**, 396 (1891).

(4) W. H. Perkin, Jr., *J. Chem. Soc.*, **65**, 950 (1894).

(5) (a) N. J. Demjanow, *Ber.*, **40**, 4961 (1907); (b) R. Skrabal, *Monatsh.*, **70**, 420 (1937).

(6) J. D. Roberts and R. H. Mazur, THIS JOURNAL, **73**, 2509 (1951).