Esr spectra of the radicals were taken in aqueous solution at various pH's. The spectrum of radical 1 was almost independent of pH. The coupling constants were slightly different from those observed in toluene (Table I). The spectrum of radical 2 showed a marked pH dependence. In basic or neutral solutions the α-methylene protons were not equivalent and five quartets were observed. The methyl splittings were not resolved. As the pH was lowered the inner lines moved together, broadened, and collapsed into a single line. The intensity of this line was not twice that of the outer lines indicating that the protons are not completely equivalent at low pH values. The pH dependence of the spectrum probably results from protonation of the pyridine nitrogen at lower pH. If the average twist angles in the protonated species are different from those of the free base one predicts a change in the coupling constants. Differences in solvation may also affect the twist angles and be partially responsible for the changes in the methylene couplings with solvent and pH.

A full account of the pH dependence of the spectra of 2 and other nitronylnitroxides will be presented elsewhere.

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Nuclear Magnetic Resonance Spectra of *endo*-Bicyclo[2.1.0]pentan-2-ol, Cyclobutanol, and *cis*-1,3-Dibromocyclobutane[1]

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Abstract: Detailed analyses of the nmr spectra of the title compounds have been performed. The results permit one to compare the coupling constants for planar and puckered cyclobutane rings. The planar ring gave $J_{cis} = 9$ and $J_{trans} = 3.5$ Hz. The puckered ring gave $J_{ae} = 9.7$ and 7.9, $J_{aa} = 10.4$, and $J_{ee} = 2.3$ Hz. All of these values are in agreement with those expected based on the dihedral angles. The long-range coupling between equatorial hydrogens was 5.2 and 5.6 Hz and had a positive sign. The coupling constants for two related cyclobutane derivatives were found to be quite similar suggesting that the values given herein should provide useful starting points for the analysis of other cyclobutanes.

Although considerable data are now available on the nmr spectra of cyclopropane derivatives,[2] relatively few simple cyclobutanes have been studied.[3] One reason is that the nmr spectra of cyclobutane derivatives are generally quite complex and involve large numbers of overlapping lines. This makes the analysis of the spectra quite difficult.

It was of particular interest to us to examine representative compounds in which the difference in coupling constants between a planar cyclobutane ring and a puckered ring could be obtained. Thus, we have studied the bicyclo[2.1.0]pentan-2-ols[4] in which the cyclobutane ring will be forced into near planarity by fusion to a cyclopropane ring and cyclobutanol in which the ring would be expected to be puckered by 30–35°.[5] As an added check on the cyclobutanol parameters, the spectrum of *cis*-1,3-dibromocyclobutane[6] also was studied.

The 100-MHz spectra of the two isomeric bicyclo[2.1.0]pentan-2-ols are shown in Figures 1a–e and Figures 2a–c, respectively. The one later identified as the *exo* isomer consisted of four multiplets and a hydroxyl band. The two high-field multiplets represent one hydrogen each and almost certainly correspond to the cyclopropyl methylene hydrogens. The low-field multiplet must correspond to the hydrogen adjacent to the hydroxyl group. The remaining four hydrogens lead to a single complex multiplet.

The spectrum of the *endo* isomer is much simpler since each multiplet corresponds to only one hydrogen. Again the two high-field multiplets must result from the cyclopropane methylene hydrogens, and the low-field multiplet corresponds to the hydrogen adjacent to the hydroxyl group. In the following discussion, the seven multiplets and the corresponding hydrogen atoms have been numbered from 1 through 7 in the direction of increasing field.

Initial decoupling experiments at a 500-Hz sweep width provided identification of all large coupling constants in the spectrum of the *endo* isomer even though fine details could not be observed. Multiplets 3, 4, and 7 were complex patterns which resembled quartets of

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[1] This investigation was supported by the U. S. Army Research Office. The nmr spectrometer was obtained through a departmental instrument grant from the National Science Foundation.

[2] W. Brügel, "Nuclear Magnetic Resonance Spectra and Chemical Structure," Vol. 1, Academic Press, New York, N. Y., 1967, pp 66–69; K. B. Wiberg and B. J. Nist, *J. Am. Chem. Soc.*, **85**, 2788 (1963).

[3] *Cf.* I. Fleming and D. H. Williams, *Tetrahedron*, **23**, 2747 (1967).

[4] K. B. Wiberg, V. Z. Williams, Jr., and L. E. Friedrich, *J. Am. Chem. Soc.*, 90, 5338 (1968).

[5] Cyclobutyl bromide (W. G. Rothschild and B. P. Dailey, *J. Chem. Phys.*, 36, 2931 (1962)), cyclobutyl chloride (H. Kim and W. D. Gwinn, *ibid.*, 44, 865 (1966)), and *cis*- and *trans*-1,3-dibromocyclobutane (ref 6) have been found to be puckered by 30–35°. Similar results have been obtained for cyclobutane itself (P. Skanke, Thesis, Oslo, 1960).

[6] K. B. Wiberg and G. M. Lampman, *J. Am. Chem. Soc.*, **88**, 4429 (1966).

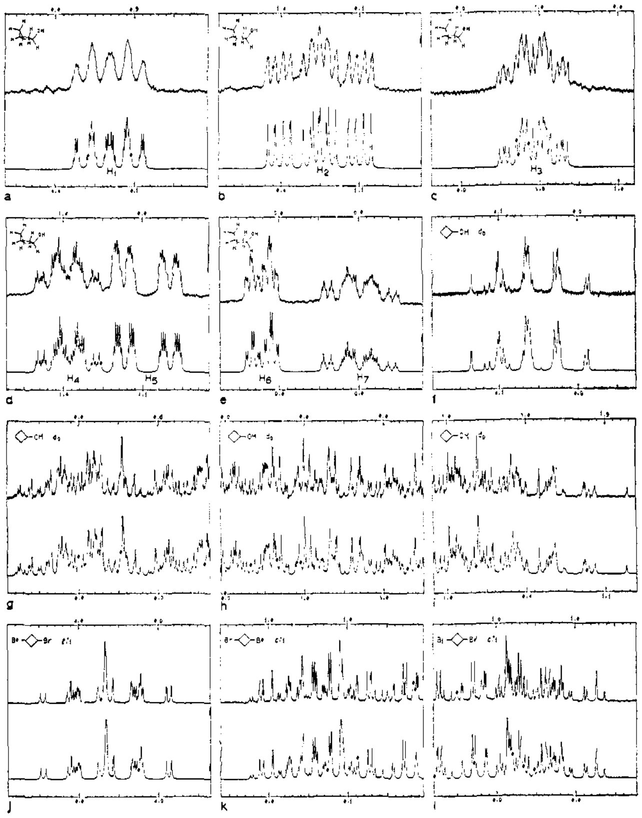

Figure 1. Experimental (upper traces) and calculated (lower traces) 100-MHz nmr spectra of (a–e) *endo*-bicyclo[2.1.0]pentan-2-ol, (f–i) cyclobutanol, and (j–l) *cis*-1,3-dibromocyclobutane.

equally spaced lines at this sweep width. Multiplet 6 appeared as a doublet with further small splitting. Irradiation of hydrogen 6 sharpened the quartet patterns of multiplets 3 and 4 while irradiation of hydrogen 7 converted these multiplets to complex triplet patterns. Irradiation of either hydrogen 3 or 4 caused sharpening of the doublet pattern of multiplet 6 and caused multiplet 7 to change from a complex quartet to a complex triplet.

The similar behavior of multiplets 3 and 4 toward irradiation of the cyclopropyl methylene hydrogens, and *vice versa*, suggested that these multiplets are due to the bridgehead hydrogens. It was evident from the irradiation experiments that $J_{36} \approx J_{46} < J_{37} \approx J_{47}$. Hydrogen 7 is probably in the *exo* position since the *cis*-vicinal cyclopropyl coupling constants should be greater than the *trans* coupling constants.[2]

The remaining hydrogens, 2 and 5, must then be the cyclobutyl methylene hydrogens. Multiplet 5, a doublet of doublets at a 500-Hz sweep width, was converted to a broad singlet by irradiation of hydrogen 2. This confirmed the assignment of hydrogens 2 and 5 since the 11.5-Hz splitting removed by this irradiation is the only one which is in the 11–14.5-Hz range expected for cyclobutyl geminal coupling.[3]

Irradiation of hydrogen 7 removed the 1.9-Hz splitting from multiplet 2 as shown in Figure 2f, while irradiation of hydrogen 6 had no effect on this multiplet. This confirmed the *exo* assignment of hydrogen 7 and suggested that hydrogen 2 also is in the *exo* position since this type of geometry is known to be required for long-range coupling.[7] Multiplet 5 was not changed by irradiation of hydrogen 7. The effect of irradiation of hydrogen 6 could not be determined because of the small chemical-shift difference between multiplets 5 and 6.

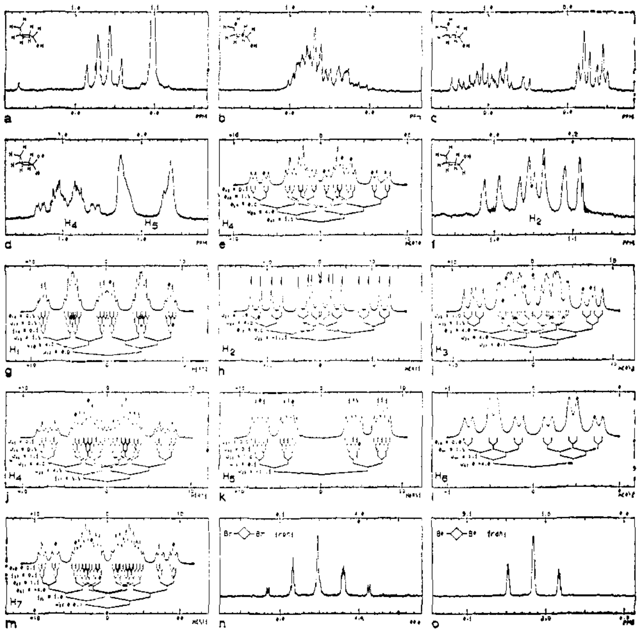

Figure 2. Experimental 100-MHz nmr spectra of (a–c) *exo*-bicyclo[2.1.0]pentan-2-ol, (d) *endo*-bicyclo[2.1.0]pentan-2-ol hydrogens 4 and 5 decoupled from hydrogen 1, (f) *endo*-bicyclo[2.1.0]-pentan-2-ol hydrogen 2 decoupled from hydrogen 7, and (n, o) *trans*-1,3-dibromocyclobutane. First-order analyses of nmr spectrum of (e) hydrogen 4 of *endo*-bicyclo[2.1.0]pentan-2-ol ignoring coupling with hydrogen 1 and (g–m) all hydrogens of *endo*-bicyclo-[2.1.0]pentan-2-ol except hydroxyl.

Irradiation of hydrogen 4 converted multiplet 2 to a fairly sharp equally spaced triplet. Irradiation of hydrogen 3 changed multiplet 1 from a quintet to a doublet of doublets. A first-order analysis of the spectrum suggested $J_{13} = 4.2$ Hz and $J_{24} = 4.0$ Hz. For puckered cyclobutanes, we have found cross-ring coupling constants this large only between equatorial hydrogens. These values are approximately twice the 2.3-Hz maximum previously reported for cross-ring coupling in the cyclobutane ring.[3] Thus, hydrogen 4 must be located adjacent to the cyclobutane ring methylene group since neither hydrogen 1 nor hydrogen 2 is in an equatorial location. A first-order analysis of multiplet 4 indicated that the smallest coupling to hydrogen 4 is 0.5 Hz, and the same splitting appears in multiplet 5. Examination of models of bicyclo[2.1.0]pentane suggests that the dihedral angle between bridgehead hydrogen 4 and the *endo*-cyclobutyl methylene hydrogen is nearly 90° which would lead to a very small vicinal coupling constant.[8] It therefore seemed likely that multiplet 5 corresponds to the *endo*-cyclobutyl methylene hydrogen.

The first-order analysis of the spectrum also showed that J_{12} is about twice as large as J_{15}. This indicated that hydrogen 1 is in the *exo* position *cis* to hydrogen 2 since the *cis*-vicinal coupling constant for a planar ring should be larger than the *trans* coupling constant.[2] This conclusion is further strengthened by the observa-

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[7] J. Meinwald and A. Lewis, *J. Am. Chem. Soc.*, **83**, 2769 (1961); K. B. Wiberg, B. R. Lowry, and B. J. Nist, *ibid.*, **84**, 1594 (1962).

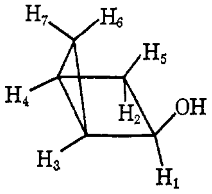
[8] *Cf.* H. Conroy in "Advances in Organic Chemistry, Methods and Results," Vol. 2, R. A. Raphael, E. C. Taylor, and H. Wynberg, Ed., Interscience Publishers, New York, N. Y., 1960, p 265.

tion that $J_{13} \approx J_{24}$. Hydrogen 1 is coupled by only 0.5 Hz to the *exo*-cyclopropyl methylene hydrogen. The relatively small long-range constant is probably at least in part due to electron withdrawal by the hydroxyl group.

First-order splitting networks could now be drawn for multiplets 2 and 6. Additional information was sought for the remaining multiplets *via* decoupling experiments at a 50-Hz sweep width. Irradiation of hydrogen 7 converted multiplet 5 from a doublet of doublets of quintets to a doublet of doublets of quartets by removal of one of the 0.5-Hz couplings. Irradiation of hydrogen 3 converted multiplet 5 to a doublet of wide doublets, evidently by removal of a 1.0-Hz coupling. The remaining 0.5-Hz coupling was assigned to J_{45} as noted above. This accounted for all lines in multiplet 5 since the two large splittings had been assigned as due to J_{25} and J_{15}.

Irradiation of hydrogen 6 converted multiplet 3 to a pattern recognizable as a doublet of triplets of doublets by removal of a 1.5-Hz splitting. The largest splitting was assigned to J_{37}. The triplet structure obviously originated from two similar coupling constants, one of which was J_{13}. Tentative assignment of the second of these couplings as J_{34} was later confirmed by observation of the same splitting in multiplet 4.

Irradiation of hydrogen 1 converted multiplet 4 to the simplified pattern shown Figure 2d. All lines in the decoupled pattern could be assigned as shown in Figure 2e on the basis of the splittings observed in the other multiplets. The data given above indicate the numbering of the hydrogens to be



Further refinement of the coupling constants and chemical shifts was accomplished using the LAOCN3 computer program.[9] Most lines of multiplets 2, 3, 4, 5, and 6 were initially matched with observable peaks. Only the outermost 16 lines of multiplet 7 were assigned. No lines in multiplet 1 were used for the initial fit because the individual lines had not been clearly observed in the broad bands of the quintet. The resultant computer fit allowed identification of all lines in multiplet 7, and indicated that additional small splittings should be seen in multiplet 1. Fourteen of the expected peaks could be located, but coupling with the hydroxyl proton obscured much of the structure.[10] A total of 400 lines could be assigned after the final computer fit with an rms error in frequency of 0.088 Hz. The calculated spectrum based on the calculated line positions and intensities is shown in Figures 1a–e as envelopes of summed Lorentzian curves with a 0.3-Hz width at half-height. The complete first-order analysis of the spectrum is diagramed in Figures 2g–m. The coupling constants and chemical shifts are summarized in Table I.

Table I. Chemical Shifts[a] and Coupling Constants[b] for *endo*-Bicyclo[2.1.0]pentan-2-ol

δ_1	4.2611	J_{12}	9.04
δ_2	2.2990	J_{13}	4.22
δ_3	1.8151	J_{14}	±0.49
δ_4	1.3874	J_{15}	3.52
δ_5	1.1911	J_{16}	±0.47
δ_6	0.8403	J_{17}	±0.47
δ_7	0.6029	J_{23}	±0.10
		J_{24}	3.98
		J_{25}	−11.54
		J_{26}	±0.01
		J_{27}	±1.87
		J_{34}	4.47
		J_{35}	±1.00
		J_{36}	1.46
		J_{37}	6.11
		J_{45}	0.48
		J_{46}	1.49
		J_{47}	5.52
		J_{56}	0.00
		J_{57}	±0.48
		J_{67}	−4.64

[a] Chemical shifts are given in parts per million downfield from internal TMS. [b] Values in hertz. The relative signs of the long-range coupling constants could not be deduced from the analysis of the spectrum in this case.

We may now consider the *exo* isomer, Figures 2a–c. Again, the two upfield multiplets correspond to one hydrogen each and must originate with the cyclopropyl methylene group. The appearance of the multiplets clearly indicates that the relative chemical shifts of hydrogens 6 and 7 (using the numbering system for the *endo* isomer) have inverted, and that the multiplet farthest upfield corresponds to hydrogen 6. The coupling constants to hydrogen 6 are the same as for the *endo* isomer ($J_{36} = J_{46} = 1.4$ Hz, $J_{67} = -4.6$ Hz) except that the 0.5-Hz J_{16} is lost since hydrogen 1 is now *endo*.

The multiplet at lowest field again must correspond to hydrogen 1. The multiplet corresponding to hydrogens 2, 3, 4, and 5 is too complex at 100 MHz to permit a detailed interpretation. However, it is clear that the chemical shift for all four hydrogens is 1.7 ± 0.1 ppm. A comparison of the values for the *exo* and *endo* isomers is given in Table II.

Table II. Comparison of Spectral Parameters[a] for *exo*- and *endo*-Bicyclo[2.1.0]pentan-2-ols

Parameter	*exo*	*endo*	Difference
δ_1	3.73	4.26	0.53
δ_2	1.7 ± 0.1	2.30	0.6
δ_3	1.7 ± 0.1	1.82	0.1
δ_4	1.7 ± 0.1	1.39	−0.3
δ_5	1.7 ± 0.1	1.19	−0.5
δ_6	0.54	0.84	−0.30
δ_7	0.79	0.60	−0.19

[a] In parts per million.

The change in chemical shift of hydrogen 1 on being moved from the *endo* to the *exo* position (0.5 ppm) is expected since hydrogens placed over a cyclopropane ring normally experience an upfield shift.[11] The next obvious change is the shift in position of hydrogens 2 and 5. Although their chemical-shift difference is 1.1 ppm in the *endo* isomer, it is only about 0.1 ppm in the

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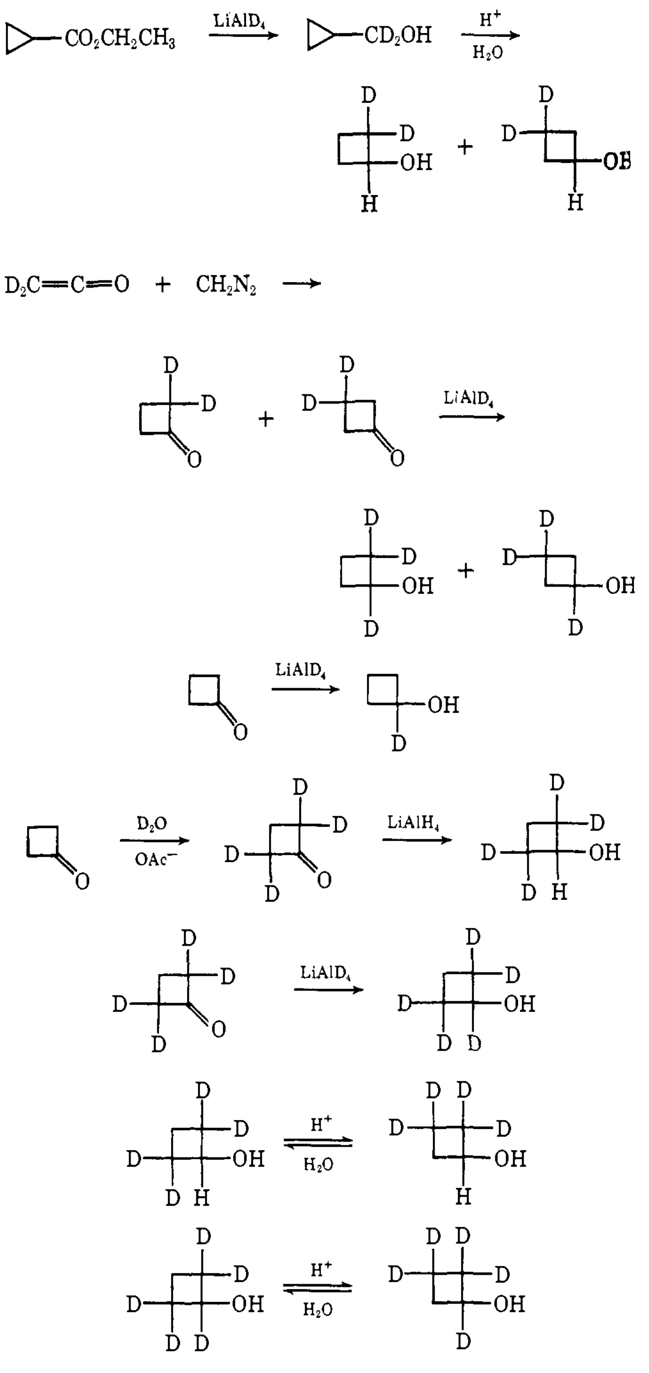
(9) A. A. Bothner-By and S. M. Castellano in "Computer Programs for Chemistry," Vol. I, D. F. DeTar, Ed., W. A. Benjamin, Inc., New York, N. Y., 1968, Chapter 3.

(10) Elimination of the coupling to the hydroxyl proton by the addition of acid was not possible with the *endo* isomer because of its marked reactivity toward acid.

(11) W. G. Dauben and W. T. Wipke, *J. Org. Chem.*, 32, 2976 (1967).

Scheme I



exo isomer. In the absence of the hydroxyl group, we would expect the band for hydrogen 5 to be 0.5 ppm upfield from that of hydrogen 2 because of the effect of the cyclopropane ring. The hydroxyl group will probably lead only to a relatively small difference in chemical shift between the two hydrogens.[12] In each case the hydroxyl group will probably lead to a small local distortion which will bring the group toward an equatorial position. With the *endo* isomer, such deformation will move hydrogen 5 nearer the cyclopropane ring giving an upfield shift and, with the *exo* isomer, it will be moved away from the cyclopropane ring and should lead to a band farther downfield.

The chemical-shift difference between hydrogens 6 and 7 presumably arise from the hydroxyl group. It would be interesting to try to compare the chemical-shift difference between these protons with that between protons 2 and 5 using the magnetic anistropy of the C–O bond. However, the necessary structural information concerning the bicyclo[2.1.0]pentane ring is not available. The relative positions of hydrogen 6 and the hydroxyl group are particulary uncertain.

We next shall consider the spectrum of cyclobutanol. The spectrum contains over 200 peaks or reproducible shoulders (Figures 1f–i). A total of five sets of chemical shifts and thirteen sets of coupling constants are needed in order to reproduce the spectrum. Since only the α-hydrogen chemical shift could be measured directly, it was decided to obtain these parameters through an analysis of the spectra of specifically deuterated cyclobutanols. The syntheses of the species of interest are indicated in Scheme I.

The four different methylene hydrogen chemical shifts and the two geminal coupling constants were obtained from the doublet of doublets spectra of cyclobutanol-1,2,2,3,3-d_5 and of cyclobutanol-1,2,2,4,4-d_5. The geminal couplings were each 10.9 Hz and were assumed to be negative. The β-hydrogens were at lower field than the γ-hydrogens although it was not possible to distinguish between axial and equatorial chemical shifts. Because of incomplete deuterium substitution, the spectrum of the cyclobutanol-1,2,2,4,4-d_5 sample contained additional small peaks due to cyclobutanol-1,2,2-*cis*-4-d_4 and cyclobutanol-1,2,2-*trans*-4-d_4. The β-hydrogens of these compounds appear as doublets of doublets with splittings which were used as initial estimates for the corresponding coupling constants. The intensities of the central pair of peaks of the high-field β-hydrogen doublet of doublets ran counter to the pronounced over-all increase of intensity in the direction of the γ-hydrogens. The observed intensities of the high-field β-hydrogen doublet of doublets were reproduced only when its 9.0- and 10.3-Hz splittings were assigned as the coupling constants with the low-field γ-hydrogen and with the high-field γ-hydrogen, respectively. All major lines of this spectrum were observed experimentally. The low-field β-hydrogen doublet of doublets showed splittings of 2.4 and 7.7 Hz. The corresponding γ-hydrogen pattern was seen to consist of two doublets of doublets with the high-field doublet of doublets showing both the 7.7-Hz vicinal splitting and the 10.9-Hz geminal splitting. Two peaks of the low-field γ-hydrogen doublet of doublets were hidden under the intense cyclobutanol-1,2,2,4,4-d_5 spectrum so that the 2.4-Hz splitting was not observed, but the remaining two peaks showed the 10.9-Hz geminal splitting.

The coupling between the low-field β-hydrogen and the low-field γ-hydrogen was therefore considerably smaller than the other three vicinal couplings between these hydrogens. The coupling constants should be roughly proportional to the squares of the cosines of the dihedral angles which were estimated from the coordinates for cyclobutyl chloride[5] to be as shown in Table III. It is evident that the low-field β-hydrogen and the low-field γ-hydrogen must be in the equatorial positions.

The equatorial location of the low-field γ-hydrogen was further supported by the spectrum of cyclobutanol-2,2,4,4-d_4 in which only the low-field γ-hydrogen was

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[12] The hydrogens *trans* to the hydroxyl group of cyclopropanol were found to give a band at 0.08 ppm higher field than the *cis* hydrogens (D. E. Barth, unpublished results).

Table III

β-Hydrogen	γ-Hydrogen	Angle, deg	cos^2
Equatorial	Equatorial	115.9	0.191
Equatorial	Axial	11.8	0.958
Axial	Equatorial	15.7	0.927
Axial	Axial	143.5	0.646

split by the α-hydrogen. This 1.0 cross-ring coupling was assumed to be negative.

The spectrum of cyclobutanol-2,2,3,3-d_4 consisted of three doublets of doublets. These confirmed the value of the geminal coupling constant between the β-hydrogens and established that the couplings between α-hydrogen and equatorial β-hydrogen and between α-hydrogen and axial β-hydrogen were 7.0 and 8.1 Hz, respectively.

With these data, the coupling constants and chemical shifts necessary for the calculation of the spectrum of cyclobutanol-2,2-d_2 were available. After minor adjustment of the chemical shifts to compensate for the differing deuterium substitution, all peaks expected for the compound were found in the spectrum of the mixture of cyclobutanol-2,2-d_2 and cyclobutanol-3,3-d_2. A set of 80 trial spectra were calculated in an attempt to match the peaks left when those due to cyclobutanol-2,2-d_2 were subtracted. A good visual match was obtained with the following cross-ring coupling constants: $J_{\text{equatorial-equatorial}} = -5.0$ Hz, $J_{\text{equatorial-axial}} = -1.0$ Hz, and $J_{\text{axial-axial}} = 0.0$. It was, however, evident that these coupling constants were not correct since the rms error in peak positions remained considerably greater than the expected experimental error when a least-squares fit was attempted.

At this stage it was decided that it might be helpful to analyze the AA'BB' spectrum of cyclobutanol-1,3,3-d_3. The spectrum of this compound was obtained by subtracting the calculated spectrum of cyclobutanol-1,2,2-d_3 from the spectrum of the mixture of the two compounds. Two triplets flanked by triplets of doublets remained when this was done. The triplets were actually triplets of closely spaced doublets since 24 lines should have been observed. Weak double irradiation was not used for the construction of the energy level diagram since in no instance could only a single line be irradiated. The four-spin system was, however, small enough for a computer search of all probable values of the three unknown coupling constants. The first half of the nmr fitting program LAOCOON-II[13] was modified to perform such a search with the coupling constants being stepped at 0.5-Hz intervals. Gates were installed which checked both line intensities and the rms error in line positions after each trial spectrum was calculated. Only spectra which passed through these gates were printed. The ranges over which the coupling constants were searched were as follows: $J_{\text{equatorial-equatorial}} = -6.0$ to -4.0 and 4.0 to 6.0 Hz, $J_{\text{equatorial-axial}} = -3.0$ to 3.0 Hz, and $J_{\text{axial-axial}} = -1.0$ to 1.0 Hz. Two minima in rms error were found for the spectra which matched the gate requirements. The coupling constants which corresponded to these minima were as follows: $J_{\text{equatorial-equatorial}} = +5.0$ and -5.0 Hz, $J_{\text{equatorial-axial}} = -1.0$ and -0.5 Hz, and $J_{\text{axial-axial}} =$

Table IV. Chemical Shifts[a] and Coupling Constants[b] for Cyclobutanol

	d_0	1-d_1	2,2-d_2	3,3-d_2	1,2,2-d_3	1,3,3-d_3	1,2,2-*cis*-4-d_4	1,2,2-*trans*-4-d_4	2,2,3,3-d_4	2,2,4,4-d_4	1,2,2,3,3-d_5	1,2,2,4,4-d_5
δ_1	4.1230		4.1069	4.1138					4.0981	4.0920		
$\delta_2 = \delta_3$	2.1959	2.1880	2.1875	2.1787	2.1808	2.1712	2.1576		2.1722		2.1656	
$\delta_4 = \delta_5$	1.8772	1.8651	1.8632	1.8510	1.8575	1.8456		1.8384	1.8454		1.8394	
δ_6	1.6293	1.6245	1.6106		1.6076		1.5996	1.5995		1.5956		1.5929
δ_7	1.4067	1.3987	1.3865		1.3794		1.3691	1.3707		1.3684		1.3616
$J_{12} = J_{13}$	6.96		6.91	6.94					7.01			
$J_{14} = J_{15}$	8.09		8.04	8.03					8.12			
J_{16}	−1.07		−0.97							−1.05		
J_{17}	−0.01		0.00							0.05		
J_{23}	5.16	5.15		5.14		5.24						
$J_{24} = J_{35}$	−10.91	−10.91	−10.88	−10.89	−10.82	−10.87			−10.93		−10.90	
$J_{25} = J_{34}$	−0.93	−0.93		−0.90		−0.88						
$J_{26} = J_{36}$	2.25	2.26	2.27		2.25		2.15					
$J_{27} = J_{37}$	7.90	7.89	7.98		7.91		7.87					
J_{45}	0.01	0.00		0.00		0.07						
$J_{46} = J_{56}$	9.65	9.65	9.62		9.69			9.66				
$J_{47} = J_{57}$	10.37	10.37	10.35		10.38			10.34				
J_{67}	−10.95	−10.96	−10.93		−10.92		−10.95	−10.97		−10.90		−10.85
No. of lines assigned	299	152	81	61	31	24	10	11	11	12	4	4
Rms error of line positions, Hz	0.065	0.062	0.066	0.069	0.053	0.070	0.024	0.019	0.021	0.041	0.000	0.025

[a] In parts per million (ppm). [b] In hertz (Hz).

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(13) S. M. Castellano and A. A. Bothner-By, *J. Chem. Phys.*, 41, 3863 (1964).

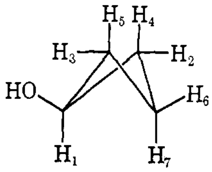
Table V. Chemical Shifts[a] and Coupling Constants[b] for *cis*-1,3-Dibromocyclobutane

	cis-1,3-Dibromo-cyclobutane	Cyclobutanol
$\delta_1 = \delta_2$	4.1257	4.1230
$\delta_3 = \delta_4$	3.2734	2.1959
$\delta_5 = \delta_6$	2.9166	1.8772
J_{12}	Not observable	−0.01
$J_{13} = J_{14} = J_{23} = J_{24}$	7.11	6.96
$J_{15} = J_{16} = J_{25} = J_{26}$	8.84	8.09
J_{34}	5.57	5.16
$J_{35} = J_{46}$	−12.42	−10.91
$J_{36} = J_{45}$	−1.14	−0.93
J_{56}	−0.30	0.01
No. of lines assigned	125	
Rms error of line positions, Hz	0.056	

[a] In parts per million (ppm). [b] In hertz (Hz).

0.0 and 0.0 Hz. Fitting of peak positions was attempted with both sets of initial values. Only the set having the positive equatorial–equatorial cross-ring coupling resulted in a low rms error in peak positions. No spectra with a positive equatorial–axial cross-ring coupling passed through the gates. This also confirmed the assumed sign of the coupling between the α-hydrogen and the equatorial γ-hydrogen which was of similar magnitude.

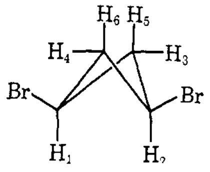
The spectra of cyclobutanol-3,3-d_2, cyclobutanol-1-d, and cyclobutanol all were matched easily without any further difficulty. The chemical shifts and coupling constants found for each of the 12 cyclobutanol species are listed in Table IV. The number system adopted for the cyclobutanol hydrogens is based on the order of their appearance in the spectrum and is as follows.



As a check on the coupling constants which had been obtained for cyclobutanol, the spectrum of *cis*-1,3-dibromocyclobutane also was examined (Figures 1j–l). The 100-MHz nmr spectrum of this compound contains 100 peaks. Three sets of chemical shifts and six sets of coupling constants are necessary to reproduce the spectrum. The coupling constant between the hydrogens on the bromine bearing carbons was not determined as it has no effect on the spectrum. These two hydrogens have equal chemical shifts and are identically coupled to each of the methylene hydrogens. Peaks at 3.099 and 3.035 ppm in the experimental spectrum are due to a small amount of *trans*-1,3-dibromocyclobutane (Figures 2n–o) in the sample.

Coupling constants for trial spectra were based on those found for cyclobutanol. The three sets of chemical shifts were estimated from the experimental spectrum. The lowest field chemical shift was obviously that of the hydrogens on the bromine-bearing carbons. However, similar spectra were calculated for both possible assignments of the two remaining chemical shifts to axial and equatorial methylene hydrogens. An accurate least-squares fit of line positions was obtained only when it was assumed that the axial methylene hydrogens appeared at highest field.

The numbering system adopted for the *cis*-1,3-dibromocyclobutane hydrogens is based on the order of their appearance in the spectrum and is as follows.



The final set of chemical shifts and coupling constants is summarized in Table V.

We may now consider the coupling constants for the planar and puckered cyclobutane rings. For the planar ring, J_{cis} = 9 Hz and J_{trans} = 3.5 Hz. The large difference between the coupling constants with $J_{cis} > J_{trans}$ is similar to that observed with the cyclopropanes. With the puckered ring J_{cis} = 9.7 and 7.9 Hz and J_{trans} = 2.3 (e,e) or 10.4 Hz (a,a) depending on whether the coupling is between equatorial or axial hydrogens.[14] The difference in coupling constants in each case agrees with those expected based on the dihedral angles between the C–H bonds, remembering that $J_{180°} > J_{0°}$.

The cyclobutane ring was found to give long-range coupling constants between the equatorial hydrogens of 5.2 and 5.6 Hz in cyclobutanol and *cis*-1,3-dibromocyclobutane. The similarity of the coupling constants suggests that the second equatorial substituent does not significantly affect the conformation of the cyclobutane ring. The constant is smaller than that for bicyclo[2.1.1]hexanes (J = 6.8–8.1 Hz)[7] and bicyclo[3.1.1]heptanes (J = 5.5–6.0 Hz).[15] Thus, it is clear that the magnitude of the coupling constant is a measure of the puckering of the ring.[16]

The relatively fixed geometry of substituted cyclobutanes has the potential for estimating the magnetic anisotropy of substituent groups. The four types of hydrogens which are not connected to the carbon bearing the substituent are located in space in such a way as to give a good measure of the anistropy. This will be considered in detail in connection with the spectra of the halocyclobutanes which are under study.

Experimental Section

Nmr Spectra. All samples were purified by preparative gas chromatography.[17] The samples were mixed with carbon tetrachloride containing 4% by volume of tetramethylsilane, degassed, and sealed under vacuum. The *endo*-bicyclo[2.1.0]pentan-2-ol and *cis*-1,3-dibromocyclobutane concentrations were 0.5 and 1.0 *M*, respectively. The total concentration in each of the various deuterated cyclobutanol mixtures was 2.0 *M*.

Spectra were obtained using a Varian HA-100 nmr spectrometer equipped with a Nuclear Magnetic Resonance Specialties SD-60 heteronuclear spin decoupler. The frequency sweep mode was used. All spectra of deuterium-labeled compounds were hydrogen–deuterium decoupled. The magnet temperature was maintained at 31.5°. The methylene region of cyclobutanol proved to be quite temperature dependent. Each peak position was measured to ±0.1 Hz by stopping the frequency sweep at the peak maximum

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(14) The coupling constants given are between the β- and γ-hydrogens. The values are somewhat smaller between the α- and β-hydrogens (J_{ae} = 7.0 Hz and J_{aa} = 8.1 Hz).

(15) K. B. Wiberg and B. A. Hess, *J. Org. Chem.*, 31, 2250 (1966).

(16) *Cf.* K. B. Wiberg, G. M. Lampman, R. P. Ciula, D. S. Connor, P. Schertler, and J. Lavanish, *Tetrahedron*, 21, 2749 (1965).

(17) Samples of the 1,3-dibromocyclobutanes were provided by G. M. Lampman[6] and samples of the bicyclo[2.1.0]pentan-2-ols were provided by V. Z. Williams, Jr.[4]

and counting the difference in frequency between the observing and locking oscillators.

Spectra were calculated using the first half of LAOCOON-II.[13] Once a visual fit had been achieved, the chemical shifts and coupling constants were adjusted using LAOCN3.[9] Calculated spectra were plotted as envelopes of summed Lorentzian curves with 0.3 Hz half-height peak widths using SPCTRM-II.[18]

Cyclobutanol. Cyclobutanol was prepared by the acid-catalyzed rearrangement of cyclopropylcarbinol.[19] Cyclobutanone was prepared by the chromic acid oxidation of cyclobutanol and was obtained in a 20% yield. The lithium aluminum deuteride reduction of cyclobutanone gave cyclobutanol-1-d. Cyclopropylcarbinol-d_2 was obtained by the lithium aluminum deuteride reduction of ethyl cyclopropanecarboxylate and was treated with aqueous acid to give a mixture of cyclobutanol-2,2-d_2 and cyclobutanol-3,3-d_2.

A 1:1 mixture of cyclobutanone-2,2-d_2 and cyclobutanone-3,3-d_2 was prepared by the reaction of ketene-d_2 with diazomethane.[20] Ketene-d_2 was obtained by the pyrolysis of acetone-d_6 in a miniature ketene lamp.[21] Reduction of the ketone mixture with lithium aluminum deuteride gave a mixture of cyclobutanol-1,2,2-d_3 and cyclobutanol-1,3,3-d_3.

The exchange of the α-hydrogens of cyclobutanone with deuterium oxide was effected using sodium acetate as the catalyst.[19] Reduction with lithium aluminum hydride gave cyclobutanol-2,2,4,4-d_4. Reduction with lithium aluminum deuteride gave cyclobutanol-1,2,2,4,4-d_5. The acid-catalyzed rearrangement of cyclobutanol-2,2,4,4-d_4 using the conditions for the cyclopropylcarbinol rearrangement gave a mixture of the reactant and cyclobutanol-2,2,3,3-d_4. The acid-catalyzed rearrangement of cyclobutanol-1,2,2,4,4-d_5 gave a mixture of the reactant and cyclobutanol-1,2,2,-3,3-d_5.

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Solvolysis of Organic Phosphates. I. Pyridylmethyl Phosphates

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Abstract: Spontaneous hydrolyses of 2-, 3-, and 4-pyridylmethyl phosphates investigated at 90° and $\mu = 0.10$ over the $-\log [H^+]$ range from 1 to 8.7 followed first-order kinetics with respect to unreacted phosphate species, and the maximum rate was observed at approximately 2.5 in $-\log [H^+]$ for all the phosphates. Reactive species of each phosphate in hydrolysis were the neutral zwitterion and the monoanion, where the former was found to be more labile. A profound reactivity of the zwitterion form of 2-pyridylmethyl phosphate was attributed to the unique intramolecular proton-transfer mechanism. Among various bivalent metal ions used in hydrolysis of pyridylmethyl phosphates at 90° and $\mu = 0.10$, only the copper ion promoted the reaction rate of 2-pyridylmethyl phosphate to a considerable extent in a $-\log [H^+]$ range above 3.3. Since the copper ion did not demonstrate any meaningful catalysis for other pyridylmethyl phosphates, the particular copper complex formed with 2-pyridylmethyl phosphate in the transition state was put forward to elucidate this enhanced catalytic effect.

The considerable importance of phosphate esters in biological systems has prompted the solvolysis study of various organic phosphates in recent years, and a large amount of experimental results has been accumulated on the hydrolyses of monoalkyl phosphates. Reviews which treated the recent progress in this field have also appeared.[2–4] In spite of these active investigations hitherto carried out, the hydrolysis of organic phosphate esters, which contain heteroaromatic moieties, such as pyridine nuclei, has never been investigated to any extent.

On the other hand, the effect of metal ions on the hydrolytic reactions of phosphate monoesters is one of the interesting aspects of metal ion catalysis, and has been the subject of a number of research groups.[5] For example, the specific activities of some metal ions in the hydrolysis of salicyl phosphate have been investigated by Martell and his coworkers, and the catalytic process has been discussed in the light of the mechanistic structures of metal complexes formed with the substrate in the course of reaction.[6–8] However, previous investigations have not provided any convincing explanation of the reaction mechanism involved in these metal ion catalyses.

In the present work, the spontaneous hydrolyses of the three isomeric pyridylmethyl phosphates, *i.e.*, 2-pyridylmethyl phosphate, 3-pyridylmethyl phosphate, and 4-pyridylmethyl phosphate, were studied in aqueous media, and the catalytic effects of some bivalent metal ions on the hydrolysis reactions were investigated. In addition, the hydrolysis of phenyl phosphate was also studied in the presence of various metal ions. Since metal ions are expected to interact with phenyl phosphate at only the phosphate group in the course of reac-

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