Irradiation of Chlorobenzene in Cyclohexane in the Presence of Triethylamine. A solution (5 mL, 0.025 M) of chlorobenzene (**I**) and 0.038 M triethylamine (XVII) in cyclohexane (II) was irradiated for 3 h after degassing. The reaction mixture consisted of a colorless liquid and a white precipitate. This precipitate was found to be the hydrochloride of triethylamine (NMR, D_2O). The solution analyzed by VPC showed consumption of chlorobenzene (60%), little or no chlorocyclohexane (III), but a significant amount of bicyclohexyl (XV, 21%).

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References and Notes

(1) Contribution No. 164 from the Photochemistry Unit. A portion of this work was presented at the Chemical Institute of Canada meeting, June 1976, No. Org. 49a.

(2) (a) M. A. Fox, W. C. Nichols, and D. M. Lemal, *J. Am. Chem. Soc.*, **95**, 8164 (1973); (b) M. A. Fox, Ph.D. Thesis, Dartmouth College, 1974.

(3) (a) A. L. J. Beckwith and W. B. Gara, *J. Chem. Soc., Perkin Trans. 2*, 593 (1975); (b) *ibid.*, 795 (1975).

(4) The published account made no mention of XV; however, the thesis described this compound as a minor product (11%).[2]

(5) H. A. J. Carless, *Photochemistry*, **6**, 531 (1975).

(6) G. Porter and B. Ward, *Proc. R. Soc. London, Ser. A*, **287**, 457 (1965).

(7) T. Ichimura and Y. Mori, *J. Chem. Phys.*, **58**, 288 (1973).

(8) J. T. Pinhey and R. D. G. Rigby, *Tetrahedron Lett.*, 1267 (1969).

(9) It is not clear how much of the pinacol came from the secondary irradiation of acetone under these conditions.

(10) G. E. Robinson and J. M. Vernon, *J. Chem. Soc. C*, 3363 (1971).

(11) W. A. Cramer, *J. Phys. Chem.*, **71**, 1171 (1967).

(12) (a) P. J. Kropp, *J. Am. Chem. Soc.*, **91**, 5783 (1969); (b) R. Bonneau, J. Joussot-Dubien, L. Salem, and A. J. Yarwood, *ibid.*, **98**, 4329 (1976).

(13) J. A. Barltrop, N. J. Bunce, and A. Thomson, *J. Chem. Soc. C*, 1142 (1967).

(14) T. Tosa, C. Pac, and H. Sakurai, *Tetrahedron Lett.*, 3635 (1969).

(15) S. W. Massie, U.S. Patent 3 812 448; *Chem. Abstr.*, **81**, 25324u (1974).

(16) "Dictionary of Organic Compounds", Vol. 2, Eyre and Spottiswoode, London, 1970, p 683.

Flow Nuclear Magnetic Resonance Investigation of the Intermediates Formed during the Bromination of Phenols in Acetic Acid[1]

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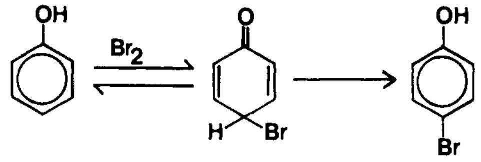
Abstract: High-resolution flow nuclear magnetic resonance spectroscopy has been used to detect and to characterize the 2,5-cyclohexadienone intermediates formed from the reaction of 2,6-disubstituted phenols ($R_1 = R_2 =$ *t*-Bu; $R_1 = R_2 =$ *sec*-Bu; $R_1 = R_2 =$ *i*-Pr; $R_1 = CH_3$, $R_2 =$ *t*-Bu; $R_1 = R_2 = CH_3$; $R_1 = H$, $R_2 =$ *t*-Bu) with bromine in aqueous acetic acid solution. The lifetimes of these intermediates have been measured as a function of both temperature and acetic acid concentration and the results are compared with literature data on the reaction.

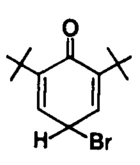
Originally, the characterization of intermediates depended on their isolation from the reaction mixture. The advent of spectroscopic techniques has since made possible the investigation of such species "in situ" and the development of flow and stopped-flow techniques employing UV-visible spectroscopy has made possible the investigation of very short-lived species. Although high-resolution nuclear magnetic resonance spectroscopy has become one of the most successful methods for the determination of organic structures, until very recently it has not been used in flow or stopped-flow methods. We have developed in our laboratory equipment and techniques for the measurement of high-resolution NMR spectra of flowing chemically reacting systems. The apparatus[2,3] and its application to the investigation of transient species[2,4-6] and effects[7] have been described. The main disadvantage of the flowing system compared to stopped-flow methods[8-11] is the relatively large quantity of material required, but it makes possible the measurement of spectra whose peak intensities are reliable, of transient species with half-lives which can be as short as 100 ms, and thus makes possible their identification. The purpose of the present work was to apply these techniques to the investigation of the transient intermediate species that are postulated to be formed during the electrophilic bromination of phenols with bromine in aqueous acetic acid solution.

The proposed mechanism[12] for this reaction involves the formation of a dienone intermediate **1** (eq 1).



1

Considerable support for the intermediacy of species of this general type in the reaction comes from the work of Ershov and Vold'kin[13] and subsequently De la Mare and co-workers,[14] who were able to isolate the corresponding species (4-bromo-2,6-di-*tert*-butylcyclohexa-2,5-dien-1-one, **2**) from the action of bromine on 2,6-di-*tert*-butylphenol in acetic acid solution. Similar species have been detected during the reaction of bromine with 3,5-dibromo-4-hydroxybenzenesulfonate,[15] 3,5-dibromo-4-hydroxybenzoic acid,[16] and 4-R-2,6-di-*tert*-butylphenols.[17]



2

De la Mare has extensively investigated the isomerization of **2** to 4-bromo-2,6-di-*tert*-butylphenol and its catalysis by acid, base, and halide ions[18-20] and has related these measurements to the detailed mechanism of the reaction.[19,21] The second step in the reaction (1) is the rate-determining step when the substrate is 2,6-di-*tert*-butylphenol, owing to the steric effects of the two *tert*-butyl groups, which inhibit proton addition at the carbonyl oxygen. However, the isolation of **2** also depends critically on its insolubility under the reaction conditions.

It was hoped that the application of flow NMR techniques would permit the direct observation of **2** "in situ" during the reaction, and also that it might make possible the observation and characterization of the analogous intermediate species from much less sterically hindered systems where isolation is not possible, including, perhaps, the case of phenol itself.

Experimental Section

Equipment. Spectra were recorded at 100 MHz on a Varian HA-100 spectrometer. The equipment and techniques used to record the flow NMR spectra were as previously described,[2,3,5] with the exception of a new flow NMR cell designed to minimize the time between mixing and observation which is described in the text. UV-visible spectra were recorded on Unicam S.P. 800 and Cary 118 spectrophotometers.

Data Treatment. Peak areas were measured using a planimeter. Least-squares fits to the experimental data were performed using standard routines on an IBM 360 computer.

Chemicals. All chemicals used were from commercial sources (see Acknowledgments). After purification, the phenols and the reaction products, the corresponding 4-bromo-substituted phenols, had melting points or boiling points consistent with literature data and gave NMR and mass spectral data in agreement with their proposed structures.

Preparation of the Intermediate 2 from 2,6-Di-*tert*-butylphenol. The isolation of this species has been previously reported[13,14] but some difficulties were experienced using the procedure described.[14] As discussed in the text, the isolation of this species depends not only on its relative stability but also on its insolubility in the reaction mixture used. The following conditions were found to consistently yield the intermediate: 2,6-di-*tert*-butylphenol (2 g) is dissolved in 80% HOAc (100 mL, 80 mL of acetic acid containing 20 mL of water). The solution is then cooled to 3 °C and stirred. A solution of bromine (0.51 mL of Br_2 in 9.49 mL of 80% HOAc) at 3 °C is gradually added to the solution. Upon addition of the bromine solution, a precipitate quickly appears. The precipitate is immediately filtered and recrystallized from light petroleum ether.

Results and Discussion

The phenols studied were 2,6-di-*tert*-butylphenol, 2,6-di-*sec*-butylphenol, 2,6-diisopropylphenol, 2-methyl-6-*tert*-butylphenol, 2,6-dimethylphenol, and 2-*tert*-butylphenol. All the reactions were carried out under similar conditions in aqueous acetic acid solutions. The intermediates formed from different substrates were of widely differing stabilities, and since the experimental approach used depended on the half-life of the intermediate species, the different cases will be discussed individually. Kinetic parameters are summarized in Table II and the NMR parameters of the intermediates are presented in Table III.

A. Reaction of 2,6-Di-*tert*-butylphenol with Bromine. The intermediate complex **2** was isolated as described in the Experimental Section. The NMR (Table III) and UV-visible (λ_{max} 250 nm) spectra agreed with those previously reported.[14,18] The results of the flow NMR investigation (in 90% HOAc and 25 °C) are shown in Figure 1. Thus, there is the very fast disappearance of the multiplet at δ 7.0 due to the ring protons of the phenol and the appearance of two new signals at δ 6.9 (rel intensity 2) and 5.6 (rel intensity 1) due to the intermediate. At the fastest flow rates used, only the spectrum of the intermediate was observed. On stopping the flow, the spectrum of the intermediate disappeared with the concurrent formation of a new peak at δ 7.3 due to the two equivalent ring protons of the product 4-bromo-2,6-di-*tert*-butylphenol.

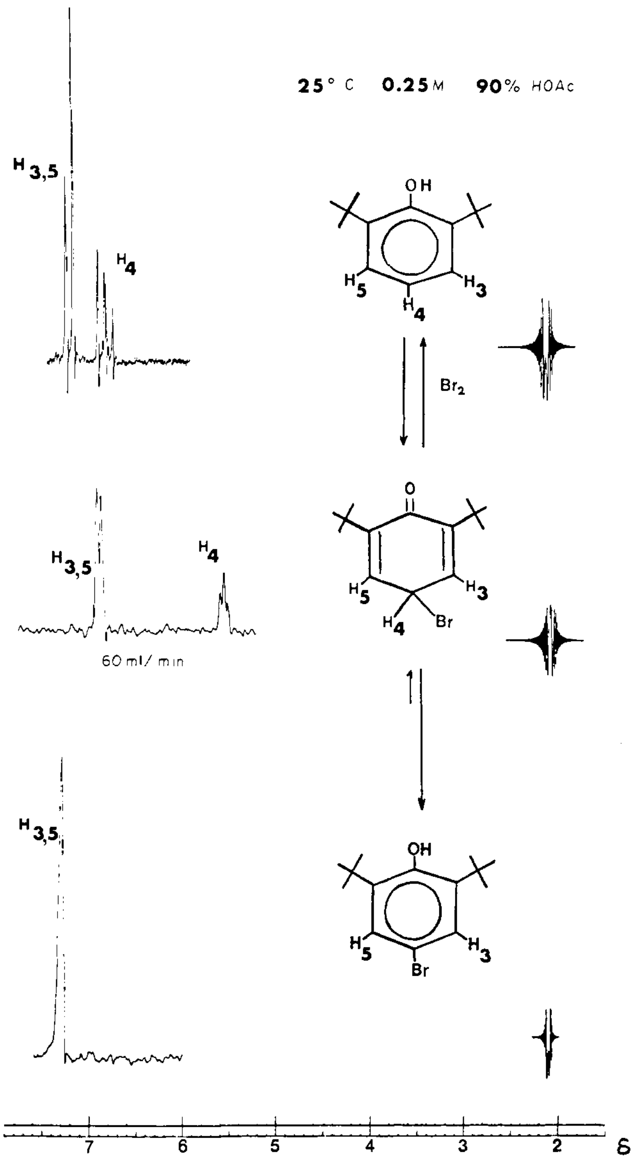


Figure 1. 100-MHz ^1H NMR spectra of the ring proton absorptions of the substrate during the reaction of 2,6-di-*tert*-butylphenol (0.25 M in 90% acetic acid) with bromine (0.25 M in 90% acetic acid) at 30 °C. Top spectrum: substrate alone before mixing. Middle spectrum: flow NMR spectrum recorded during reaction at a flow rate of 60 mL/min (0.5 s after mixing). Bottom spectrum: static spectrum 10 min after stopping the flow.

The reaction was sufficiently slow under these conditions that the decomposition of the intermediate could be monitored by stopping the flow and rapidly and repeatedly scanning the two peaks at δ 6.9 and 7.3 due to the intermediate and product, respectively, giving the results shown in Figures 2 and 3. The decomposition is a first-order process under these conditions and the intermediate has a half-life of 49 s (90% HOAc, 25 °C).

B. Reaction of 2,6-Di-*tert*-butylphenol with Bromine. Variation of Temperature and Acetic Acid Concentration. The effect of temperature and the concentration of acetic acid in the solvent were both investigated in an attempt to determine the optimum conditions for stabilizing this type of intermediate species prior to attempting to detect such compounds in less sterically hindered systems where they will be predictably much shorter lived. The results of these investigations are shown in Table I. As can be seen from the table, the intermediate is stabilized by both lowering the temperature and also

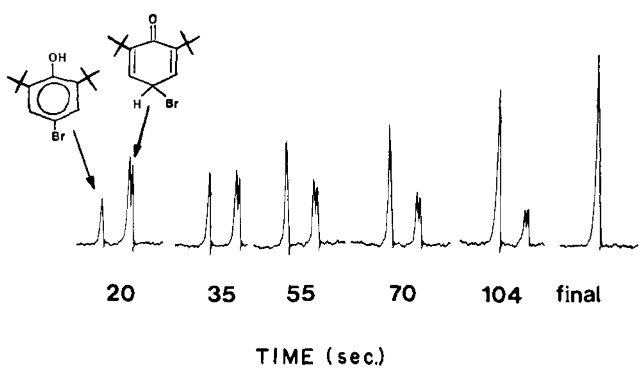


Figure 2. Ring proton absorptions of the intermediate and final product from the reaction of 2,6-di-*tert*-butylphenol (0.25 M in 90% acetic acid) with bromine (0.25 M in 90% acetic acid) at 25 °C, recorded as a function of time after stopping the flow. The times indicated are for the start of each doublet corresponding to the intermediate.

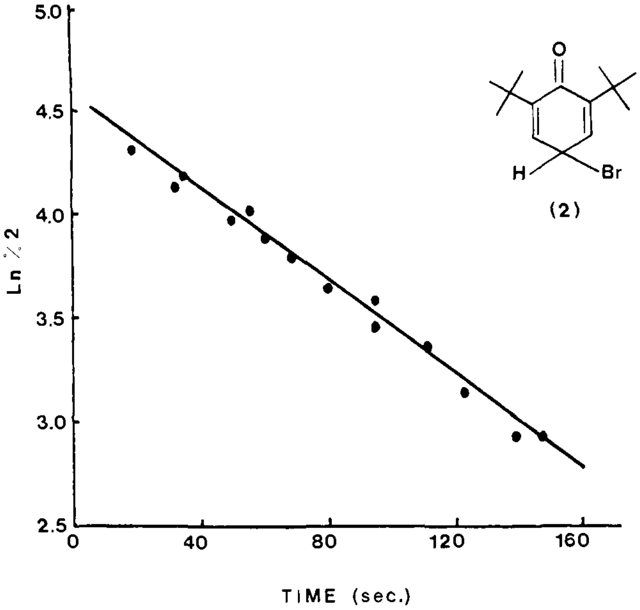


Figure 3. First-order kinetic plot for the disappearance of the cyclohexadienone intermediate in the reaction of 2,6-di-*tert*-butylphenol (0.25 M in 90% acetic acid) with bromine (0.25 M in 90% acetic acid) at 25 °C.

increasing the water concentration in the solvent mixture. In fact, these two variables are not completely independent, since the water concentration in the solvent determines the freezing point of the solution and thus limits the lowest temperature that may be reached. The solubility of the substrate and intermediate will also be important and may necessitate the use of a higher temperature than the freezing point of the mixed solvent. Also, the OH resonance of the combined water and acid signals is concentration dependent, shifting to higher fields as the amount of water in the mixture is increased, and at high water concentrations it completely obscures the spectral region of interest. However, it appears that, in general, the optimum conditions for the direct observation of intermediate species of this type should be those of lowest temperature and highest water concentration that the particular system can support within the restrictions noted above.

C. Reaction of 2,6-Di-*sec*-butylphenol with Bromine. This system was investigated using flow techniques over a temperature range of 10–30 °C and a range of water concentrations of 85–90%. In all cases, the intermediate dienone was very short lived in sharp contrast to the case of 2,6-di-*tert*-butylphenol discussed above.

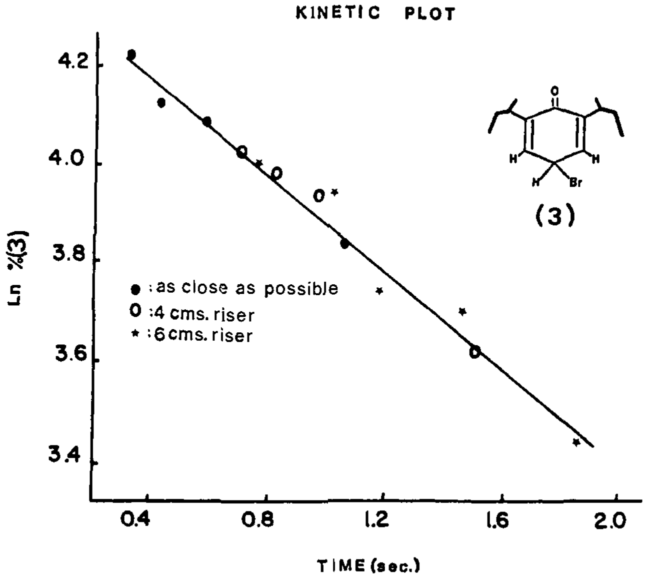


Figure 4. Kinetic plot for the decay of the cyclohexadienone intermediate formed in the reaction of 2,6-di-*sec*-butylphenol (0.25 M in 85% acetic acid) at 15 °C. Readings taken at different flow rates at a fixed distance between mixing and observation are shown with the same symbol. Different symbols indicate measurements made at different distances between mixing and observation. Thus: ●, mixing chamber as close as possible to the point of observation; O, mixing chamber raised a further 4 cm from the point of observation; *, mixing chamber raised a further 6 cm from the point of observation.

Table I. Effect of Variation of Temperature and of Acetic Acid Concentration on the Stability of the Cyclohexadieone Intermediate **2** from the Reaction of 2,6-Di-*tert*-butylphenol with Bromine as Indicated by the Half-Life of the Intermediate

Temp, °C	% HOAc	Half-life, s
15	85	240
	90	93
	94	27
25	85	158
	90	49
	94	17

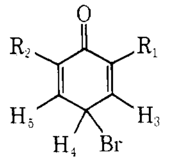
Thus, on reaction of the two solutions, there is the immediate disappearance of the signals due to the substrate at δ 7.9 and the immediate appearance of two new signals at δ 6.9 (rel intensity 2) and 5.6 (rel intensity 1) due to the intermediate. The spectrum of the intermediate is very similar to that of species **2** from 2,6-di-*tert*-butylphenol (Table III). On stopping the flow, there is the immediate disappearance of this spectrum and the appearance of a new spectrum due to the final product consisting of a single signal at δ 7.1. In this case, the intermediate has such a short half-life that it is not possible to investigate its decay to product by stopping the flow and scanning the spectrum as was done in the case of **2** (section A, above), and a different approach must be used. As described previously,[2,5] measurements may be made at different flow rates (thus altering the time between mixing and observation) and the distance between the mixing chamber and receiver coils may also be varied (thus also changing the time between mixing and observation). Permutation of these two variables should yield an accurate and self-consistent set of measurements of the concentrations of the intermediate and product as a function of time, since the spectral intensities are reliable using the flow technique. The results of these measurements for one set of reaction conditions are shown as a kinetic plot in Figure 4. In the figure, the points relating to measurements made by varying the flow rate for a fixed distance between mixing and observation are represented by a common symbol.

Table II. Rates of Decomposition of the Intermediates Formed in the Bromination of the Appropriate Phenols at the Temperatures and Solvent Composition Indicated, as Indicated by the Time (s) for 50% Conversion of Intermediate to Product[a]

% HOAc	Temp, °C	2,6-Di-*tert*-butylphenol	2,6-Di-*sec*-butylphenol	2,6-Di-isopropyl-phenol	2-Methyl-6-*tert*-butylphenol
85	4				
	10		1.05		
	15	240	0.88	0.85	1.1
	20	200	0.43	0.52	0.80
	25	158	0.34	0.42	0.35
	30	126		0.2	0.25
90	4				
	10		0.44		
	15	93	0.32	0.36	0.25
	20	64	0.26	0.22	0.23
	25	49	0.23	0.16	0.21
	30	39	0.11	0.15	0.13
94	4				
	10				
	15	27			
	20	23			
	25	17			
	30	12			

[a] In the case of 2,6-di-*tert*-butylphenol, these values correspond to the proper kinetic half-life ($t_{1/2}$) for the decomposition of the intermediate.

Table III. NMR Chemical Shift Parameters (δ, ppm) for the proton Resonances of the Cyclohexadienone Intermediates of General Structure 3 in Aqueous Acetic Acid Solution



3

R_1	R_2	Temp, °C	HOAc, %	H_3	H_4	H_5
tert-Butyl	*tert*-Butyl	20	85	6.8	5.5	6.8
Methyl	*tert*-Butyl	15	85	6.9	5.6	6.9
sec-Butyl	*sec*-Butyl	15	85	6.8	5.6	6.8
Isopropyl	Isopropyl	15	85	6.8	5.6	6.8
Methyl	Methyl	3	85	6.9	5.5	6.9
H	*tert*-Butyl[a]	−15	70	Not obsd	5.6	Not obsd

[a] H_1 not observed.

As can be seen from the figure, the data are self-consistent and show clearly the decay of the intermediate. Taking a linear extrapolation of the data does not, however, yield an intercept of 4.6 (corresponding to 100% intermediate). Although this may be due partly to experimental errors in the measurements, it was thought that it might be indicative of a curvature in the plot at very short reaction times, due to the influence of the first step forming the intermediate (the decomposition of the intermediate is now very fast), and that the apparent linearity of the decay might be deceptive. For this reason, in this and in the case of the other less sterically hindered phenols, the rates of decomposition of the intermediate species have been documented by measurement of the time required for conversion of the intermediate species 50% to product, rather than by taking a half-life from the assumption that the decomposition is a simple first-order process. These times for 50% conversion are listed in Table II.

D. Reaction of 2,6-Diisopropylphenol with Bromine. This system was investigated over a range of temperature of 10–30 °C and HOAc concentrations of 85–90%. Similar results were obtained to those of 2,6-di-*sec*-butylphenol discussed above. The spectrum of the intermediate (Table III) is similar to those discussed above. Again the decomposition of the intermediate must be investigated using continuous flow techniques as described in section C above. Times for 50% conversion of the intermediate to product are listed in Table II for the various conditions. The lifetimes of the intermediates are comparable to these from 2,6-di-*sec*-butylphenol.

E. Reaction of 2-*tert*-Butyl-6-methylphenol with Bromine. This system was investigated over a range of temperature of 10–30 °C and water concentrations of 85–90% HOAc and was found also to be very similar to that of 2,6-di-*sec*-butylphenol discussed above. The spectrum of the intermediate (Table III) is similar to those discussed above, except that the system no longer has a twofold symmetry axis. Again continuous flow techniques must be used, as described in section C. The times for 50% conversion to product are again listed in Table II. The lifetimes of the intermediates are again very short.

F. Reaction of 2,6-Dimethylphenol with Bromine. Attempts to investigate this system using the equipment and techniques described above were only moderately successful. Thus, the spectrum of the intermediate could be observed at very fast flow rates, but because of its very short lifetime, it was present to the extent of only 20% of the reaction mixture, the rest being product, even at the fastest flow rates. Further complications were that the signal of the two equivalent ring protons in the product 4-bromo-3,6-dimethylphenol coincide almost exactly with the signal of the two alkene protons in the dienone intermediate and that there was in addition considerable line broadening at the very fast flow rates which had to be used.

A new flow cell was designed to circumvent these problems by reducing the time between mixing and observation by decreasing the volume of solution between the mixing chamber and receiver coils, and thus making a given flow rate correspond to a much shorter time between mixing and observation. Using this cell it was hoped to obtain good spectra of the intermediate where it was the major component of the reaction mixture and to determine the complete curve for its decay to product. The cell used is shown in Figure 5. The solution is mixed in a high-pressure mixing chamber as before, but is now supplied via a capillary (i.d. 1 mm) to the observation point in the detector coils (i.d. 4 mm) and then exits around the outside

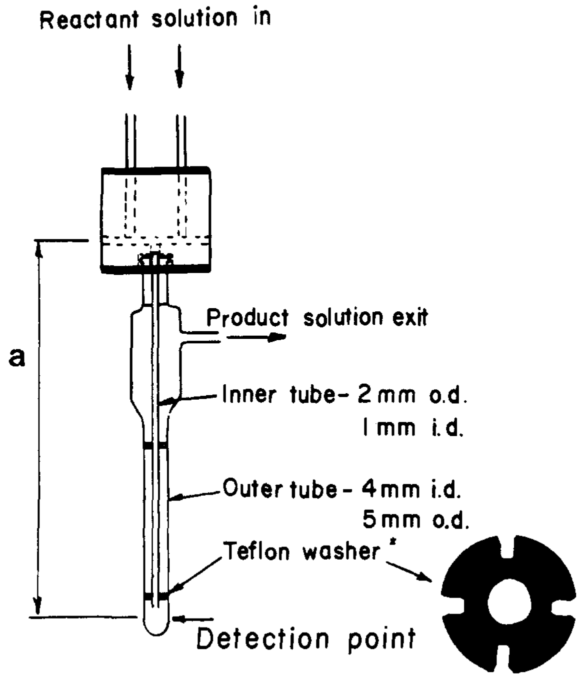


Figure 5. Schematic diagram of the flow NMR cell described in the text designed to minimize the time between mixing and observation for use in the detection of very short-lived intermediate species.

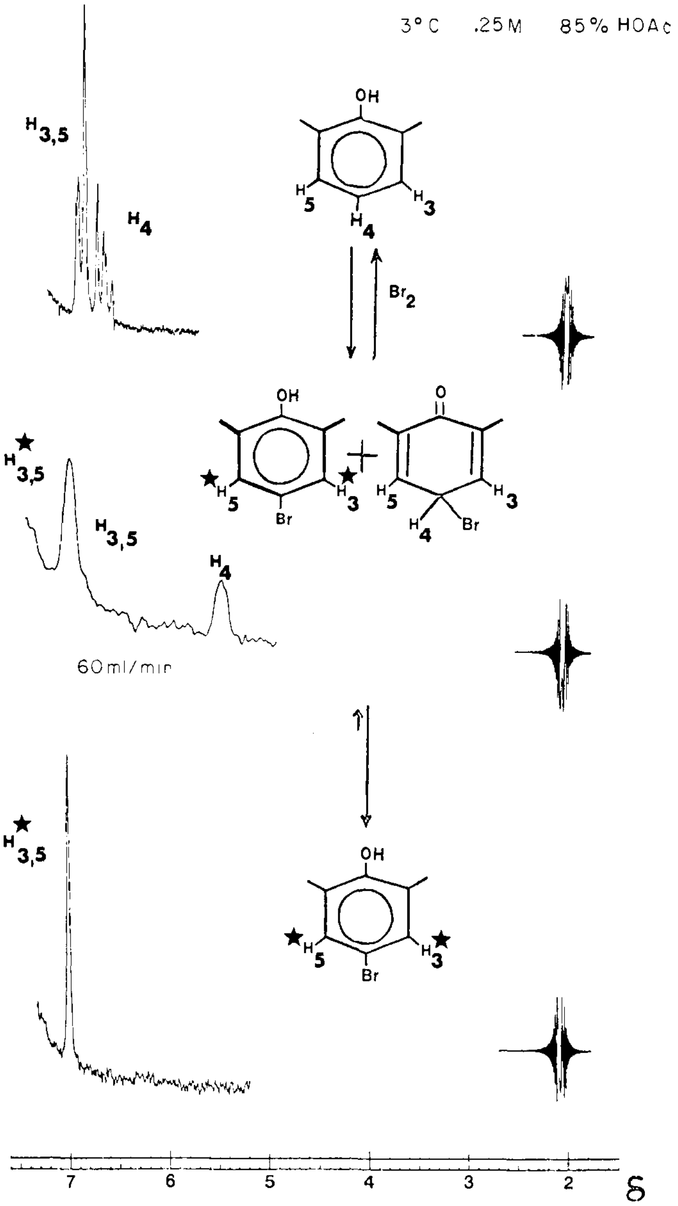


Figure 6. 100-MHz ^{1}H NMR spectra of the ring proton absorptions of the substrate during the reaction of 2,6-dimethylphenol (0.25 M, 85% acetic acid) with bromine (0.25 M, 85% acetic acid) at 3 °C. Top spectrum: static spectrum of reactant before mixing. Middle spectrum: flow NMR spectrum of the reacting solution at a flow rate of 60 mL/min (~0.1 s after mixing). Bottom spectrum: static spectrum recorded immediately after stopping the flow. The flow NMR cell designed to minimize the time between mixing and observation described in the text was used to obtain these spectra.

of the capillary. Such an arrangement lowers the time between mixing and observation by about a factor of 4, making possible good spectral measurements about 40 ms after mixing at the higher flow rates. The limiting factor is the volume at the point of observation which must be relatively large for optimum S/N. Thus, times of this order are approaching the lower limit for this technique.

This cell was used to investigate the reaction of 2,6-dimethylphenol at a temperature of 3 °C and water concentrations of 80–85%. Spectra from a typical run are shown in Figure 6. Using this equipment, at relatively slow rates, the intermediate comprises up to 70% of the total reaction mixture. The NMR parameters for the intermediate (Table III) are in excellent agreement with the others.

With this cell, a large fraction of the total volume of liquid between the mixing chamber and detection coils in fact is within the detection coils and is difficult to estimate accurately and it was felt that the potential errors introduced by this greatly limited the accuracy of quantitative kinetic data which could be obtained using this cell, and that this type of design would be most useful for the identification of very short-lived species but that its use should probably be restricted to these more qualitative measurements.

G. Reaction of 2-*tert*-Butylphenol with Bromine. This system was investigated in an attempt to see if it was possible to observe intermediates formed by reaction of a monosubstituted phenol where the steric interactions would be much less and where two isomeric intermediates are possible. For this substrate, the maximum water concentration that could be used was ~30% giving a freezing point for the phenol solution of ~−20 °C. Observations were made at −15 °C using the flow cell described in section E above. Under these conditions of water concentration and temperature, the OH resonance obscures the spectral region where the ring protons of intermediate and product appear and only the peak due to the hydrogen on the sp^3-hybridized carbon in the intermediate may be observed. The position of this peak, however, will be quite characteristic (Table II). Spectra were then recorded during the reaction of 2-*tert*-butylphenol and a definite broad peak was found at δ 5.6 consistent with it being a dienone intermediate. The species formed is very much shorter lived than that from 2,6-dimethylphenol.

H. Reaction of Phenol with Bromine. Attempts to observe intermediate species in this reaction were unsuccessful at 30% water concentration at −18 °C. Although phenol is soluble at higher water conentrations at these temperatures, no significant gain in temperature results, and the water peak eventually obscures the complete spectral region where all the signals occur.

Conclusions

The flow NMR studies have clearly established the generality of the occurrence of cyclohexadienone intermediates in the bromination reactions of phenols.

The stabilities of these intermediate species depend very markedly on the steric effects of the blocking groups in the 2 and 6 positions as expected, the limiting case of phenol itself giving no detectable intermediate under the optimum conditions for this solvent system. UV/visible spectral measurements give only a small shoulder for the intermediate species on the high wavelength side of the large absorption due to the solvent acid, and cannot be considered diagnostic for systems where no intermediate has been identified by NMR. The relative magnitudes of the two peaks will in any case limit the accuracy of such measurements.

However, neither the sensitivity of UV-visible measurements nor the diagnostic capabilities of NMR have been fully utilized to date (the latter by the low temperature limits imposed by the solvent system) and further work to find an alternate solvent system which is transparent in the region of the UV-visible and NMR absorptions of the intermediates and which can be taken to low temperatures would be worthwhile.

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References and Notes

(1) (a) Presented in part at the 170th National Meeting of the American Chemical Society, Chicago, Ill., Aug 1975; (b) From the M.S. Thesis of L. VanVeen Jr., presented in partial fulfillment of the degree requirements, 1976.
(2) S. W. H. Damji, Ph.D. Thesis, University of Guelph, 1975.
(3) C. A. Fyfe, M. Cocivera, and S. W. H. Damji, *J. Magn. Reson.*, **23**, 377 (1976).
(4) C. A. Fyfe, M. Cocivera, and S. W. H. Damji, *J. Chem. Soc., Chem. Commun.*, 743 (1973).
(5) C. A. Fyfe, M. Cocivera, and S. W. H. Damji, *J. Am. Chem. Soc.*, **97**, 4707 (1975).
(6) M. Cocivera, C. A. Fyfe, A. Effio, S. P. Vaish, and H. E. Chen, *J. Am. Chem. Soc.*, **98**, 1573 (1976).
(7) M. Cocivera, C. A. Fyfe, H. E. Chen, and S. P. Vaish, *J. Am. Chem. Soc.*, **96**, 1611 (1974).
(8) J. J. Grimaldi and B. D. Sykes, *J. Am. Chem. Soc.*, **97**, 273 (1975).
(9) J. A. Richards and D. H. Evans, *Anal. Chem.*, **47**, 964 (1975).
(10) M. J. T. Robinson and S. M. Rosenfield, *Tetrahedron Lett.*, 1431 (1975).
(11) D. A. Couch, O. W. Howarth and P. Moore, *J. Phys. E*, 381 (1975).
(12) P. B. D. de la Mare, "Aromatic Substitution", Butterworths, London, 1959.
(13) Ershov and Vold'kin, *Izv. Akad. Nauk SSSR, Otd. Khim. Nauk*, 730 (1962).
(14) P. B. D. de la Mare, O. M. H. el Dusouqui, J. C. Tillett, and M. Zeltner, *J. Chem. Soc.*, 5306 (1964).
(15) L. G. Cannell, *J. Am. Chem. Soc.*, **79**, 2927 (1957).
(16) E. Grovenstein, Jr., and U. V. Henderson, Jr., *J. Am. Chem. Soc.*, **78**, 569 (1956).
(17) E. Baciocchi and G. Illuminati, *J. Am. Chem. Soc.*, **89**, 4017 (1967).
(18) P. B. D. de la Mare, A. Singh, J. C. Tillett, and M. Zeltner, *J. Chem. Soc. B*, 1122 (1971).
(19) P. B. D. de la Mare and A. Singh, *J. Chem. Soc., Perkin Trans. 2*, 1801 (1972).
(20) P. B. D. de la Mare and A. Singh, *J. Chem. Soc., Perkin Trans. 2*, 59 (1973).
(21) P. B. D. de la Mare, *Acc. Chem. Res.*, 7, 361 (1974).

Calculation of Carbon-14, Chlorine-37, and Deuterium Kinetic Isotope Effects in the Solvolysis of *tert*-Butyl Chloride

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Abstract: In the solvolysis of *tert*-butyl chloride, satisfactory α-carbon-14, β-deuterium, and chlorine kinetic isotope effects (KIE) may be calculated for a productlike transition state characterized by bond orders $n_{\text{C-Cl}} = 0.2$, $n_{\text{C-C}} = 1.18$, and $n_{\text{C-H}} = 0.94$, employing a diagonal valence force field, provided that allowance is made for hydrogen-bonded solvation of the developing chloride ion with $n_{\text{Cl-H}} \sim 0.05$ ($\sim$7 kcal/mol hydrogen bonds). The effect of the three solvating molecules appears to be to increase the "effective" mass of the incipient chloride ion and to decrease the loss of zero-point energy in going to the transition state. Reaction coordinates more complicated than a simple heterolysis of the carbon-chlorine bond appear to be unnecessary and there is no advantage in employing force fields more complex than a simple valence force field containing only diagonal elements for both the reactant and the transition state model. The structural and bonding features of the proposed transition state are in accord with earlier more qualitative conclusions concerning the polar nature and productlike character of the transition state, and provide a reasonable explanation of the kinetic and equilibrium isotope effects (EIE) for the reaction. An alternative transition state model involving weak solvent nucleophilic assistance provides reasonable calculated values for the KIE, but the EIE strongly suggest the importance of solvation of the leaving group which, together with the hyperconjugation of the β hydrogens, provides a preferred explanation of the *tert*-butyl solvolysis results.

The solvolysis of *tert*-butyl chloride is the prototypical example of both the $\text{S}_\text{N}1$ and E1 mechanisms.[2,3] It is generally agreed that the rate-determining process consists of heterolysis of the carbon-chlorine bond, involving a highly polar transition state.[4,5] Several estimates[6] have been made of the degree of charge separation in the transition state; for a simple electrostatic model, the charge separation in polar solvents has been estimated to be 0.8e,[7] corresponding to a nearly broken carbon-chlorine bond in a productlike transition state.

α-Carbon-14,[8] chlorine-37,[9,10] and total β-deuterium[11-13] (D_9) kinetic isotope effects (KIE) have been measured in a series of independent investigations for this reaction. Selected results from Table I are as follows: $^{12}k/^{14}k = 1.027$ (25 °C); $^{35}k/^{37}k = 1.01087\text{-}1.00953$ (10-60 °C); $^{\text{H}_9}k/^{\text{D}_9}k = 2.387$ (25 °C). Although these KIE were determined under comparable, but not strictly identical, conditions, the small effect of the solvent changes on KIE usually observed (except perhaps the chlorine KIE, vide infra) suggests that a reasonably reliable set of data is available for this reaction against which detailed calculations can be tested.

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