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THE EFFECT OF PRESSURE ON CYCLIC REACTIONS

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*Summary*

Rates of the cyclization of 4-chlorobutanol and of some analogous non-cyclic solvolysis reactions have been measured in water, methanol, and aqueous acetone at pressures up to 3000 atm. The volume of activation of the cyclic reaction is less negative than those of the linear reactions, in each solvent, but it is suggested that the transition states of both types of reaction may be solvated to about the same extent. The volume of activation for the formation of an eight-membered ring in the cyclization of 4-bromobutylcatechol monoether was also determined.

INTRODUCTION

The effect of pressure on reactions in which cyclic transition states are formed has recently been reviewed.<sup>1,2</sup>

The volume of activation  $\Delta V^*$  of such reactions is sometimes less negative than would be expected for the formation of a cyclic transition state from linear molecules, and it has been suggested that some of the solvent is excluded from the centre of a small ring,<sup>3,4</sup> thus adding to the effective volume of the transition state.

In the present work we have examined the cyclization of 4-chlorobutanol to form tetrahydrofuran. This reaction can be described as an internal  $S_N2$  reaction and, like bimolecular  $S_N2$  reactions, it proceeds by a highly polar transition state which is formed from neutral reactants. Thus a strong solvent effect on the rate of reaction is expected. We measured the rate over a range of pressures and solvents and, to have a valid comparison with analogous non-cyclic reactions, we measured a number of solvolysis reactions over the same range. We also measured the pressure effect on the cyclization of 4-bromobutylcatechol monoether (BBCE) in which an eight-membered ring is formed.<sup>5</sup>

Most of the cyclic reactions for which  $\Delta V^*$  has been determined involve either neutral molecules and largely non-polar transition states, or ions in which the charge is maintained in the transition state.<sup>1,2</sup> For either type of reaction the solvent effects are small compared with those in  $S_N2$  reactions in which highly polar transition states are formed from neutral molecules. In the discussion we have used a model of

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<sup>1</sup> Whalley, E., *Adv. phys. org. Chem.*, 1964, **2**, 93.

<sup>2</sup> Hamann, S. D., *Ann. Rev. phys. Chem.*, 1964, **15**, 345.

<sup>3</sup> Whalley, E., *Trans. Faraday Soc.*, 1962, **58**, 2144.

<sup>4</sup> Le Noble, W. J., *J. Am. chem. Soc.*, 1960, **82**, 5253.

<sup>5</sup> Ziegler, K., Lüttringhaus, A., and Wohlgemuth, K., *Liebigs Ann.*, 1937, **528**, 162.

transition state solvation suggested by Gonikberg and El'yanov<sup>6</sup> to interpret the volumes of activation of the reactions.

## EXPERIMENTAL

### Solvents

Methanol was dried by reaction with magnesium formate followed by distillation from anhydrous copper sulphate and from benzoic acid.<sup>7</sup> It was stored under anhydrous conditions. Acetone was purified by refluxing with potassium permanganate, dried, and fractionated. Water was distilled, boiled, and then deionized by passage through a bed of Biodemineralite resin for immediate use.

### Reagents

The alkyl halides were B.D.H. laboratory grade reagents and were dried by chemical means and then fractionally distilled. Benzyl chloride was also B.D.H. laboratory grade material; it was dried and fractionally distilled under reduced pressure. The 4-chlorobutanol was prepared from redistilled tetrahydrofuran<sup>8</sup> and was redistilled as required.

The 4-bromobutylcatechol monoether (BBCE) was prepared by the method described by Lüttringhaus<sup>9</sup> from catechol and 1,4-dibromobutane. The product appeared to contain some catechol (Found: Br, 31.8. Calc.: Br, 32.4%), but we found that the rate of the alkaline cyclization of BBCE was not affected by even an excess of catechol.

### Pressure Equipment

Pressure was generated by hand-operated oil pumps and was measured on Bourdon gauges to an accuracy of about 1%. The pressure vessel was similar in design to those used by Buchanan and Hamann<sup>10</sup> and by Koskikallio and Whalley,<sup>11</sup> but used a Pyrotenax thermocouple lead sealed through the pressure plug both for temperature and conductance measurements within the pressure vessel. For some reactions samples were withdrawn through a stainless-steel capillary sealed through the pressure plug. This carried the syringe-like PTFE reaction vessel on the high-pressure side and was closed by a small high-pressure valve at the low-pressure end.

The pressure vessel was immersed in an oil-bath which was maintained within 0.03° of the required temperature. Kinetic measurements were not begun until a differential thermocouple showed that thermal equilibrium between the inside of the pressure vessel and the bath was established. This usually took between 30 and 45 min from the time of altering the pressure. Measurements at atmospheric pressure were also made in the pressure vessel.

### Kinetic Measurements

All but one of the reactions were followed conductimetrically in all-glass conductance cells. These cells were made by sealing platinum electrodes through the sides of sealed-off 20-ml syringes; they had a cell constant of 0.4–0.6 cm<sup>-1</sup> and functioned well up to 3000 atm.

The cyclization of BBCE was followed by withdrawing small samples under pressure and estimating the liberated bromide ions by potentiometric titration with silver nitrate.<sup>12</sup>

## RESULTS

The results and the reaction conditions of our rate measurements are given in Table 1. In Table 2 we give the values of  $\Delta V^*$  derived graphically from plots of  $\log k$  against pressure.

<sup>6</sup> Gonikberg, M. G., and El'yanov, B. S., *Izv. Akad. Nauk SSSR, Otd. khim. Nauk*, 1960, 629.

<sup>7</sup> Grunwald, E., Jumper, C. F., and Mieboom, S., *J. Am. chem. Soc.*, 1962, **84**, 4662.

<sup>8</sup> Blatt, J., *Org. Synth.*, 1943, Coll. Vol. II, 571.

<sup>9</sup> Lüttringhaus, A., *Liebigs Ann.*, 1937, **528**, 276.

<sup>10</sup> Buchanan, J., and Hamann, S. D., *Trans. Faraday Soc.*, 1953, **49**, 1425.

<sup>11</sup> Koskikallio, J., and Whalley, E., *Trans. Faraday Soc.*, 1959, **55**, 809.

<sup>12</sup> Shiner, V. L., and Smith, M. L., *Analyt. Chem.*, 1956, **28**, 1043.