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### Abstract

The activation energies for the exchange reactions between sodium iodide and cyclopentyl, cycloheptyl, cyclopetyl, cyclopentadecyl, and 2-heptyl iodides were all in the range  $21 \pm 1$  kcal. per mole. For cyclohexyl iodide the value was 25.6 kcal. per mole. This difference seems to be explained from a consideration of the initial potential energies of the various rings. An inverse relation appears

to exist between  $\log PZ$  and  $\frac{1}{N}$ , the reciprocal of the number of carbon atoms in the iodides investigated, for all the iodides except cyclopentyl iodide. This might be due to a change in the number of equivalent constellations in the activated state.

### Introduction

Several studies with substituted alicyclic compounds (4-6, 8-11), in particular those involving nucleophilic substitution reactions of alicyclic halides (2, 12), have demonstrated an apparently anomalous behavior of cyclohexyl derivatives. With a view to obtaining more information about such systems, the type of reaction involved has been made as simple as possible in the present investigation, by studying the exchange reaction between iodide ion and alicyclic iodides. The exchange of iodide ion with 2-heptyl iodide was also studied for purposes of comparison, since exchange occurs at a secondary carbon atom in this compound, as in alicyclic iodides.

## **Experimental and Results**

Radioactive iodine, I<sup>131</sup>, was obtained from the National Research Council, Atomic Energy Project, Chalk River, Ontario, as carrier-free sodium iodide.

Sodium iodide (Merck Reagent grade) dried for several days at 110°C, was used as diluent.

Absolute ethanol was used as solvent.

The alicyclic iodides were all prepared by treating the corresponding alcohol with 57% hydriodic acid.

Cyclopentanol, cyclohexanol, and 2-heptanol were obtained commercially (Eastman Kodak). Cycloheptanol was prepared by cyclizing suberic acid (City Chemical Company, New York) to cycloheptanone (13), followed by reduction of the ketone with aluminum isopropoxide and isopropyl alcohol. Cycloöctanol and cyclopentadecanol were also obtained in a similar manner by reduction of the corresponding ketones.\*

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## VAN STRATEN ET AL.: EXCHANGE REACTIONS

The exchange reactions were followed by withdrawing samples from appropriate thermostats at suitable time intervals, and separating the organic and inorganic iodides by benzene-water extraction. Silver iodide was precipitated from each fraction by the addition of alcoholic silver nitrate. The precipitate was washed with methanol to remove benzene, heated on a steam bath with concentrated nitric acid until brown fumes appeared, washed again twice with water and twice with methanol, and slurried in dry methanol. A sample of the slurry, contained within a glass ring, was evaporated on a glass plate and the rate of exchange determined from the change in specific activity, using standard counting equipment.

Two series of experiments were made with each alicyclic iodide, except cycloöctyl iodide, which was available in amount sufficient only for one limited series of experiments. The order of the reaction was determined for each compound by varying the initial concentrations, and the activation energy determined for a range of temperature of  $20^{\circ}-30^{\circ}$ C.

The reactions were all found to conform satisfactorily to second order behavior. There was some discrepancy, for which no satisfactory explanation can be given, between the values of the second order rate constants at a given temperature in the two series of reactions with a given organic iodide. However, the activation energies obtained for the two series agreed within 400 cal. per mole, except with cyclopentyl iodide where the two values differed by 800 cal. per mole. The activation energy lines for one series of experiments with each compound (except cycloöctyl iodide) are shown in Fig. 1.



The data given in Tables I and II are typical of the results obtained in the study as a whole. For calculation of activation energies, the value of k used at each temperature was the average of the individual values, usually at least four, for different reaction times.

In Table III are summarized the results for the various reactions studied.

## TABLE I

Temp., °C.	Reaction time, min.	% Exchange	$\begin{array}{ c c c c c c c c c c c c c c c c c c c$
69.0	198	7.3	0.023
	258	7.8	0.024
	318	11.9	0.024
	383	13.5	0.022
79.9	180	17.8	0.065
	181	17.1	0.062
	240	22.2	0.063
	300	25.2	0.060
	360	30.0	0.060

 $32.0 \\ 40.2 \\ 50.0 \\ 58.2$ 

 $24.5 \\ 28.5 \\ 43.0 \\ 44.0$ 

120

 $150 \\ 190 \\ 240$ 

 $30 \\ 45 \\ 60 \\ 80$ 

89.8

100.0

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 $\begin{array}{c} 0.195 \\ 0.208 \\ 0.223 \\ 0.222 \end{array}$ 

 $\begin{array}{c} 0.576 \\ 0.464 \\ 0.577 \\ 0.442 \end{array}$ 

# The exchange of cyclohexyl iodide with sodium iodide Concentration: RI, 0.30 M.; NaI, 0.30 M

TABLE II

## THE EXCHANGE OF CYCLOPENTYL IODIDE WITH SODIUM IODIDE IN ETHANOL SOLUTION

Temp., °C.	Reactant concentration (molarity)		Maximum exchange, %	$k(ccmole^{-i}-scc.^{-i})$ $(\times 10^2)$				
	RI	NaI						
Series A								
$36.6 \\ 47.0 \\ 56.0 \\ 64.0$	$\begin{array}{c} 0.30\\ 0.30\\ 0.30\\ 0.20\\ 0.45\\ 0.30\\ 0.15\\ 0.50\\ \end{array}$	$\begin{array}{c} 0.30\\ 0.30\\ 0.30\\ 0.40\\ 0.15\\ 0.30\\ 0.45\\ 0.10\\ \end{array}$	$16 \\ 31 \\ 25 \\ 37 \\ 26 \\ 56 \\ 43 \\ 51$	$\begin{array}{c} 3.0\\ 9.0\\ 23.3\\ 24.4\\ 47.2\\ 42.0\\ 42.5\\ 44.2\end{array}$				
Series B								
$36.6 \\ 50.7 \\ 56.0 \\ 64.0$	$\begin{array}{c} 0.30 \\ 0.30 \\ 0.30 \\ 0.30 \\ 0.30 \end{array}$	$\begin{array}{c} 0.30 \\ 0.30 \\ 0.30 \\ 0.30 \\ 0.30 \end{array}$	19 37 36 70	$3.3 \\ 14.1 \\ 26.9 \\ 55.6$				

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#### TABLE III

SUMMARY OF RESULTS FOR THE EXCHANGE REACTIONS BETWEEN ALICYCLIC IODIDES AND SODIUM IODIDE IN ETHANOL SOLUTION

Alicyclic iodide	$k(\text{at } 25^{\circ}\text{C}) \times 10^{2}$ cc mole <sup>-1</sup> - sec. <sup>-1*</sup>	<i>E</i> ** kcal/mole	log <i>PZ</i> **
Cyclopentyl iodide Cyclohexyl iodide Cycloheptyl iodide Cycloöctyl iodide Cyclopentadecyl iodide 2-Heptyl iodide	$\begin{array}{c} 0.88\\ 0.0084\\ 1.2\\ 0.28\\ 0.099\\ 0.77\end{array}$	$21.0 \\ 25.6 \\ 21.3 \\ 22.0 \\ 20.1 \\ 21.8$	$     \begin{array}{r} 13.4 \\     14.7 \\     13.7 \\     13.6 \\     11.8 \\     13.9 \\     \end{array} $

\* Calculated from  $k = PZ e^{-E/RT}$ , using the values recorded for E and log PZ. \*\* Each value recorded is the average of the two values obtained for series A and series B experiments (except for cycloöctyl iodide, where only one limited series of experiments was possible). The probable error in the average values is approximately 3%.

### Discussion

The apparently anomalous behavior of a cyclohexyl derivative, referred to previously, appears to be confirmed in the present study. The considerably lower rate of exchange of cyclohexyl iodide is here accompanied by energy of activation and entropy of activation (log PZ) terms which differ considerably from those for the other compounds investigated.

There seems no good reason to believe that the carbon-iodine bond strength in cyclohexyl iodide is substantially greater than in the other alicyclic iodides. Presumably, then, the higher activation energy for the cyclohexyl iodide exchange is associated with the process of rendering coplanar the atoms at the site of reaction, prior to exchange and subsequent inversion. If it is assumed that the height of the energy barrier to be surmounted during exchange remains unaltered from member to member in the series, the greater activation energy may be attributed to the lower potential energy of the cyclohexyl ring initially (1, 7). The present results indicate that the extent of this stabilization of the cyclohexyl ring is about 4 kcal.

The larger entropy term for the cyclohexyl iodide exchange, compared with the values of log PZ for the other exchange reactions, is probably not anomalous. This is indicated by a plot of  $\log PZ$  against the reciprocal of the number of carbon atoms in the organic iodide undergoing reaction, as in Fig 2. The figure includes results for the analogous exchange reaction with amyl iodide in ethanol (3). In the figure, a straight line has been drawn through the points but it is probable that the range of values involved represents the mid-portion

of a sigmoid relation which rises rapidly as  $\frac{1}{N}$  approaches zero and drops rapidly

to a constant value of about 16 for small values of  $\frac{1}{N}$  (3). Greater accuracy than that attained in the present work would be necessary to define the exact form of the relation.

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FIG. 2. Inverse relation between number of carbon atoms and log PZ.

The inverse relation between  $\log PZ$  and the number of carbon atoms in the organic iodide may be accounted for if the entropy change associated with activation reflects a change in the number of equivalent constellations (1, 7), and this change has proportionately less effect as the number of possible equivalent constellations increases with increased ring size. The failure of cyclopentyl iodide to conform to the relation in Fig. 2 might be expected, since the cyclopentyl ring is approximately planar in the initial state (Fisher-Hirschfelder model) and relatively little change in it should occur as the atoms at the site of reaction are rendered coplanar during activation prior to exchange.

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