

hydrogen peroxide according to Brown and coworkers.<sup>10</sup> Attempts to isolate any possibly formed alcohols by extraction with ether were not successful. Gas chromatographic analysis of the residual mixture revealed that four new products were present which were not identified.

**b. *l*-Spirene 1 from Asymmetric Induction with *l*-Disopinocampheylborane (6).** Asymmetric hydroboration of 1.34 g (15.0 mmol) of racemic spirene **1** in 10 ml of diglyme with a borane mixture prepared from 3.26 g (23.9 mmol) of (+)- $\alpha$ -pinene,  $[\alpha]_{D}^{25} +48.4^\circ$  (neat) (Aldrich), 0.35 g (9.0 mmol or 4% excess of theoretical) of sodium borohydride, and 1.70 g (12.0 mmol) of boron trifluoride etherate was performed as described above in section a for *in situ* hydroboration in diglyme and gave after purification by glc 14 mg of diene **1**,  $[\alpha]_{D}^{25} -1.3^\circ$ ,  $[\alpha]_{D}^{25} -2.5^\circ$ ,  $[\alpha]_{D}^{25} -4.9^\circ$ ,  $[\alpha]_{D}^{25} -14.6^\circ$  (*c* 0.8, *n*-hexane). To the residual organoborane mixture **1** g (9 mmol) of *n*-oct-1-ene was added at 0°. After the mixture was stirred a further 3 hr at 0°, the volatile components were removed in the same way as described above furnishing 0.13 g of additional purified diene **1**,  $[\alpha]_{D}^{25} -3.7^\circ$  (*c* 8.4, methanol). Three reiterations of this procedure afforded 0.15 g of additional purified spirene **1**,  $[\alpha]_{D}^{25} -3.5^\circ$  (*c* 2.9, *n*-hexane). The total amount of recovered **1** was

therefore 0.36 g or 54% of theoretical excess. Dextrorotatory diene **1** could not be isolated by this asymmetric hydroboration process. Asymmetric hydroboration of 0.87 g (9.4 mmol) of racemic spirene **1** in 8 ml of diglyme with a borane mixture prepared from 2.57 g (18.8 mmol) of (+)- $\alpha$ -pinene (Aldrich), 0.28 g of sodium borohydride, and 1.34 g (9.4 mmol) of boron trifluoride etherate was performed as described above and gave in the first instance 27 mg of diene **1**,  $[\alpha]_{D}^{25} -6.7^\circ$  (*c* 1.8, pentane). Repeated addition of 1 g of *n*-oct-1-ene afforded 0.99 g with  $[\alpha]_{D}^{25} -6.0^\circ$  (*c* 6.5, pentane), 0.03 g with  $[\alpha]_{D}^{25} -5.8^\circ$  (*c* 2.1, pentane), and 0.02 g with  $[\alpha]_{D}^{25} -5.6^\circ$  (*c* 1.6, pentane) of additional purified diene **1** to a total amount of 0.18 g or 42% of theoretical excess.

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## Mechanisms of Elimination Reactions. XXII. Stereochemistry of Elimination Reactions of 3-Hexyltrimethylammonium Ion Promoted by Phenoxide Bases. The Role of Ion Pairing<sup>1</sup>

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**Abstract:** The *trans*-3-hexene from 3-hexyltrimethylammonium iodide and potassium phenoxide in mixtures of *tert*-butyl alcohol and dimethyl sulfoxide is formed *via* both syn and anti paths, the proportion of syn elimination ranging from 14% to 0% to 38% at 95% dimethyl sulfoxide. In contrast, the *cis*-3-hexene is the result of 94–98% anti elimination. With substituted phenoxides, the syn path for formation of *trans*-3-hexene ranges from 26% for *p*-MeO to 69% for *p*-NO<sub>2</sub> in 95% dimethyl sulfoxide. The cation of the metal phenoxide affects the proportion of syn elimination. In 20% dimethyl sulfoxide the syn  $\rightarrow$  trans path ranges from 34% for potassium to 74% for lithium phenoxide. Temperature and base concentration also affect the proportion of syn elimination, but the effect of dicyclohexyl-18-crown-6 ether is negligible. These results are all compatible with a mechanism in which ion-paired metal phenoxide favors anti, but free, or more loosely ion-paired, phenoxide favors syn elimination. An ion-pair exchange equilibrium between the metal phenoxide and the quaternary ammonium salt fits these and other observations. The relative importance of free ions, solvent-separated ion pairs, and contact ion pairs is discussed.

The syn–anti dichotomy, in which E2 reactions give *trans* olefins partly or mainly by syn elimination and *cis* olefins almost entirely by anti elimination, is by now quite firmly established for eliminations from quaternary ammonium salts under a variety of conditions. It was first noticed with medium-ring compounds<sup>2–5</sup> but has also been found to occur with open-chain compounds.<sup>6–12</sup> A number of structural and

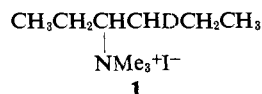
environmental factors seem to be conducive to syn elimination, but one of the earliest to be implicated was base strength. The more strongly basic the medium, the greater is the propensity toward syn elimination.<sup>5,7–9,11,13</sup> While the qualitative correlation is quite clear, not only the base strength but also the solvent and the steric requirements of the base were varied in most of these studies. The present research

(1) This work was supported by the National Science Foundation.  
(2) J. Sicher, J. Závada, and J. Krupicka, *Tetrahedron Lett.*, 1619 (1966).  
(3) J. Závada, M. Svoboda, and J. Sicher, *Tetrahedron Lett.*, 1627 (1966).  
(4) J. Závada and J. Sicher, *Collect. Czech. Chem. Commun.*, 32, 3701 (1967).  
(5) J. Sicher and J. Závada, *Collect. Czech. Chem. Commun.*, 33, 1278 (1968).  
(6) M. Pánková, J. Sicher, and J. Závada, *Chem. Commun.*, 394 (1967).  
(7) M. Pánková, J. Závada, and J. Sicher, *Chem. Commun.*, 1142 (1968).

(8) D. S. Bailey and W. H. Saunders, Jr., *Chem. Commun.*, 1598 (1968).  
(9) D. S. Bailey and W. H. Saunders, Jr., *J. Amer. Chem. Soc.*, 92, 6904 (1970).  
(10) D. S. Bailey, F. C. Montgomery, G. W. Chodak, and W. H. Saunders, Jr., *J. Amer. Chem. Soc.*, 92, 6911 (1970).  
(11) J. Sicher, J. Závada, and M. Pánková, *Collect. Czech. Chem. Commun.*, 36, 3140 (1971).  
(12) M. Pánková, A. Vitek, S. Vašičková, R. Řeřicha, and J. Závada, *Collect. Czech. Chem. Commun.*, 37, 3456 (1972).  
(13) K. C. Brown and W. H. Saunders, Jr., *J. Amer. Chem. Soc.*, 92, 4292 (1970).

was originally undertaken in an effort to isolate the base-strength effect, though it subsequently led in different directions.<sup>14</sup>

In order to vary the base strength independently, we chose to use meta- and para-substituted phenoxides. We first sought to establish conditions under which the phenoxides would give substantial but not exclusive syn elimination by studying 3-hexyl-4-*d*-1-trimethylammonium iodide (**1**) with potassium phenoxide in



mixtures of *tert*-butyl alcohol and dimethyl sulfoxide (Table I). The procedures followed our earlier work,<sup>9</sup> except that we were successful in preparative-scale separation of the products into two fractions containing *cis*-2- and *cis*-3-hexene and *trans*-2- and *trans*-3-hexene, respectively, before deuterium analysis. Consequently, our previous assumption that the syn  $\rightarrow$  *cis* path is negligible was no longer necessary. The deuterium analyses plus olefin proportions from analytical-scale glpc then enabled us to calculate separately proportions of syn elimination to give *trans*- or *cis*-3-hexene.

As before, these figures must be corrected for isotope effects to give the proportions of syn elimination which would be observed with the undeuterated reactants. Isotope effects computed from deuterium analyses plus product proportions<sup>15</sup> can be quite sensitive to experimental error, so averages of the more reliable values for syn and anti elimination were used, as in our previous work,<sup>9</sup> rather than the actual values calculated from the individual experiments. In nearly all cases, where both isomers were run, the calculated percentages of syn elimination from the threo and erythro isomers of **1** agree within a few per cent, thereby showing the assumed isotope effects to be realistic choices.

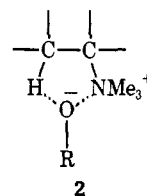
The first seven entries in Table II show the effect of adding dimethyl sulfoxide to *tert*-butyl alcohol solutions of potassium phenoxide on the stereochemistry of formation of *trans*-3-hexene from **1**, and the next five entries give the same information for *cis*-3-hexene. The results follow the pattern of the syn-anti dichotomy with syn elimination contributing less than 5% to formation of *cis* olefin but 14–38% to formation of *trans* olefin. Curiously, nearly all of the increase in the syn  $\rightarrow$  *trans* path occurs between 0 and 20% dimethyl sulfoxide, with only a few per cent further increase from 20 to 95%. While the basicities of these particular media have not been measured, previous studies on basicities of alkoxides in alcohol-dimethyl sulfoxide mixtures show a regular increase as the proportion of dimethyl sulfoxide increases<sup>16,17</sup> not an asymptotic approach to a limiting value.

The results with the substituted phenoxides in 95% dimethyl sulfoxide, entries 13–18 of Table II, are still more unexpected. Instead of the increase in the syn  $\rightarrow$  *trans* path previously observed with increasing basicity,

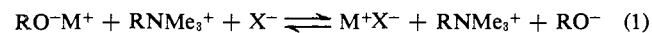
the greatest proportion of syn elimination (69%) is found with *p*-nitrophenoxide and the least (26%) with *p*-methoxyphenoxide. A similar trend is found in 5% dimethyl sulfoxide (entries 19–21 of Table II), though the range of 18–22% syn elimination is barely beyond experimental error.

It is evident from the results so far that base strength cannot be the controlling factor with the phenoxide bases. Another property of the media which undoubtedly is affected by the above variation in solvent composition and base is the tendency toward ion pairing of the base. Direct evidence for such variation is the observation of Zaugg and Schaefer<sup>18</sup> that the positions of the maxima in the uv spectra were different for the various alkali metal phenoxides but not for the alkali metal *p*-nitrophenoxides in dimethylformamide solution, indicating that the phenoxides exist as ion pairs but the *p*-nitrophenoxides either as free ions or distinctly looser ion pairs, presumably because of their more delocalized negative charge.

Further evidence linking the extent of ion pairing of the base with stereochemistry of elimination is afforded by entries 4 and 22–24 in Table II showing the effect of varying the cation. Values range from 34% syn  $\rightarrow$  *trans* with potassium to 74% syn  $\rightarrow$  *trans* with lithium phenoxide in 20% dimethyl sulfoxide. The effect is not a simple one, however, for the lithium ion would be expected to ion pair most and the tetramethylammonium ion least strongly, yet both give higher values than potassium or sodium, which should be intermediate. It has been predicted<sup>4,5</sup> that free base should be more effective than ion-paired base in promoting syn elimination from ionium salts because electrostatic interaction or pairing of the negative base with the positive leaving group would put the base into a favorable position for attack on a syn  $\beta$  hydrogen (**2**).



A resolution of the above inconsistencies, and an explanation compatible with the other data as well, is afforded if we remember that both base and substrate are ionic compounds and may engage in ion-pair exchange equilibria. The equilibrium of eq 1 is con-



sistent with our results, as will be shown below. It is not, however, simply an *ad hoc* hypothesis, for it was proposed some time earlier to account for unusual kinetic behavior in the reaction of 2-phenylethyltrimethylammonium bromide with sodium and potassium *tert*-butoxide in *tert*-butyl alcohol.<sup>19</sup> The kinetic order with respect to quaternary ammonium salt had been found to be 1.5 rather than the expected 1.0. If the equilibrium of eq 1 were far to the right and RO<sup>-</sup> were the only effective base, an order of 2.0 in quaternary salt would be expected (1.0 in its role as sub-

(14) A preliminary account is given by J. K. Borchardt and W. H. Saunders, Jr., *Tetrahedron Lett.*, 3439 (1972).

(15) M. P. Cooke, Jr., and J. L. Coke, *J. Amer. Chem. Soc.*, **90**, 5556 (1968).

(16) K. Bowden, *Chem. Rev.*, **66**, 119 (1966).

(17) D. Bethell and A. F. Cockerill, *J. Chem. Soc. B*, 913 (1966).

(18) H. E. Zaugg and A. D. Schaefer, *J. Amer. Chem. Soc.*, **87**, 1857 (1965).

(19) W. H. Saunders, Jr., D. G. Bushman, and A. F. Cockerill, *J. Amer. Chem. Soc.*, **90**, 1775 (1968).

Table I. Product Proportions in Eliminations from 3-Hexyl-4-*d*<sub>1</sub>-trimethylammonium Iodides in Mixtures of *tert*-Butyl Alcohol and Dimethyl Sulfoxide<sup>a</sup>

% DMSO	Base	Reactant	Hexenes, % <sup>b</sup>			
			<i>trans</i> -3	<i>cis</i> -3	<i>trans</i> -2	<i>cis</i> -2
0	PhOK	H	7.3	17.2	22.5	53.1
		er <sup>c</sup>	2.7	15.9	25.0	56.4
		th <sup>d</sup>	7.2	6.2	28.8	57.7
5	PhOK	H	7.5	16.4	24.0	52.3
		er <sup>c</sup>	2.8	15.4	25.4	56.5
		th <sup>d</sup>	7.4	6.4	26.5	59.7
10	PhOK	H	7.7	16.3	23.3	52.8
		er <sup>c</sup>	2.7	15.8	25.9	55.6
		th <sup>d</sup>	7.1	7.1	26.5	59.3
20	PhOK	H	8.4	16.0	24.1	51.5
		er <sup>c</sup>	2.4	18.7	24.3	54.8
		th <sup>d</sup>	8.0	6.8	28.4	56.8
50	PhOK	H	8.7	17.1	23.9	50.2
		er <sup>c</sup>	2.7	15.9	25.6	55.8
		th <sup>d</sup>	8.2	5.7	27.6	58.6
70	PhOK	H	8.9	17.1	23.9	50.0
		er <sup>c</sup>	2.9	15.9	26.0	55.3
		th <sup>d</sup>	8.2	6.1	26.8	58.9
95	PhOK	H	9.1	16.8	23.4	50.6
		er <sup>c</sup>	2.8	17.7	25.1	54.5
		th <sup>d</sup>	8.5	5.6	27.6	58.4
95	<i>p</i> -MeOPhOK	H	8.1	16.9	23.6	51.5
		er <sup>c</sup>	3.4	16.7	25.8	54.1
		th <sup>e</sup>	8.5	5.7	28.4	57.4
95	<i>p</i> -HOPhOK	H	9.2	16.7	23.1	51.0
		er <sup>c</sup>	3.1	15.5	25.9	55.6
		th <sup>e</sup>	8.8	17.6	23.2	50.5
95	<i>m</i> -MeOPhOK	H	8.8	17.6	23.2	50.5
		er <sup>c</sup>	2.4	16.4	26.2	55.0
		th <sup>e</sup>	9.7	17.5	23.6	49.2
95	<i>m</i> -ClPhOK	H	9.7	17.5	23.6	49.2
		er <sup>c</sup>	3.2	16.8	26.5	53.4
		th <sup>e</sup>	10.2	18.6	23.7	47.4
95	<i>m</i> -NO <sub>2</sub> PhOK	H	3.2	17.7	25.2	54.0
		er <sup>c</sup>	11.1	14.2	26.3	48.4
		th <sup>e</sup>	6.0	15.0	31.4	47.6
95	<i>p</i> -NO <sub>2</sub> PhOK	H	9.6	6.8	38.8	44.8
		er <sup>c</sup>	11.0	16.2	26.6	46.2
		th <sup>e</sup>	6.0	15.5	32.3	46.2
5	<i>p</i> -MeOPhOK	H	7.3	17.8	23.8	51.0
		er <sup>c</sup>	3.2	16.8	26.4	53.6
		th <sup>e</sup>	7.6	16.6	24.2	51.6
5	<i>m</i> -ClPhOK	H	7.6	16.6	24.2	51.6
		er <sup>c</sup>	2.8	14.3	26.6	56.3
		th <sup>e</sup>	7.6	17.2	23.1	52.2
5	<i>m</i> -NO <sub>2</sub> PhOK	H	2.2	15.1	25.4	57.2
		er <sup>c</sup>	6.0	13.6	35.3	45.0
		th <sup>e</sup>	4.0	16.4	30.6	49.0
20	PhOLi	H	7.7	16.0	27.0	49.3
		er <sup>f</sup>	2.0	12.9	38.6	46.5
		th <sup>e</sup>	7.8	16.4	25.4	50.4
20	PhONa	H	7.8	16.4	25.4	50.4
		er <sup>f</sup>	2.3	15.7	27.6	54.3
		th <sup>e</sup>	8.1	17.1	27.3	47.6
20	PhONMe <sub>4</sub>	H	4.0	16.1	31.2	48.7
		er <sup>g</sup>	10.7	17.9	23.7	47.8
		th <sup>e</sup>	4.0	16.8	26.2	53.0
95	PhOK <sup>i</sup>	H	10.1	18.5	24.4	47.0
		er <sup>c</sup>	4.2	18.4	26.1	51.3
		th <sup>e</sup>	10.4	17.6	25.1	46.8
95	PhOK <sup>j</sup>	H	9.0	15.0	25.8	50.2
		er <sup>c</sup>	18.4	8.0	35.6	38.0
		th <sup>e</sup>	14.0	8.2	38.7	39.0
0	<i>t</i> -BuOK	H	15.8	8.5	32.5	43.3
		er <sup>c</sup>	12.4	7.7	39.1	40.8
		th <sup>e</sup>	17.0	8.3	34.2	40.5
0	<i>t</i> -BuONa	H	15.4	8.0	32.7	43.9
		er <sup>c</sup>	11.8	7.6	32.1	48.5
		th <sup>e</sup>	6.1	17.1	19.0	57.9
0	<i>n</i> -BuOK <sup>n,o</sup>	H	2.1	16.0	19.6	62.3
		er <sup>c</sup>	7.1	15.9	22.7	54.3
		th <sup>e</sup>	3.1	14.7	20.8	61.4
0	<i>n</i> -BuOK + CE <sup>n,p</sup>	H	8.0	16.4	16.7	58.9
		er <sup>c</sup>	4.8	16.1	20.5	58.6
		th <sup>e</sup>	8.0	16.4	16.7	58.9

<sup>a</sup> Except as otherwise noted, base concentrations were 0.09–0.25 *M* with a phenol concentration 0.5 times the phenoxide concentration, substrate concentration was 0.004 *M*, temperature 135°, and reaction time 24–48 hr. <sup>b</sup> Corrected for incomplete deuteration of substrate. <sup>c</sup> See Experimental Section. <sup>d</sup> Contained 5.62% undeuterated material. <sup>e</sup> Contained 3.35% undeuterated material. <sup>f</sup> Contained 4.48% undeuterated material. <sup>g</sup> Contained 5.40% undeuterated material. <sup>h</sup> Contained 6.29% undeuterated material. <sup>i</sup> Contained 10.34% undeuterated material. <sup>j</sup> 0.02 *M* base. <sup>k</sup> At 105°. <sup>l</sup> At 60°. <sup>m</sup> At 35°. <sup>n</sup> At 70°. <sup>o</sup> At 85°. <sup>p</sup> From ref 9. <sup>q</sup> CE = dicyclohexyl-18-crown-6 ether.

**Table II.** Deuterium Analyses of Hexenes and Per Cent Syn Elimination from 3-Hexyl-4-*d*<sub>1</sub>-trimethylammonium Iodides in Mixtures of *tert*-Butyl Alcohol and Dimethyl Sulfoxide<sup>a</sup>

	% DMSO	Base	Reactant	Olefin frac <sup>b</sup>	<i>d</i> <sub>0</sub> , % obsd <sup>c</sup>	% syn	
						Uncorr	Corr <sup>d</sup>
(1)	0	PhOK	er <sup>e</sup>	t	11.53	30.4	13.1
			th <sup>d</sup>	t	4.83	7.4	15.0
(2)	5	PhOK	er <sup>e</sup>	t	11.15	44.4	21.0
			th <sup>d</sup>	t	5.75	11.0	19.7
(3)	10	PhOK	er <sup>e</sup>	t	10.52	48.9	24.2
			th <sup>d</sup>	t	6.32	14.1	26.5
(4)	20	PhOK	er <sup>e</sup>	t	9.19	60.3	33.6
			th <sup>d</sup>	t	7.69	19.6	34.9
(5)	50	PhOK	er <sup>e</sup>	t	9.26	61.9	35.1
			th <sup>d</sup>	t	8.11	20.8	36.6
(6)	70	PhOK	er <sup>e</sup>	t	9.28	63.5	36.7
			th <sup>d</sup>	t	8.50	22.0	37.7
(7)	95	PhOK	er <sup>e</sup>	t	9.08	65.6	38.9
			th <sup>d</sup>	t	8.37	21.3	37.3
(8)	0	PhOK	er <sup>e</sup>	c	7.21	7.2	2.5
(9)	10	PhOK	er <sup>e</sup>	c	6.86	5.6	2.0
			th <sup>d</sup>	c	13.82	2.0	1.9
(10)	50	PhOK	er <sup>e</sup>	c	7.62	9.0	3.2
			th <sup>d</sup>	c	11.67	6.2	2.2
(11)	70	PhOK	er <sup>e</sup>	c	7.14	6.8	2.4
			th <sup>d</sup>	c	10.78	16.1	6.0
(12)	95	PhOK	er <sup>e</sup>	c	5.70	3.8	1.8
			th <sup>d</sup>	c	10.84	14.3	5.3
(13)	95	<i>p</i> -HOPhOK	er <sup>e</sup>	t	10.65	53.0	27.2
(14)	95	<i>p</i> -MeOPhOK	er <sup>e</sup>	t	11.66	48.1	26.4
			th <sup>e</sup>	t	7.66	13.8	26.1
(15)	95	<i>m</i> -ClPhOK	er <sup>e</sup>	t	8.51	73.2	47.6
(16)	95	<i>m</i> -NO <sub>2</sub> PhOK	er <sup>e</sup>	t	7.70	81.6	59.7
(17)	95	<i>p</i> -NO <sub>2</sub> PhOK	er <sup>e</sup>	t	7.9	85.2	65.4
			th <sup>d</sup>	t	14.1	54.4	72.4
(18)	95	<i>o</i> -NO <sub>2</sub> PhOK	er <sup>e</sup>	t	8.54	81.4	59.4
(19)	5	<i>p</i> -MeOPhOK	er <sup>e</sup>	t	13.08	37.2	17.8
(20)	5	<i>m</i> -ClPhOK	er <sup>e</sup>	t	11.47	46.9	21.7
(21)	5	<i>m</i> -NO <sub>2</sub> PhOK	er <sup>e</sup>	t	9.68	49.1	22.4
(22)	20	PhOLi	er <sup>f</sup>	t	7.69	89.6	74.1
(23)	20	PhONa	er <sup>g</sup>	t	7.33	78.9	55.5
(24)	20	PhONMe <sub>4</sub>	er <sup>g</sup>	t	7.39	85.7	66.8
(25)	20	PhOK <sup>i</sup>	er <sup>g</sup>	t	14.70	26.0	11.0
(26)	95	PhOK <sup>j</sup>	er <sup>e</sup>	t	9.26	72.6	43.9
(27)	95	PhOK <sup>k</sup>	er <sup>e</sup>	t	7.57	86.0	46.9
(28)	95	PhOK <sup>l</sup>	er <sup>e</sup>	t	7.83	91.4	57.6
(29)	0	<i>t</i> -BuOK	er <sup>e</sup>	t	7.31	93.6	83.4
(30)	0	<i>t</i> -BuONa	er <sup>e</sup>	t	6.50	96.3	89.6
(31)	0	<i>t</i> -BuOK <sup>m,o</sup>					80
(32)	0	<i>t</i> -BuOK + CE <sup>r</sup>	er <sup>h</sup>	t	12.16	93.2	82.1
(33)	0	<i>n</i> -BuOK <sup>n,o</sup>					16.6
(34)	0	<i>n</i> -BuOK + CE <sup>r</sup>	er <sup>h</sup>	t	18.45	37.8	16.9
(35)	0	<i>n</i> -BuONMe <sub>4</sub>	er <sup>e</sup>	t	22.26	38.6	17.4

<sup>a</sup> See corresponding footnote, Table I. <sup>b</sup> t = *trans*-3- and *trans*-2-hexene, c = *cis*-3- and *cis*-2-hexene. <sup>c-o</sup> See corresponding footnotes, Table I. <sup>p</sup> Per cent undeuterated material in mixture of *trans*-2 + *trans*-3, or *cis*-2 + *cis*-3 olefin after correction for incomplete deuteration of starting material. <sup>q</sup> Corrected to value which would be observed in the absence of an isotope effect, assuming  $(k_H/k_D)_{anti} = 3.0$  and  $(k_H/k_D)_{syn} = 2.2$ . <sup>r</sup> CE = dicyclohexyl-18-crown-6 ether.

strate and 1.0 in its role of determining base concentration). Consequently, we suggested that both free and ion-paired base contributed to the reaction. Independent evidence for the states of aggregation pictured in eq 1 was afforded by conductivity data, which showed that 0.1 *M* sodium *tert*-butoxide in *tert*-butyl alcohol was almost entirely undissociated, while the conductivity of 0.002–0.01 *M* benzyltrimethylammonium chloride in *tert*-butyl alcohol was linearly related to concentration, suggesting free ions.

One of the inconsistencies in the effect of the counterion of the base on the stereochemistry of elimination is cleared up immediately by reference to eq 1. Adding a quaternary ammonium salt, such as tetramethylammonium iodide, which cannot itself undergo elimination, would still shift the equilibrium to the right and

increase the concentration of free base, thereby increasing the proportion of syn elimination. Some additional assumption is required to account for the order with the different metal alkoxides. One attractive hypothesis is that the stability of the ion pair  $M^+X^-$  controls the position of equilibrium, so that free base concentration increases in the order  $K < Na < Li$ . Another possibility is that reactivity of the ion-paired base decreases in the order  $RO^-K^+ > RO^-Na^+ > RO^-Li^+$ , so that the proportion of reaction with free base increases in the same order.

Extension of our explanation to the data with the substituted potassium phenoxides is straightforward, for the equilibrium of eq 1 would be farther to the right with the more weakly ion-paired bases such as *p*-nitrophenoxide. There may also be a greater tendency

for the benzene ring of the phenoxides with a more delocalized negative charge to be attracted to the leaving group, thereby putting the oxygen in a better position to attack the syn  $\beta$  hydrogen.

The exact mechanism of the effect on stereochemistry of elimination of adding dimethyl sulfoxide to potassium phenoxide in *tert*-butyl alcohol cannot be deduced without additional information. An immediately obvious possibility is that dimethyl sulfoxide increases the concentration of free ions so that the free base becomes dominant by the time 20% dimethyl sulfoxide has been added. That the proportion of free ions is indeed related to the stereochemistry is suggested by the conductivities of the potassium phenoxide solutions, which increase 100-fold from 0 to 20% dimethyl sulfoxide but only about 15-fold from 20 to 95%.<sup>20</sup> This simple picture, however, fails to explain why added tetramethylammonium iodide or sodium or lithium phenoxides give still more syn elimination. Either more than one type of ion pair is involved or else the solvent change alters the syn/anti ratio in some way even without a change in the nature of the reactive base.

Some additional effects on stereochemistry of elimination were noted. Comparison of entries 4 and 25 in Table II shows that decreasing the concentration of potassium phenoxide from 0.2 to 0.02 *M* results in a decrease from 34 to 11% syn elimination. The interpretation of this result is not clear, for decreased concentration of ionic species generally favors dissociation of ion pairs. On the other hand, the concentration of free base generated by the equilibrium of eq 1 would decrease. Decreasing temperature increases the proportion of syn elimination (entries 4 and 26–28 of Table II), a trend difficult to evaluate without knowing the temperature dependence of the equilibrium of eq 1. Entries 29 and 30 show that the effect on stereochemistry of changing from potassium to sodium *tert*-butoxide is in the same direction as with the corresponding phenoxides.

The last five entries in Table II show that dicyclohexyl-18-crown-6 ether has no significant effect on the proportion of syn elimination either with potassium *tert*-butoxide in *tert*-butyl alcohol or potassium *n*-butoxide in *n*-butyl alcohol. A change from potassium to tetra-*n*-butylammonium *n*-butoxide is also without effect. At first sight the failure of crown ether to increase syn elimination is surprising, for the ether should complex strongly with potassium ion and thereby increase the concentration of free base, or at least convert the base from contact to separated ion pairs.<sup>21,22</sup> On the other hand, we have already noted that free base can be generated by the equilibrium of eq 1, and it may be that the crown ether does not generate enough additional free base to increase further the proportion of syn elimination. Evidence for this possibility is afforded by Bartsch,<sup>23</sup> who observed that dicyclohexyl-18-crown-6 ether dramatically increased the trans/cis ratio of the 2-butene from 2-butyl bromide and potassium *tert*-butoxide in *tert*-butyl alcohol, an effect

(20) J. K. Borchardt, unpublished results in these laboratories.

(21) C. J. Pedersen, *J. Amer. Chem. Soc.*, **89**, 7017 (1967).

(22) K. H. Wong, G. Konizer, and J. Smid, *J. Amer. Chem. Soc.*, **92**, 666 (1970).

(23) R. A. Bartsch, G. M. Pruss, R. L. Buswell, and B. A. Bushaw, *Tetrahedron Lett.*, 2621 (1972); R. A. Bartsch, G. M. Pruss, D. M. Cook, R. L. Buswell, B. A. Bushaw, and K. E. Wieggers, *J. Amer. Chem. Soc.*, **95**, 6745 (1973).

Table III. Percentages of *cis*-3-Hexene and Syn Elimination in Reactions of 3-Hexyltrimethylammonium Iodides

Reaction condition	Cis ene, % <sup>b</sup>	Syn elim, % <sup>c</sup>
MeOH–MeOK (130°) <sup>a</sup>	74.9	20
<i>n</i> -BuOH– <i>n</i> -BuOK (85°) <sup>a</sup>	73.8	17
<i>t</i> -BuOH–PhOK (135°)	70.2	14
<i>t</i> -BuOH–20% DMSO–PhOLi (135°)	69.4	74
<i>t</i> -BuOH–20% DMSO–PhONMe <sub>4</sub> (135°)	67.8	67
<i>t</i> -BuOH–20% DMSO–PhONa (135°)	67.6	55
<i>t</i> -BuOH–20% DMSO–PhOK (135°)	65.6	34
<i>t</i> -BuOH–95% DMSO–PhOK (135°)	64.9	38
<i>t</i> -BuOH–95% DMSO– <i>o</i> -NO <sub>2</sub> PhOK (135°)	59.6	59
<i>t</i> -BuOH–95% DMSO– <i>p</i> -NO <sub>2</sub> PhOK (135°)	56.1	69
<i>sec</i> -BuOH– <i>sec</i> -BuOK (85°) <sup>a</sup>	48.8	68
Pyrol RNMe <sub>3</sub> OH <sup>a</sup>	45.7	60
<i>t</i> -BuOH– <i>t</i> -BuOK (70°) <sup>a</sup>	33.3	80
<i>t</i> -PeOH– <i>t</i> -PeOK (85°) <sup>a</sup>	27.0	83

<sup>a</sup> From ref 9. <sup>b</sup> Out of total 3-hexene. <sup>c</sup> For 3-hexyl → *trans*-3-hexene.

plausibly ascribed to decrease in base association. The same effect is observed, however, upon the addition of tetra-*n*-propylammonium bromide, demonstrating that quaternary ammonium salts can have as powerful an influence on base association as crown ethers.

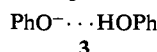
In earlier work, we observed a marked decrease in percentage of *cis* olefin as the percentage of syn elimination increased.<sup>10</sup> In Table III we assemble selected data from the present work, plus a few examples from our earlier studies, which used mainly alkoxides in the corresponding alcohols as bases.<sup>10</sup> It is evident that almost no correlation between per cent *cis*-3-hexene and per cent syn elimination remains when our phenoxide data are included. The change from potassium to lithium phenoxide in 20% dimethyl sulfoxide, for example, results in an increase from 34 to 74% syn elimination but only a change from 66 to 69% *cis*-3-hexene, in the opposite direction from the earlier correlation. Only the results with the *o*- and *p*-nitrophenoxides are at all in line with the expected trend.

Detailed interpretation of the breakdown of the correlation would require partial rates instead of just percentages for the various processes. It is evident, however, that the ion-pairing effects which seem to control the present results do not produce a correlation between per cent syn elimination and per cent *cis* olefin. The existence of such a correlation in some sets of data, then, probably arises from factors other than ion pairing. We suggest that base-strength effects, and possibly solvation effects as well, are still important in the change from one alkoxide–alcohol medium to another. Thus, there are at least three properties (base strength, ion pairing, and solvation) of the base–solvent system which must be considered, no one of them being capable of accounting for all changes in stereochemistry of elimination.

We have discussed ion-pairing effects in terms of free ions vs. ion pairs, but the actual situation must be more complex. If truly free alkoxide ions were responsible for syn elimination, then the proportion of syn elim-

ination should be highest in the most dissociating solvents, such as water and the *n*-alcohols, contrary to fact. Perhaps the factors favoring syn elimination act by converting contact ion pairs to solvent-separated ion pairs rather than all the way to free ions. It has been reported that crown ethers convert carbanion alkali metal salts from contact ion pairs to species with uv spectra characteristic of solvent-separated ion pairs.<sup>22</sup> Possibly syn elimination occurs *via* a tetra-alkylammonium-alkoxide ion pair which is not favored in a highly ionizing solvent. Although conductivity studies suggest equilibria between ion pairs and free ions under the elimination conditions,<sup>19,20,24</sup> more quantitative information on the species present in these solutions is still needed. One should keep in mind that the relationship between conductivity and the concentration of free ions *vs.* ion pairs is not so simple as when the equilibrium is between free ions and neutral molecules.<sup>25-27</sup>

A final point is that the phenoxide solutions probably contain at least some biphenoxide ion, **3**. A 50%



excess of phenol over phenoxide was used to suppress reaction *via* the conjugate base of the solvent, and biphenoxide has been suggested to explain rate effects of excess phenol under similar conditions.<sup>28,29</sup> While **3** would be expected to be less reactive than uncomplexed phenoxide, we cannot exclude the possibility that reaction with **3** contributes to some extent to the over-all elimination process.

### Experimental Section<sup>30</sup>

**3-Hexyltrimethylammonium iodide** was prepared by adding dropwise 0.14 mol of methyl iodide in 10 ml of ether to 0.085 mol of 3-hexyldimethylamine in 50 ml of ether at 0°. The mixture was stirred for 3 hr more, let stand in the refrigerator overnight, and filtered. The white precipitate was collected by filtration and recrystallized twice from ethanol-ether to give 85% of product, mp 196-197° dec (lit.<sup>9</sup> 195-197° dec).

**erythro-3-Hexyl-4-*d*<sub>1</sub>-trimethylammonium iodide** was prepared from **erythro-3-hexyl-4-*d*<sub>1</sub>-dimethylamine** (prepared by the method of ref 9) and methyl iodide by the same procedure as the undeuterated salt to give 65% of product, mp 193-194° dec (lit.<sup>9</sup> 193-194° dec). Two batches had 0.944 and 0.937 atom D per molecule as determined by mass spectrometry.

**threo-3-Hexyl-4-*d*<sub>1</sub>-trimethylammonium iodide** was prepared from **threo-3-hexyl-4-*d*<sub>1</sub>-dimethylamine** (prepared by the method of ref 9) and methyl iodide by the same procedure as the undeuterated salt to give product of mp 196-197° dec (lit.<sup>9</sup> 195-197° dec). Two batches had 0.966 and 0.953 atom D per molecule as determined by mass spectrometry.

**Solvents.** *tert*-Butyl alcohol was distilled twice after treatment with potassium, and *n*-butyl alcohol was distilled twice after treatment with sodium. They were shown to contain less than 0.03% water by glpc analysis on a 10-ft × 0.125-in. Poropak-Q column (Waters Associates) at 200°. Dimethyl sulfoxide was refluxed over calcium hydride and distilled. None was stored more than 5 days. Mixed solvents were prepared volumetrically.

**Base Solutions.** The metal (lithium, sodium, or potassium) was scraped clean under hexane. It was washed twice in, and then dis-

solved in, the appropriate alcohol, all in a drybox. Concentrations were determined by titration at room temperature, and values quoted do not include a correction for solvent expansion at higher reaction temperatures. Purification of the phenols used for the phenoxide solutions was effected by distillation followed by recrystallization from benzene for unsubstituted phenol, distillation for *m*-chlorophenol, and sublimation for the rest. The phenoxide solutions were prepared by adding a 50% excess of the phenol to the alkoxide solution, except as otherwise noted.

**Elimination Reactions.** The quaternary ammonium salts were dried in an Abderhalden apparatus prior to use and dissolved in the base solution in a drybox. The solution was transferred to a stainless steel reaction tube<sup>31</sup> which was then placed in a constant-temperature bath for the appropriate period of time. The contents of the tube was added to 0.5 ml of spectral grade *n*-pentane in a 50-ml round-bottom flask and then rinsed twice with 0.5-ml portions of *n*-pentane. The contents of the flask and the rinsings were subjected to short-path distillation into a receiver immersed in Dry Ice and acetone. When dimethyl sulfoxide was present in the reaction medium, *ca.* 0.5 ml of 4 *N* sodium hydroxide was added before distillation to ensure complete extraction of the olefins into the pentane layer. The distillate was separated and analyzed by glpc as described below.

**Elimination Product Separation and Analysis.** Analyses of the pentane solutions of the hexenes employed a 20-ft × 0.125-in. column of 20% adiponitrile on Chromosorb P connected to an 8-ft × 0.125-in. column of 20% saturated silver nitrate in ethylene glycol on Chromosorb P-AW operated at room temperature in an F and M Model 700 gas chromatograph equipped with flame ionization detectors. Analysis on the adiponitrile column alone established the absence of 1-hexene, which would have been found in the same peak as *trans*-3-hexene if present.<sup>9</sup> Other details of the analysis procedure were essentially as previously reported.<sup>9</sup> The olefin proportions for the deuterated ammonium salts were corrected for incomplete deuteration by multiplying the percentages for the undeuterated reactant by the fraction of undeuterated material in the deuterated reactant, subtracting the resulting numbers from the observed percentages for the olefins from the deuterated reactant, and renormalizing the corrected figures to 100%. The product percentages in the tables have been corrected in this fashion.

Separation of the olefins for mass spectrometric analysis employed a 15-ft × 0.25-in. column of 20% adiponitrile on Chromosorb P connected to a 9-ft × 0.25-in. column of 20% saturated silver nitrate in ethylene glycol on Chromosorb P-AW operated at room temperature in a Varian Aerograph A-90P gas chromatograph. Two fractions were collected. The first consisted of *trans*-3- and *trans*-2-hexene and the second of *cis*-3- and *cis*-2-hexene. Each sample was transferred to a vacuum line, degassed, dried over Drierite, and condensed into a mass spectrometer sample tube.

**Mass Spectrometric Analysis.** Analyses were carried out on a Hitachi Perkin-Elmer RMU-6E mass spectrometer using the flat-top peak technique. The hexenes were analyzed at 15 eV and the amines at 8 eV to suppress the P-1 peaks. The hexene analyses are the averages of three determinations, and the percentages are calculated as described by Biemann.<sup>32</sup>

**Control Experiments.** Subjection of 3-hexyltrimethylammonium iodide to 0-95% dimethyl sulfoxide in *tert*-butyl alcohol in the absence of base gave less than 1% yield of olefin. Subjection of synthetic mixtures of olefin to phenoxide bases in the same solvent mixtures led to no isomerization, which also shows that no isomerization occurs during the glpc analysis. Detector responses to the isomeric olefins were shown to be equal within experimental error. Use of cyclohexane as an internal standard gave total olefin yields of 87% or better. The *n*-pentane used in the isolation was shown to contain nothing which could interfere with the glpc or mass spectrometric analyses. The short-path distillation of the pentane solution of the product olefins was shown to have no effect on product proportions. *tert*-Butyl methyl ether was absent from the products of reaction with phenoxide bases, indicating that *tert*-butoxide ion was not present in sufficient concentration to effect substitution or, presumably, elimination.

**Calculations.** Product proportions from Table I were combined with deuterium analyses of the starting material to calculate the expected deuterium content of the olefin fraction in question for all syn and all anti elimination, respectively. Comparison of

(24) M. Svoboda, J. Hapala, and J. Závada, *Tetrahedron Lett.*, 265 (1972).

(25) D. N. Bhattacharyya, C. L. Lee, J. Smid, and M. Szwarc, *J. Phys. Chem.*, **69**, 608 (1965).

(26) R. M. Fuoss, *J. Amer. Chem. Soc.*, **57**, 488 (1935).

(27) R. M. Fuoss and C. A. Kraus, *J. Amer. Chem. Soc.*, **55**, 478 (1933).

(28) J. F. Bunnett and G. T. Davis, *J. Amer. Chem. Soc.*, **80**, 4337 (1958).

(29) C. L. Liotta and R. L. Karelitz, *J. Org. Chem.*, **32**, 3090 (1967).

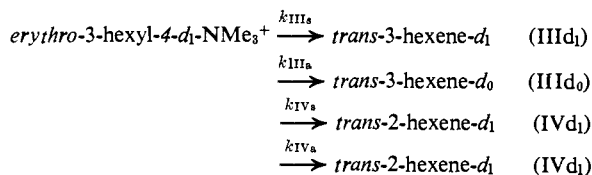
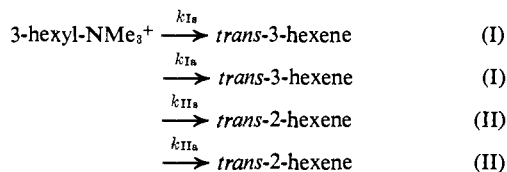
(30) Melting points and boiling points are uncorrected.

(31) W. H. Saunders, Jr., and T. A. Ashe, *J. Amer. Chem. Soc.*, **91**, 4473 (1969).

(32) K. Biemann, "Mass Spectrometry: Organic Chemical Applications," McGraw-Hill, New York, N. Y., 1962, Chapter 5.

these values with the observed deuterium content of the fraction gave the per cent syn uncorrected values listed in Table II. These were converted to per cent syn corrected values (those values which would be found in the absence of an isotope effect) by means of  $k_{\text{H}}/k_{\text{D}}$  values for the syn or anti elimination as described by Bailey and Saunders.<sup>9</sup> The  $k_{\text{H}}/k_{\text{D}}$  values used were average or compromise figures instead of those calculated from experimental data for the particular reaction (see the discussion). The values actually used are given in footnote *q* to Table II.

In the course of the work, we derived a modified version of the equation of Cooke and Coke<sup>16</sup> which enabled us to estimate the error introduced by assuming no secondary isotope effect when hydrogen is removed from a deuterium-bearing carbon atom. The definitions of terms and the result are as follows (a refers to syn and a to anti):



We assume that  $k_{\text{IIIa}} = k_{\text{IVa}}$  and that  $k_{\text{IIIa}} = k_{\text{IVa}}$  (no secondary isotope effect on elimination into the branch away from that bearing deuterium) but let  $k_{\text{Ia}}/k_{\text{IIIa}} = S$ . We then define product ratios in terms of the relevant rate constants and solve for  $k_{\text{Ia}}/k_{\text{IIIa}}$  (which is  $(k_{\text{H}}/k_{\text{D}})_{\text{anti}}$ ).

$$\frac{k_{\text{Ia}}}{k_{\text{IIIa}}} = \frac{(\text{I})/(\text{II})}{(\text{III})/(\text{IV})} \left[ 1 + \frac{(\text{III d}_1)}{(\text{III d}_0)} \right] - \frac{(\text{III d}_1)}{(\text{III d}_0)} S$$

When the *threo*-3-hexyl-4-d<sub>1</sub> reactant is used, an analogous equation gives  $(k_{\text{H}}/k_{\text{D}})_{\text{syn}}$ . As an example of the expected influence of a secondary isotope effect of reasonable magnitude, we found  $k_{\text{Ia}}/k_{\text{IIIa}}$  of 2.54 when  $S = 1$  and 2.45 when  $S = 1.1$ . Consequently, we neglected  $S$  in our calculations.

### Mechanisms of Elimination Reactions. XXIII. Stereochemistry of Elimination Reactions of 3-Hexyl Tosylate and Fluoride. The Role of Ion Pairing<sup>1</sup>

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**Abstract:** 3-Hexyl tosylate with phenoxide bases in 95% dimethyl sulfoxide–5% *tert*-butyl alcohol gives *trans*-3-hexene predominantly *via* an anti route. The proportion of syn elimination runs PhOLi, 16.5%; PhOK, 9.3%; *p*-NO<sub>2</sub>PhOK, 3.3%; PhOLi + NMe<sub>4</sub>I, 0%. The order is also that of decreasing ion pairing of the base, indicating that ion-paired base favors syn elimination. 3-Hexyl fluoride gives only 14% syn → *trans* elimination with potassium *n*-butoxide in *n*-butyl alcohol but 68% with potassium *tert*-butoxide in *tert*-butyl alcohol. The latter figure shows that a large leaving group is not a necessary condition for obtaining substantial proportions of *syn* elimination from open-chain reactants.

Most of the examples of *syn* elimination from simple open-chain reactants are found with quaternary ammonium salts. Few comparisons with other substrates are available, but it has been established that tosylates show much less propensity for *syn* elimination than do alkyltrimethylammonium salts.<sup>2,3</sup> We proposed that a key factor in this difference was the greater size of the trimethylammonio group, which forced the alkyl chain into a conformation that hindered approach to the anti β hydrogen.<sup>4,5</sup> The trimethylammonio group is also a poor leaving group, and this property should contribute to the propensity for *syn* elimination by causing the transition state to be relatively reactant like. We suggested, however, that a poor leaving group that was not bulky, such as fluorine, should give much less *syn* elimination.<sup>4</sup> The present work was

undertaken to test this prediction and also to compare some effects of ion pairing on stereochemistry of elimination with charged<sup>6</sup> and uncharged substrates. It was predicted<sup>7,8</sup> that a free anionic base should effectively promote *syn* elimination with charged substrates, and our results<sup>6</sup> support this prediction. A base ion paired with a metal ion, however, was predicted to promote *syn* elimination with neutral substrates because of coordination of the metal ion with the leaving group as in 1.<sup>9,10</sup> Additional evidence on these points appeared in the literature during the course of these studies and will be discussed below along with our results.

Data on olefin proportions are given in Table I and on deuterium analyses in Table II for reactions of stereospecifically deuterated 3-hexyl-4-*d* fluorides and tosyl-

(1) This work was supported by the National Science Foundation.

(2) J. Sicher, J. Závada, and M. Pánková, *Collect. Czech. Chem. Commun.*, **36**, 3140 (1971).

(3) J. Závada, M. Pánková, and J. Sicher, *Chem. Commun.*, 1145 (1968).

(4) D. S. Bailey and W. H. Saunders, Jr., *J. Amer. Chem. Soc.*, **92**, 6904 (1970).

(5) D. S. Bailey, F. C. Montgomery, G. W. Chodak, and W. H. Saunders, Jr., *J. Amer. Chem. Soc.*, **92**, 6911 (1970).

(6) J. K. Borchardt and W. H. Saunders, Jr., *J. Amer. Chem. Soc.*, **96**, 3912 (1974).

(7) J. Závada and J. Sicher, *Collect. Czech. Chem. Commun.*, **32**, 3701 (1967).

(8) J. Sicher and J. Závada, *Collect. Czech. Chem. Commun.*, **33**, 1278 (1968).

(9) J. Závada, J. Krupicka, and J. Sicher, *Collect. Czech. Chem. Commun.*, **33**, 1393 (1967).

(10) M. Svoboda, J. Závada, and J. Sicher, *Collect. Czech. Chem. Commun.*, **33**, 1415 (1967).