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THE REACTIVITY OF ALKENES IN THE OXYMERCURATION REACTION

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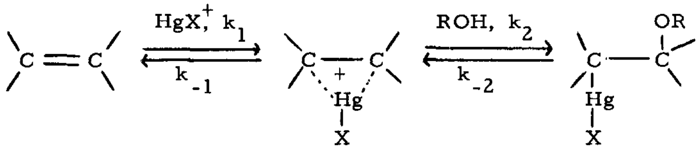
The preferred mechanism of the oxymercuration reaction involves the fast reversible formation of a bridged π-complex (k_1) with rate limiting attack by solvent (k_2) on this mercurinium ion intermediate (eq. 1). It has generally been assumed that electrophilic



(eq. 1)

addition to alkenes will be facilitated by increased alkyl substitution[1] of the double bond or by an increase in the ground state energy of the alkene due to angle strain.[2] However, the oxymercuration reaction has been shown to be anomalous in several respects. For example, a recent study of the hydroxymercuration reaction has shown that terminal alkenes are more reactive than disubstituted alkenes and that tetrasubstituted alkenes exhibit unusually low reactivity.[3] We now report conclusive evidence that neither the rate of the oxymercuration reaction nor the degree of π-complex formation with silver ion is increased by an increase in strain energy of the alkene.

Since a systematic study of the effects of alkene strain energy on oxymercuration has not been reported, we first examined the position of equilibrium for π-complex formation (k_1). However, this equilibrium cannot be measured by conventional methods so we elected to determine the Argentation constants for a series of alkenes given in Table I. The similarity of the bonding mode of Ag^+ and HgX^+ with a double bond[4] suggests that silver ion should serve as a suitable model to examine the effects of strain energy on the equilibrium constant for π-complex formation.

It is clearly evident from the data in Table I that a linear correlation between alkene strain energy and K_{Ag} is not in evidence. With the exception of *trans*-cyclooctene, where torsional strain can be relieved on π-complex formation by additional out-of-plane twist of the double bond, the K_{Ag} are not markedly influenced by an increase in ground state energy of the alkene. Indeed steric effects appear to be far more important than strain energy as evidenced by the relatively weak complexes formed with alkenes **5** and **15**. These data strongly suggest that rate acceleration due to relief of angle strain on π-complex formation should not be anticipated in the oxymercuration reaction. Moreover, our results suggest that k_2 is also the rate limiting step for highly strained alkenes.

Our study on the effect of strain energy on the rate limiting step (k_2) utilized cyclohexene as the unstrained reference alkene and the relative rates of all other alkenes were measured by competition experiments. A 1:1 ratio of each of two alkenes (0.33M) was added to a stirring solution of methanol at 25°. A solution of $Hg(OAc)_2$[5] in CH_3OH was introduced until the alkenes were present in a ten-fold excess. The product ratios were determined by $NaBH_4$ reduction and subsequent gas chromatographic analysis of the resulting methyl ethers. With alkenes of widely different reactivity, internal consistency was achieved using two competing alkenes of comparable reactivity and relating these rates to that of cyclohexene.

Examination of the data in Table I indicates that the alkenes chosen vary over four orders of magnitude in reactivity toward $Hg(OAc)_2$. However, a general increase in the reactivity of the alkene with its strain energy was not observed. For example, 1-octene exhibits a reactivity comparable to that of trans-cyclooctene and greater than that of norbornene.[7] The unusually low reactivity of cyclobutene and the cis-fused cyclobutene **10** further demonstrates that relief of strain in the rate limiting step is not appreciable.

Steric hindrance also obviously plays a major role in the rate of methoxymercuration as exemplified by the fact that the relatively unstrained but hindered trans-di-t-butylethylene is unreactive toward $Hg(OAc)_2$ in CH_3OH. Steric retardation is not observed if the t-butyl group is one or more carbon atoms removed from the double bond as evidenced by the relative rate of **8**. Although the trisubstituted alkene **5** reacts 2.2 times faster than cyclohexene, tetramethylethylene has a relative reactivity of only 0.061.[3] This behavior is markedly different from that observed in the bromination reaction where tetramethylethylene has a reactivity of 10^7 relative to ethylene.[9] This observation is consistent with the contention that the rate limiting step in the bromination reaction is formation of a bridged bromonium ion intermediate, while nucleophilic attack by solvent on a mercurinium ion is rate determining in the oxymercuration reaction. Therefore, one should anticipate rate retardation when nucleophilic attack at a tertiary or highly hindered center is involved. Thus, the highly hindered alkene **20** exhibits no measurable reactivity toward $Hg(NO_3)_2$ in CH_3OH. Moreover, the low reactivity of medium ring alkenes most likely reflects an increase in transannular strain in addition to steric hindrance of attack by solvent in the transition state.

The above data provide convincing evidence that the rate of methoxymercuration is not markedly influenced by bond angle strain inherent in the alkene. Our results also suggest that rate acceleration due to π-complex formation should not be anticipated. In addition, the lack of correlation of relative reaction rate with the calculated energy difference between the alkene and its corresponding alkane (Table I) suggests that substantial relief of strain in the transition for oxymercuration does not obtain.

The above results provide dramatic evidence that the relative rate of syn- and anti-methoxymercuration is not related to the ground state energy of the alkene. Steric effects and torsional or twist strain[2] effects in the transition state are dominate factors that determine the rate of reaction. Thus, we may conclude that our results are consistent with a rate limiting step involving attack by solvent on a mercurinium ion intermediate.

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4. R. D. Bach and H. F. Henneike, J. Amer. Chem. Soc., **92**, 5589 (1970).
5. Addition of solid $Hg(OAc)_2$ to the solution of competing alkenes gave smaller relative rate values for alkenes that are more reactive than cyclohexene. Control experiments were carried out to insure that we were measuring the kinetic products rather than the thermodynamic products as a result of alkene exchange reactions.[6]
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7. In comparing relative rates alkenes should be divided into two classes, those which afford syn-adducts and those which proceed by anti-addition. Using the principle of microscopic reversibility of the ΔH^o of isomerization of the syn- to the anti-transition state should be $\sim$ 5 kcal/mole based upon deoxymercuration studies.[8]
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TABLE I

	Alkene	Mode of Oxymercuration	Relative Rate	Relative[a] K_{Ag}	Strain[b] Energy	ΔE[c]
1	norbornadiene	syn	27.0	8.5	31.59	7.97[d]
2	*trans*-cyclooctene	syn	10.1[4]	7300	17.85	6.33
3	1-octene	anti	9.5[4]	1.3		
4	norbornene	syn	4.5[4]	13.	23.62	5.72
5	1-methylcyclohexene	anti	2.2	0.07	2.68	
6	benzonorbornadiene	syn	1.1			
7	cyclohexene	anti	1.0	1.00	2.61	0.86
8	4-*t*-butylcyclohexene	anti	0.96	0.60		
9	cyclobutene	anti	0.40	0.76		
10	bicyclo[4.2.0]oct-7-ene	syn/anti	0.17	0.39		
11	bicyclo[3.2.1]oct-2-ene	syn/anti	0.065	0.76		
12	bicyclo[2.2.2]octene	syn/anti	0.030	1.1	15.99	4.30
13	*cis*-cyclooctene	anti	0.004	3.04	8.81	-2.71
14	*cis*-di-*t*-butylethylene	anti	0.001[4]	1.0	16.37	9.82
15	*trans*-di-*t*-butylethylene	syn	no reaction[4]	0.026	6.01	-0.54
16	*cis*-cyclodecene	anti	slow		11.63	-5.41
17	*trans*-cyclodecene	syn	slow		11.95	-4.05
18	dibenzobicyclo[2.2.2]octatriene	syn/anti	slow			
19	[4.4.2]propell-11-ene	anti	no reaction[e]			
20	adamantylidene adamantane		no reaction			

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[a] The relative Argentation constants were determined by the glpc method of Muhs and Weiss, *J. Amer. Chem. Soc.*, **84**, 4697 (1962).

[b] The values were taken from N. L. Allinger and J. T. Sprague, *J. Amer. Chem. Soc.*, **94**, 5734 (1972).

[c] Strain energy difference (alkene minus alkane).

[d] Strain energy of **1** minus strain energy of **4**.

[e] Anti addition was observed with $Hg(NO_3)_2$.