Table II. Apparent Values of K_e and $k^{H}_{cat.}$ for Hydrolysis of DE-2 in 1:9 (v/v) Dioxane–Water (25 °C, μ = 0.1 ($NaClO_4$)) Catalyzed by FMN, 5′-Mononucleotides, and Ribose 5-Phosphate

phosphate	pK_a	K_e (M^{-1})	$k^{H}_{cat.}$ (s^{-1})
FMN[a]	6.46	3.4×10^3	0.06
5′-GMP[b]	6.50	<100	>0.30
5′-AMP[b]	6.64	<100	>0.27
5′-CMP[b]	6.49	<100	>0.035
ribose 5-phosphate[a,b]	6.60	<25	>0.032

[a] Reference 10. [b] Values of K_e and $k^{H}_{cat.}$ are estimated from the values of $k(\mathrm{ROPO_3H^-})$ listed in Table I and the fact that rate plots of k_{obsd} vs. $(f)\ [\mathrm{RO}\textcircled{P}]_{TOT}$ show no curvature at $(f)[\mathrm{RO}\textcircled{P}]_{TOT} <$ 0.005 M for 5′-GMP, 5′-AMP, and 5′-CMP and no curvature at $(f)[\mathrm{RO}\textcircled{P}]_{TOT} <$ 0.02 M for ribose 5-phosphate (ref 10).

$^1/_2(f)[\mathrm{RO}\textcircled{P}]_{TOT}$. The minimum values for $k^{H}_{cat.}$ and maximum values for K_e can therefore be estimated and are provided in Table II for the 5′-mononucleotides and ribose 5-phosphate. The published values of K_e and $k^{H}_{cat.}$ for the FMN-catalyzed reaction of DE-2 are also given for comparison.

It is clear from the data of Table II that the equilibrium constants for association of DE-2 with mononucleotides and ribose 5-phosphate are very much less than that for association of DE-2 with FMN. However, calculated minimum values of $k^{H}_{cat.}$ for 5′-GMP and 5′-AMP are substantially larger than $k^{H}_{cat.}$ for FMN. For concentrations of 5′-GMP and 5′-AMP in the monohydrogen phosphate ionization state greater than 2 mM, the catalytic effectiveness of these nucleotides in promoting the hydrolysis of DE-2 exceeds that of FMN. The pK_a values of 5′-GMP and 5′-AMP are very similar to that of FMN, and therefore the larger values of $k^{H}_{cat.}$ for these nucleotides is not due to greater acidities of their monohydrogen phosphate groups relative to that in FMN. Rather, a combination of proton-donating ability of the monohydrogen phosphate group and favorable stacking interactions at the transition state must account for their greater catalytic effectiveness. It should be possible to design other phosphate catalysts in which there is proper orientation of a phosphate group with a second group capable of complexing with the diol epoxide such that $k^{H}_{cat.}$ is comparable to or greater than that for 5′-GMP or 5′-AMP, but in addition K_e is equal to or greater than that for FMN. Such catalyst, without being any more acidic than FMN, would be far more effective than FMN at promoting the hydrolysis of DE-2 at low catalyst concentrations.

In an effort to further demonstrate that secondary stacking abilities of groups within a general acid molecule also play a role in determining its effectiveness as a catalyst in the hydrolysis of DE-2, we have determined the second-order rate constants for the hydrolysis of DE-2 catalyzed by $H_2PO_4^-$, phenyl hydrogen phosphate ($C_6H_5OPO_3H^-$), and 1-naphthyl hydrogen phosphate ($C_{10}H_7OPO_3H^-$) (Table I). Phenyl hydrogen phosphate and 1-naphthyl hydrogen phosphate have almost identical pK_a's and on this basis should be comparable as general acid catalysts. Dihydrogen phosphate anion ($H_2PO_4^-$) has a somewhat higher pK_a value but is a diprotic acid. Consequently it should be almost as efficient as phenyl hydrogen phosphate and 1-naphthyl hydrogen phosphate anions in promoting the hydrolysis of DE-2. Yet the data of Table I show that $k(\mathrm{ROPO_3H^-})$ for 1-naphthyl hydrogen phosphate anion is more than three times larger than that for phenyl hydrogen phosphate anion, which is in turn four times greater than that for $H_2PO_4^-$. We conclude, therefore, that favorable stacking interactions between DE-2 and general acids at the transition state can contribute significantly to enhanced reaction rates.[14]

Acknowledgment. This investigation was supported in part by Public Health Service Grants No. CA-26086 and CA-17278 from the National Cancer Institute. Helpful discussions with Dr. Jane M. Sayer (National Institutes of Health) are appreciated.

Registry No. DE-2, 58917-67-2; **3a**, 85-32-5; **3b**, 61-19-8; **3c**, 63-37-6; **4a**, 117-68-0; **4b**, 84-21-9; **4c**, 84-52-6; **5a**, 130-50-7; **5b**, 130-49-4; **5c**, 85-94-9.

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(14) DE-2 is much more reactive toward ellagic acid (ref 15) than it is toward other general acids of comparable pK_a values (ref 6). It was postulated that favorable stacking interactions between DE-2 and ellagic acid at the transition state accounted for the enhanced reaction rate.

(15) Sayer, J. M.; Yagi, H.; Wood, A. W.; Conney, A. H.; Jerina, D. M. *J. Am. Chem. Soc.* **1982**, *104*, 5562.

Kinetic (^{18}O and ^{14}C) and Magnetic (^{13}C) Isotope Effects in the Photo-Fries Rearrangement of 4-Methoxyphenyl Acetate

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Kinetic isotope effects (KIE) were measured for the photorearrangement of 4-methoxyphenyl acetate (**1**) into 2-acetyl-4-methoxyphenol (**2**) in ethanol solution. The KIE for labeling the phenolic oxygen atom with ^{18}O was 1.0000 ± 0.0023. The KIE for labeling with ^{14}C at the α-carbon atom of the acetyl group was measured in two ways: with recovered **1** (0.9988 ± 0.0051) and with isolated **2** (1.007 ± 0.008). Labeling with ^{13}C at the α-carbon atom led to a magnetic, inverse isotope effect (0.9511 ± 0.0042). The results show that there is not a detectable activation barrier for breaking the ester bond and that **2** is formed by recombination of a caged radical pair which originates from an excited singlet state. Surprisingly, labeling of **1** with ^{14}C in the ortho position led to a KIE, measured with recovered **1**, of 1.0286 ± 0.0021. We attribute this to a reaction of **1**, as yet unknown, which is not associated with rearrangement into **2**. It is noteworthy that rearrangement is not the major reaction pathway. The larger part (over 60%) of **1** is converted into polymeric material. The origin of the polymeric material lay in the scission product, 4-methoxyphenol (**3**), which was itself not obtained during the lengthy irradiations of the KIE work. Whether the KIE for ortho labeling is connected with polymer formation is not now known.

The photo-Fries rearrangement is the conversion of an aryl ester into an acylphenol.[2] It is exemplified, for example, by the conversion of phenyl acetate into *o*- and *p*-acetylphenol or of *p*-tolyl acetate into 2-acetyl-4-

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methylphenol.[3] Scission of the ester leading to an unacylated phenol always occurs, too. The rearrangement is now recognized, from the early results of quenching and sensitization effects, to originate in the singlet rather than the triplet excited state.[3-5] More recently magnetic isotope effects in the rearrangement of 1-naphthyl acetate have been shown to be consistent only with a singlet-state reaction.[6] Soon after its discovery,[7] opinions became divided over the reaction's mechanism. On the one hand it was proposed by Kobsa that scission into and recombination of an aryloxy and acyl radical occurred.[8] On the other hand Anderson and Reese proposed that rearrangement was an intramolecular process in which diradical intermediates were involved.[9] In the latter proposal, the formation of a deacylated phenol occurred by an independent, intermolecular process. The possibility that both scission, leading on to formation of phenol, and concerted rearrangement (in the modern sense) might occur was also considered and led to the proposal that concerted sigmatropic rearrangement of phenyl acetate occurred in an upper singlet excited state, different from that which led to scission.[10] This proposal, which would require the ratio of ortho/para products to vary with the wavelength of irradiation, was found later, from the results of such a comparison, not to be tenable, however.[4] The weight of evidence is now heavily on the side of the radical–recombination mechanism. Included in the evidence are CIDNP effects in the rearrangement of *p*-tolyl *p*-chlorobenzoate, which are also consistent only with a singlet-state reaction,[5,11] and the observation of aryloxy radicals by transient absorption[4] and Raman spectroscopy.[12] Evidence for the recombination of radicals in a cage has also been obtained with the use of cyclodextrins. Thus, the ratio of ortho/para products from rearrangement of phenyl acetate changed from 4 in water to 1.89 in the presence of α-cyclodextrin and 1.79 in the presence of β-cyclodextrin. The change was attributed to inhibition of recombination of radicals at the ortho position, caused by their inclusion in the cavity of a cyclodextrin.[13]

Early among the works which were designed to clarify the mechanism of the photo-Fries rearrangement, Kalmus and Hercules concluded that the mechanism was as Kobsa had proposed and that a mechanism other than homolytic cleavage and cage recombination should be postulated only on the basis of strong positive evidence.[14] A useful method of obtaining positive evidence for concerted rearrangements is the measurement of heavy-atom kinetic isotope effects. This is achieved by labeling the atoms at the bond-breaking and bond-making positions, particularly with nonmagnetic heavy isotopes.[15] As far as the photo-Fries rearrangement is concerned, a move in this direction was made over 20 years ago by Schutte and Havinga,[16] with 4-methoxyphenyl acetate (**1**) labeled with ^{14}C at the carbonyl carbon atom. By measuring ^{14}C abundance in both product (2-acetyl-4-methoxyphenol, **2**) and recovered **1** a KIE of 1.007 ± 0.018 was obtained, from which it was concluded that, within an experimental error of 2%, this photo-Fries reaction showed no isotope effect. Interestingly, the result was not linked to a radical recombination reaction but only, in photochemical terminology, to the conclusion that the reaction path started from the electronically excited state of the reactant and cascaded down through a series of vibrationally excited states toward the ground state of the product.

Carbon KIE are ordinarily not very large. It occurred to us that the result obtained by Schutte and Havinga might, in fact, be compromised by the rather large experimental error in the measurements. Our interest in the question of whether photochemical reactions may pass through a detectable ground-state-like barrier,[17] a question which prompted Schutte and Havinga to carry out their study, too, persuaded us to repeat their work with α-^{14}C labeling and to extend it also to KIE measurements for labeling at the other positions involved. We can now report on our measurements with [α-^{14}C]**1**, [*o*-^{14}C]**1**, [^{18}O]**1** (i.e., **1** labeled at the phenolic oxygen atom), and also [α-^{13}C]**1**. We must say right away that we confirm Schutte and Havinga's result with [α-^{14}C]**1**. That is, with our better precision we also find no KIE for labeling with ^{14}C at that position. In addition to the KIE measurements we have studied also in more detail the distribution of products from irradiating **1**. The KIE results and product studies allow us to provide a more detailed picture of the photochemistry of **1** than was available earlier.

Products of rearrangement of **1** were characterized by Stratenus, who reported also an overall quantum yield of 0.49 for rearrangement in ethanol.[18] The quantum yield is somewhat higher than those for other para-substituted phenyl acetates, for example, 0.20 for *p*-methyl and 0.22 for *p*-chloro,[3] but assures us that discrimination occurs somewhere along the initial pathways of rearrangement and thus that looking for isotope effects is not invalid.

Results and Discussion

Preparations of Labeled 1. The preparations of [α-^{14}C]**1**, [α-^{13}C]**1**, and [^{18}O]**1** were straightforward. Preparation of [*o*-^{14}C]**1** began with [2-^{14}C]azoxybenzene,[17] from which 4-hydroxy[2-^{14}C]azobenzene was obtained by Wallach rearrangement in 85% sulfuric acid. From this 4-methoxy[2-^{14}C]azobenzene was prepared and was hydrogenolyzed into a mixture of labeled aniline and labeled *p*-anisidine. Separation allowed for the conversion of the *p*-anisidine into 4-methoxy[2-^{14}C]phenol and thence into [*o*-^{14}C]**1**.

Kinetic isotope effects were calculated from isotopic abundances in either recovered **1** or **2**, as was convenient. The ester **1** was unsuited to multiscan mass spectrometry, so ^{18}O and ^{13}C KIE were obtained from the use of **2** only. Product **2** has a yellow color and, therefore, causes quenching in scintillation counting. For this reason it is not as well suited as colorless **1** for measurements of ^{14}C

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(1) Present address: Institute of Organic and Physical Chemistry, Technical University, Wroclaw, Poland.

(2) Bellus, D. *Adv. Photochem.* **1971**, *8*, 109.

(3) Shizuka, H.; Morita, T.; Mori, Y.; Tanaka, I. *Bull. Chem. Soc. Jpn.* **1969**, *42*, 1831.

(4) Kalmus, C. E.; Hercules, D. M. *J. Am. Chem. Soc.* **1974**, *96*, 449.

(5) Adam, W. *J. Chem. Soc., Chem. Commun.* **1974**, 289.

(6) Nakagaki, R.; Hiramatsu, M.; Watanabe, T.; Tanimoto, Y.; Nagakura, S. *J. Phys. Chem.* **1985**, *89*, 3222.

(7) Anderson, J. C.; Reese, C. B. *Proc. Chem. Soc., London* **1960**, 216.

(8) Kobsa, H. *J. Org. Chem.* **1962**, *27*, 2293.

(9) Anderson, J. C.; Reese, C. B. *Proc. Chem. Soc., London* **1963**, 1781.

(10) Sandner, M. R.; Hedaya, E.; Trecker, D. J. *J. Am. Chem. Soc.* **1968**, *90*, 7249.

(11) Adam, W.; Arude Sanabia, J.; Fischer, H. *J. Org. Chem.* **1972**, *33*, 14.

(12) Beck, S. M.; Brus, L. E. *J. Am. Chem. Soc.* **1982**, *104*, 1805.

(13) Chênevert, R.; Voyer, N. *Tetrahedron Lett.* **1984**, 5007. See ref 14.

(14) A similar result was obtained earlier with β-cyclodextrin, but an explanation was not given. Ohara, M.; Watanabe, K. *Angew. Chem., Int. Ed. Engl.* **1975**, *14*, 820.

(15) Rhee, E. S.; Shine, H. J. *J. Am. Chem. Soc.* **1986**, *108*, 1000 and earlier references therein.

(16) Schutte, L.; Havinga, E. *Tetrahedron* **1967**, *23*, 2281.

(17) Shine, H. J.; Subotkowski, W.; Gruszecka, E. *Can. J. Chem.* **1986**, *64*, 1108.

(18) Stratenus, J. L. "Fotoreacties van enige aromatische ethers en esters" Thesis, University of Leiden, Netherlands, 1966. We thank Prof. Havinga and the University of Leiden for the gift of a copy of this thesis.

Table I. Kinetic Isotope Effects (KIE) in the Rearrangement of 4-Methoxyphenyl Acetate (1) into 2-Acetyl-4-methoxyphenol (2)

run	isotope	F	basis[a]	KIE (k_L/k_H)	std dev
1[b]	1-^{18}O	0.40	2	1.0023	0.0021
2[b]	1-^{18}O	0.44	2	0.9969	0.0019
3[b]	1-^{18}O	0.42	2	1.0005	0.0032
6[c]	1-^{18}O	0.31	2	1.0115	0.0024
7[c]	1-^{18}O	0.32	2	0.9973	0.0037
8[c]	1-^{18}O	0.34	2	1.0033	0.0044
9[c]	1-^{18}O	0.37	2	0.9972	0.0036
10[c]	1-^{18}O	0.50	2	1.0021	0.0027
14[d]	1-^{18}O	0.36	2	1.0000	0.0069
15[d]	1-^{18}O	0.43	2	0.9994	0.0075
18	α-^{14}C	0.57	1	1.0000	0.0023
19	α-^{14}C	0.63	1	1.0020	0.0028
20	α-^{14}C	0.78	1	1.0030	0.0030
21	α-^{14}C	0.85	1	0.9901	0.0026
19[e]	α-^{14}C	0.63	2	1.013	0.0047
20[e]	α-^{14}C	0.78	2	0.996	0.0022
21[e]	α-^{14}C	0.85	2	1.012	0.0066
22[f]	o-^{14}C	0.40	1	1.0315	0.0027
23[f]	o-^{14}C	0.56	1	1.0268	0.0041
24[f]	o-^{14}C	0.70	1	1.0274	0.0031
25[g]	α-^{13}C	0.29	2	0.9602	0.0046
26[g]	α-^{13}C	0.36	2	0.9522	0.0039

[a] Compound in which isotope ratios were measured. [b] Calculation of KIE was made by comparison of isotope ratio, $(M + 2)/M$, with that from run 4, $F = 0.85$. Therefore, an iterative treatment of the usual equation for calculating product KIE was made.[30] [c] The isotope ratio, $(M + 2)/M$, at $F = 1.0$, used for these calculations was the average of the three from runs 11, 12, and 13. [e] Although the KIE was determined with product, the ^{14}C content of product at 100% conversion was not used in the calculation. Instead the ^{14}C content of the initial substrate (1) was used. [f] KIE corrected for intramolecular competition. [g] Isotope ratio, $(M + 1)/M$, for $F = 1.0$ from run 28.

Table II. Summary of KIE in the Rearrangement of 4-Methoxyphenyl Acetate (1) into 2-Acetyl-4-methoxyphenol (2)

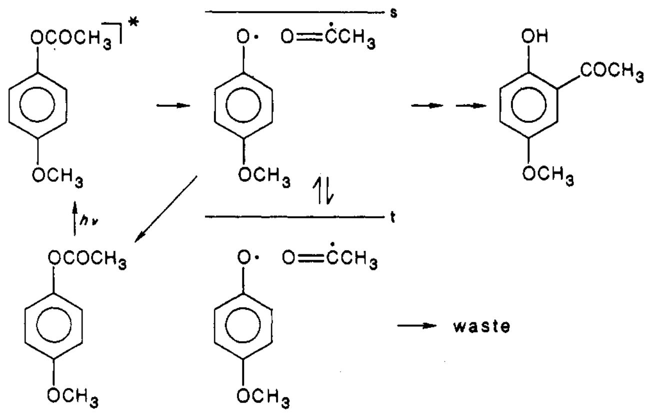
isotope	basis	KIE (k_L/k_H)
1-^{18}O	2	1.0000 ± 0.0023[a]
α-^{14}C	1	0.9988 ± 0.0051[b]
α-^{14}C	2	1.007 ± 0.008[c]
o-^{14}C	1	1.0286 ± 0.0021[d]
α-^{13}C	2	0.9511 ± 0.0042[e]

[a] Average of all runs (Table I) except run 6. Inclusion of run 6 gives 1.0011 ± 0.0041. [b] Average of runs 18–21. [c] Average of runs 19–21. Insufficient product was obtained after sublimation to obtain a product-based KIE from run 18. [d] Average of runs 22–24. [e] Average of runs 25 and 26.

KIE. We used both **1** and **2** in the rearrangements of [α-^{14}C]**1** because we were repeating the work of Schutte and Havinga.[16] Only **1** was used for counting, though, in the rearrangement of [o-^{14}C]**1**. All KIE are listed in Table I and are summarized in Table II.

[α-^{14}C]-, [α-^{13}C]-, and [^{18}O]1. Four measurements of KIE based on recovered **1** in rearrangement of [α-^{14}C]**1** averaged 0.9988 ± 0.0051. Three measurements based on **2**, made with the use of an internal standard and compensation for quenching, averaged 1.007 ± 0.008. This result is not as precise as that obtained from using recovered **1**, but, nevertheless, the two results are in agreement. The results, particularly that from the use of recovered **1**, show that an isotope effect is not caused by α-^{14}C labeling. In principle, the meaning of this answer is not unambiguous. If a concerted migration of the α-carbon atom from the phenolic oxygen to the ortho carbon atom occurred, the isotope effects for bond breaking and bond forming could cancel out. This arises becauses when bond breaking is part of the transition state its KIE is always greater than one, whereas a bond-forming KIE can, in principle, be less than one.[19] For this reason, we measured also the KIE for labeling at the phenolic oxygen atom, arguing that if a KIE for breaking the oxygen–acyl carbon bond was being obscured in the α-^{14}C labeling, it should show up in the phenolic ^{18}O labeling. The result from 10 runs was 1.0000 ± 0.0023. Certainly, a change does occur in the character of the bonding at this oxygen atom during rearrangement, in that the oxygen atom becomes a carbonyl oxygen. Consequently, a KIE here might also be obscured. Our experience with nitrogen atoms in the benzidine rearrangement,[17] and the oxygen atom in the quinamine rearrangement,[20] has shown that such changes in bonding do not obscure a real KIE, however. Thus, we feel that the ^{18}O result which we have obtained in the rearrangement of **1** shows truly that there is no KIE in breaking the O—C(=O) bond. This, in turn, shows that truly no bond-breaking KIE arises from α-^{14}C labeling, too.

Scheme I



At first sight these two results, from ^{18}O and α-^{14}C labeling seem to be clearly consistent with the breaking of the O—C(=O) bond in an electronically excited state into the familiar two radicals. This state would be energetically above the vibrational levels of a ground-state molecule, and the bond breaking would not be affected by isotopic labeling. On the other hand, as pointed out earlier by Schutte and Havinga,[16] the absence of an isotope effect may mean that the O—C(=O) bond is largely intact in the transition state. In that case, rearrangement could, in fact, still be concerted, as seems to be implied in Schutte and Having's conclusion. To settle the meaning of these KIE, therefore, we turned next to α-^{13}C labeling.

Two measurements of KIE based on **2** were made in the rearrangement of [α-^{13}C]**1**. The result was an inverse KIE, 0.9511 ± 0.0042, and is consistent only with the singlet, caged radical pair mechanism, shown in Scheme I. The principle applied here has been codified as a sign rule by Turro and has been illustrated particularly clearly with the triplet-state photolysis of benzophenone.[21,22] The photorearrangement of **1** is a singlet-state reaction. Intersystem crossing within the caged radical pair enriches the singlet pair in ^{12}C. This, leads, by return of the pair to **1**, to an enrichment of ^{12}C in **1**, increasing as rearrangement proceeds. Consequently, when isotope ratios

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(19) Fry, A. In *Isotope Effects in Chemical Reactions*; Collins, C. J., Bowman, N. S., Eds.; Van Nostrand Reinhold: New York, 1970; pp 364–414.

(20) Boduszek, B., unpublished work.

(21) Turro, N. J.; Cheng, C.-C.; Wan, P.; Chung, C.-J; Matiler, W. *J. Phys. Chem.* **1985**, *89*, 1567.

(22) Turro, N. J.; Kraeutler, B. In *Isotopes in Organic Chemistry*; Buncel, E.; Lee, C. C., Eds.; Elsevier: Amsterdam, 2984; Vol. 6, pp 107–160.

Table III. Product-Distribution Data for Rearrangement of ^{18}O-Labeled 4-Methoxyphenyl Acetate (1)[a]

					products, mg			
run[b]	$10^3[1]_0$, M	irradn time	F[c]	recovd 1, mg[d]	2[d]	polym	2, %[e]	ratio[f] polym/2
1	3.0	30 min	0.40	302	70	99	36	1.8
2	3.0	35 min	0.44	280	58	93	27	2.8
3	3.0	45 min	0.42	289	66	105	32	2.2
4	1.5	7 h	0.85	37	70	95	33	2.0
5	1.5	8 h	0.89	28	90	101	41	1.5
6	2.4	25 min	0.31	275	43	73	35	1.9
7	3.0	35 min	0.32	337	50	85	31	2.2
8	3.0	30 min	0.34	331	51	86	31	2.3
9	3.0	25 min	0.37	314	57	91	31	2.2
10	1.2	30 min	0.50	101	30	54	31	2.3
11	1.2	12 h	1.0		75	119	38	1.7
12	1.2	12 h	1.0		70	109	35	1.9
13	1.0	12 h	1.0		60	86	30	1.8
14	3.0	45 min	0.36	320	47	*g*	26	2.8
15	3.0	1 h	0.43	283	60	*g*	28	2.6
16	1.0	12 h	1.0		69	*g*	42	1.4
17	1.0	12 h	1.0		68	*g*	41	1.4

[a] A mixture of 1 and ^{18}*O*-4-methoxyphenyl [^{18}O]acetate. [b] Runs in which the solution of 1 was purged with N_2 were 1–6 and 10–12. Other runs were carried out in a stoppered vessel without purging. [c] Conversion, based on the amount of 1 which was recovered. [d] Before sublimation. [e] The % (rounded off) of 1 that was consumed, determined from the amount of 1 which was recovered. [f] This is based on the amount of 1 that was consumed, with the assumption that 1 which did not rearrange to 2 ended up as polymer. The weight of polymer recovered was not used in this expression because of the loss of acetyl group. [g] Not isolated.

are measured in 2 at low and high conversions, the enrichment of ^{12}C that has occurred in 1 shows up also in 2 and hence as an inverse KIE. This is not really a KIE, though, but a magnetic isotope effect (MIE), measured by a technique which is customary for KIE.

Zero magnetic field and applied magnetic field MIE were recently measured in the photorearrangement of 1-napthyl acetate.[6] These measurements showed that a caged, singlet radical pair was formed. In that case, the rates of rearrangement of the α-^{12}C and α-^{13}C ester were measured individually from the yield of product from each ester. The method is more convenient but not as precise as the multiscan mass spectroscopic one. Thus, the reported zero-field MIE (^{13}C/^{12}C), corresponding in magnetic environment with our rearrangement of 1, was 0.96 ± 0.02 from nine runs.

[*o*-^{14}C]1. As part of our plan to search for evidence of concerted rearrangement we measured KIE for 1 which was labeled with ^{14}C at an ortho position. Our anticipation was that, on the basis of our other results, there should not be an isotope effect. Surprisingly, there was a substantial one, averaging 1.0286 ± 0.0021. This result cannot be tied to the rearrangement of 1 into 2. The reason for our belief is that, if the *o*-^{14}C KIE were attributable to bonding with the acetyl group, we should have observed an α-^{14}C KIE for the bonding step, too. But, as we have reported, neither we nor the earlier workers[16] found such a KIE. We associate it, therefore, with an unconnected and, as yet, unknown reaction of 1, a reaction that is not affected by labeling in the other positions. It is noteworthy that the rearrangement of 1 is not the major way in which 1 is consumed by irradiation. The greater part of 1 which was consumed appeared as polymeric material. Possibly, therefore, the reaction having an *o*-^{14}C KIE of nearly 3% is bound up with polymer formation. In principle, it is possible to measure the effect of *o*-^{14}C labeling in the product (2). We chose not to do that because of the quenching errors in counting labeled, colored 2. Further insight into the total reaction is obtained from an analysis of our data on products.

Products of Rearrangement. Kalmus and Hercules have pointed out that it is important to derive mechanistic information about the photo-Fries rearrangement from products which are formed initially, because in general the products absorb light more strongly that the ester itself.[4]

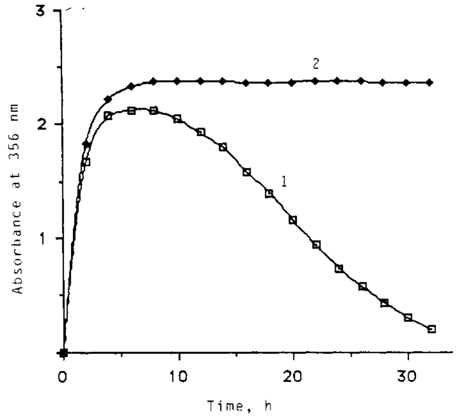

Figure 1. Plot of absorbance at 356 nm vs. time for formation of 2-acetyl-4-methoxyphenol (2), λ_{max} 356 nm, from irradiation of 4-methoxyphenyl acetate (1) in 95% ethanol solution in a quartz vessel: (1) 1 alone, initially 1×10^{-3} M; (2) 1, 1×10^{-3} M, plus propanethiol, 2×10^{-1} M.

If they are to be precise, measurements of KIE, whether made on recovered substrate or on product, require substantial conversions, however. It is possible to prepare a ^{13}C-labeled substrate with 99% of ^{13}C at the appropriate position and to make separate rate measurements with enriched and unenriched substrate, but this, as mentioned earlier, is not a precise method. As far as ^{18}O and ^{14}C labeling are concerned, preparing a totally labeled substrate is simply impractical. Therefore, measurements of KIE must be of the competitive kind, and these usually require that substantial conversions be made. The conversions we carried out and the materials isolated are listed in Tables III and IV. Rearrangements of unlabeled 1 were also followed spectroscopically and are illustrated with Figures 1 and 2.

Although *p*-hydroxyanisole (3) is represented as a product of photolysis of 1, we could not find 3 among our products. Instead, a polymeric material was obtained by column chromatography. The amount of this polymer corresponded reasonably well with the amount of 1 which was consumed but not converted into 2. In fact, in many runs we found a fairly good correlation between the amount of polymer and the amount of 3 that should have been formed. Further, 3 was found to be more photoactive

Table IV. Product-Distribution Data for Rearrangement of Carbon-Labeled 4-Methoxyphenyl Acetate (1)[a]

						products, mg			
run[b]	label	$10^3[1]_0$, M	irradn time	F^c	recovd 1, mg[d]	2[d]	polym	2 %[e]	ratio[f] polym/2
18	α-^{14}C	3.0	30 min	0.57	215	71	160	25	3.0
19	α-^{14}C	3.0	1 h	0.63	186	93	151	30	2.4
20	α-^{14}C	3.0	2 h	0.78	108	124	181	29	2.1
21	α-^{14}C	3.0	4 h	0.85	76	137	192	33	2.1
22	o-^{14}C	3.0	1 h	0.40	300	50	g	25	3.0
23	o-^{14}C	3.0	2 h	0.56	221	89	g	32	2.1
24	o-^{14}C	3.0	4 h	0.70	152	118	g	34	1.9
25	α-^{13}C	3.0	30 min	0.29	352	44	54	30	2.3
26	α-^{13}C	3.0	45 min	0.36	321	59	58	33	2.0
27	α-^{13}C	3.0	1 h	0.43	286	74	64	35	1.9
28	α-^{13}C	1.0	12 h	1.0		67	101	40	1.5
29	α-^{13}C	1.0	20 h	1.0		39	122	24	3.3
30	α-^{13}C	1.0	12 h	1.0		69	100	42	1.4

[a] A mixture of labeled and unlabeled 1 as described in the Experimental Section. [b] Runs in which the solution of 1 was purged with N_2 were 18–21. Other runs were carried out in a stoppered vessel without purging. [c–g] See Table III.

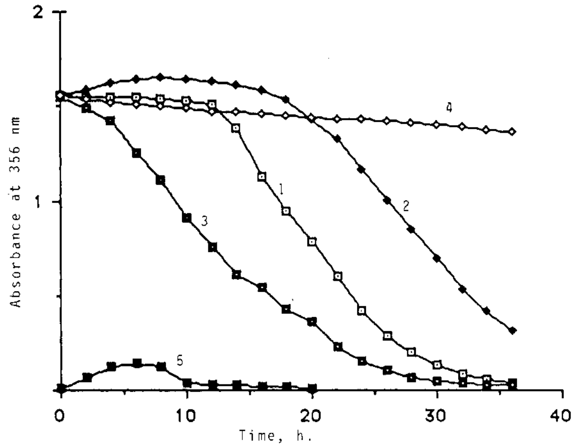

Figure 2. Effect of prolonged irradiation of a 4 × 10^{-4} M solution of 2-acetyl-4-methoxyphenol (2) in 95% ethanol in a quartz vessel. Plot of absorbance at 356 nm vs. time: (1) 2 alone; (2) with added 4-methoxyphenol, 4 × 10^{-3} M; (3) with added 2,3-butanedione, 4 × 10^{-3} M; (4) with added propanethiol, 8 × 10^{-3} M; (5) 4-methoxyphenol alone, 4 × 10^{-3} M.

than 1. Ghibaudi and Colussi noted also that phenol could no longer be found in irradiations of phenyl acetate in hexane and Freon-113 beyond 1 h.[23]

The product 2 was found to be stable to long periods of continuous irradiation. This can be seen in two ways. The yields of 2 do not vary greatly with time of irradiation of 1. In fact, some of the higher yields were obtained when complete conversions were made (Tables III and IV). Very long irradiation (20 h, run 29) did result in substantial loss of 2. These features can also be seen in the figures. In Figure 1 is plotted the change in absorbance at 356 nm which occurred during the irradiation of 1 for 30 h. The absorbance rose over a period of 10 h and slowly fell. When propanethiol was included in the solution, irradiation caused the absorbance at 356 nm to rise much in the same way as earlier but not to undergo the subsequent fall. The maximum yield of 2 indicated by absorbance at 356 nm was 54% in the absence and 59% in the presence of propanethiol. Thus, again it seems that in our solutions 2 was stable to irradiation for periods of 10–12 h.

The effect of irradiation on 2 is seen more directly in Figure 2. Little decrease in absorbance occurred during 12 h of irradiation (curve 1). Propanethiol prevented serious decomposition of 2 over 30 or more hours of irradiation. The presence of 4-methoxyphenol (curve 2) also appeared to delay the decomposition of 2, but the result is somewhat ambiguous because 4-methoxyphenol itself was photoactive and its irradiation product(s) absorbed at 356 nm (curve 5). The presence of 2,3-butanedione (curve 3) led to immediate and steady decomposition of 2. We assume that acetyl (or methyl) radicals were responsible. If this is correct, it suggests that free acetyl radicals are not formed in sufficient quantities in the irradiation of 1 to cause serious harm to the 2 which is also formed. The overall appearance from our results is that 2 is formed continuously without great loss during the periods of time we used for KIE sampling.

Two other aspects of our product studies call for comment, too. The yields of 2 (54% and 59%) represented by maximum absorbances after 10–12 h in Figure 1 appear to be misleadingly high. Product 2 was never isolated in yields of this magnitude. Furthermore, 2 was isolated after 12 h of irradiation of 1 in a solution containing propanethiol. Four experiments gave 2 in the yield of 38.3 ± 0.5%. It seems, therefore, from Figure 1, that in the irradiation of 1 something else is formed, besides 2, which absorbs at 356 nm. This may originate in 3 and may also involve the ortho position of 1, but we did not pursue this further.

The presence of 2,3-butanedione caused 2 to be unstable to irradiation. We assume that acetyl radicals were formed from the 2,3-butanedione[24,25] and that these or methyl radicals derived from them caused the decomposition of 2. If this assumption is correct, the stability of 2 during the photolysis of 1 suggests that not many free acetyl radicals are formed in that photolysis. In that connection, Ghibaudi and Colussi have concluded, from studies with phenyl acetate, that, for the most part, phenol is formed inside rather than outside of the radical pair cage by disproportionation. Thus, acetyl radicals are, for the most part, converted inside the cage into ketene.[23] If this is true, too, in the irradiation of 1 we can see why 2 remains reasonably unaffected during long periods of irradiation. That is, both direct and induced decomposition do not occur during the first several hours of continuous irradiation.

Conclusion. The rearrangement of 1 into 2 follows the pathway of the singlet-state, caged radical pair mechanism. KIE evidence for a concerted pathway could not be found. At the same time, the fate of 1 in irradiation is more complex than represented only by rearrangement. The phenolic scission product, which is customarily depicted for photo-Fries rearrangements, here 3, is itself unstable to irradiation and is converted into polymeric material. This conversion may involve a reaction with 1 and may

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[23] Ghibaudi, E.; Colussi, A. J. *Chem. Phys. Lett.* **1983**, *94*, 121.

[24] Calvert, J. G.; Pitts, J. N. *Photochemistry*; Wiley: New York, 1966; p 421.

[25] Blacet, F. E.; Bell, W. E. *J. Am. Chem. Soc.* **1954**, *76*, 5332.

be the origin of the KIE of ortho labeling.

Experimental Section

^{18}*O*-4-Methoxyphenyl [$^{18}O_1$]Acetate. 4-Methoxybenzenediazonium tetrafluoroborate (3 g), prepared in 77% yield as described in Vogel,[26] was dissolved in a mixture of 6 g of labeled water (Norsk Hydro, 10% ^{18}O) and 3 mL of concentrated sulfuric acid. The solution was boiled for 20 min and, after cooling for 2 h, was extracted with 4 × 20 mL of ether. The ether solution was washed, dried, and evaporated to give crude phenol, which was acetylated in toluene solution with acetyl chloride. Workup gave crude 4-methoxyphenyl acetate. The crude ester was chromatographed on silica gel with 2:1 benzene/cyclohexane as eluent and then purified by sublimation at 30–40 °C and 1 mmHg. Several runs gave yields of 391–411 mg (17.5–18.4%), mp 31–32 °C (lit.[16] mp 31–32 °C). The product was found by mass spectrometry to have 7 mol % of ^{18}O and was diluted with 4-methoxyphenyl acetate to give 5.5 mol % of ^{18}O for photorearrangements.

4-Methoxyphenyl [1-^{13}C]Acetate. To a solution of 4.00 g (32.3 mmol) of 4-methoxyphenol in 15 mL of dry toluene was added a mixture of 1.0 g (12 mmol) of sodium acetate and 1.0 g of sodium [1-^{13}C]acetate (99% ^{13}C, Sigma-Aldrich). To the stirred mixture, cooled in an ice bath, was added 3 mL (41 mmol) of thionyl chloride during 5 min. The mixture was stirred at room temperature for 1.5 h, boiled for 4 h, cooled, and poured onto ice. Extraction with ether, workup, and chromatography gave 2.9 g of crude ester. Two sublimations gave 2.67 g (16.0 mmol, 66%) of 4-methoxyphenyl [1-^{13}C]acetate, mp 31–32 °C, estimated to contain 50% of carbonyl ^{13}C. This was diluted to 25% enrichment for photorearrangements.

4-Methoxyphenyl [1-^{14}C]acetate was prepared as described above from 4.0 g of 4-methoxyphenol, 2.0 g of sodium acetate, and 1.5 mg of sodium [1-^{14}C]acetate (13.3 mCi/mmol, Pathfinder Labs). Workup and sublimation gave 2.0 g (48.3%) of 4-methoxyphenyl [1-^{14}C]acetate with an estimated radioactivity of 10 mCi/mol, mp 30–31 °C. This was diluted to 7.5 mCi/mol for photorearrangements.

4-Methoxy[2-^{14}C]phenyl Acetate. [2-^{14}C]Azoxybenzene, 30 mCi/mmol, was prepared from [2-^{14}C]nitrobenzene as described earlier,[17] mp 34 °C.

A solution of 8.0 g (40 mmol) of labeled azoxybenzene in 200 mL of 85% sulfuric acid was allowed to stand at room temperature for 6 days. The solution was poured onto crushed ice, giving a dark-colored solid, which was filtered and dried. The solid was extracted (Soxhlet) three times with hexane, each time for 12 h. Evaporation of the hexane gave a solid residue, which was dissolved in ether. The ether solution was washed with 2 × 50 mL of sodium bicarbonate solution, with water, and with 8 × 50 mL of 10° sodium hydroxide solution. Acidification of the sodium hydroxide solution with hydrochloric acid and extraction with 10 × 50 mL of ether gave 2.8 g (14.1 mmol, 35%) of **4-hydroxy[2-^{14}C]azobenzene**, mp 153 °C (lit.[27] mp 155–156 °C). Acidification of the sodium bicarbonate solution gave 70 mg of sulfonated products. Workup of the ether solution remaining after extractions with base gave 2.5 g (33.5%) of [2-^{14}C]azobenzene, mp 68–69 °C.

To a solution of 2.8 g of 4-hydroxy[2-^{14}C]azobenzene in 50 mL of 20% potassium hydroxide at 0 °C was added 5 mL of dimethyl sulfate. After the mixture was stirred for 24 h a solid had precipitated. This was filtered, and a further 2 mL of dimethyl sulfate was added to the filtrate. More solid precipitated after 20 h. The collected solids were chromatographed on silica gel with benzene as eluent to give crude 4-methoxy[2-^{14}C]azobenzene. This was sublimed in four portions giving a total of 2.5 g (11.8 mmol, 84%) of **4-methoxy[2-^{14}C]azobenzene**, mp 56 °C (lit.[28] mp 56 °C).

All of the 4-methoxy[2-^{14}C]azobenzene was dissolved in 150 mL of absolute ethanol and was hydrogenolyzed under balloon pressure over 5% Pd/C for 15 h. The ethanol was removed, and the residue was chromatographed on silica gel with 10:6 cyclohexane/benzene, giving 20 mg of recovered substrate, 1.26 g (10.2 mmol, 86%) of **4-methoxy[2-^{14}C]aniline**, and 1.01 g (10.9 mmol, 92%) of [2-^{14}C]aniline.

The 4-methoxy[2-^{14}C]aniline was dissolved in a mixture of 10 mL of water and 2.6 mL of concentrated hydrochloric acid at 0 °C. To this solution was added 860 mg of sodium nitrite in 6 mL of water. The solution was kept at 0–5 °C for 20 min, and to it was added 200 mg of urea to destroy nitrous acid. The solution was then added dropwise to a boiling solution of 8.6 mL of concentrated hydrochloric acid in 43 mL of water. Crude 4-methoxyphenol was extracted with ether and acetylated with acetyl chloride as described earlier. Chromatography on silica gel with 2:1 benzene/petroleum ether and two sublimations gave 420 mg (2.53 mmol, 23%) of 4-methoxy[2-^{14}C]phenyl acetate, mp 30–31 °C, approximately 15 mCi/mmol. This was diluted to 4 mCi/mmol for photorearrangement.

Rearrangements of 4-Methoxyphenyl Acetate (1) for KIE Measurements. Rearrangements were carried out by irradiation with 300-nm U-tube lamps in a Rayonet reactor. Air was blown via a duct into the top of the reactor to maintain an inner temperature of 25–30 °C. The 95% ethanol solution (1 L) to be irradiated was placed in a cylindrical quartz vessel. In most of the irradiations the solution was purged with nitrogen during irradiation, while in some cases the vessel was stoppered without purging. Irradiations of unlabeled 1 were first monitored spectrophotometrically so as to know the approximate times of conversions. Initial concentrations of 1, times of irradiation, and conversions are listed in the tables. The conversions listed were calculated on the basis of the amount of recovered 1. After irradiation was stopped the solvent was evaporated under vacuum. The residue was dissolved in 100 mL of ether, and this solution was extracted with 4 × 25 mL of 2% sodium hydroxide and 3 × 30 mL of water. The ether was then evaporated to give unused 1, which was chromatographed on silica gel with 2:1 benzene/petroleum ether. The collected sodium hydroxide solution was acidified with concentrated hydrochloric acid and extracted with 4 × 30 mL of ether. The ether solution was evaporated to give a mixture of 2-acetyl-4-methoxyphenol (2) and what appeared to be a polymer. This mixture was chromatographed to give 2, on silica gel with 2:1 benzene/petroleum ether. The polymer was then removed from the column with large amounts of methanol. Recovered 1 was sublimed and had mp 31 °C. Isolated 2 was sublimed and had mp 50 °C (lit.[29] mp 50 °C). Two sublimations were carried out for mass spectrometric assays, while five were carried out for ^{14}C counting assays. The conversions (F) obtained by irradiating solutions of 1 which had been purged with N_2 were, in general, larger than those obtained with unpurged solutions (Tables III and IV). This might suggest that quenching by oxygen occurred in the unpurged solutions, but earlier evidence has shown that oxygen affected neither the products nor quantum yield of the rearrangement of phenyl acetate.[4] There appears to be no correlation in our results between extent of conversion and either the fraction of 1 which was converted into 2 or the ratio polymer/2.

KIE Measurements. Assays of stable isotopic abundances were made by whole-molecule-ion mass spectrometry (WMIMS) in the SIM mode of a Hewlett-Packard Model 5995 quadrupole mass spectrometer. Samples of product (2) were placed in the direct insertion probe. From two to five runs per sample were made, each run having 3000 scans of the appropriate ions. Data were then analyzed in 25 blocks, each block having 120 scans, and the resulting set of 25 isotope ratios was treated statistically. Masses scanned were 168 and 166 for ^{18}O KIE and 167, 166, and 165 for ^{13}C KIE. Details have been given earlier.[30] Assays of ^{14}C abundances were made by scintillation counting as described earlier. When [α-^{14}C]1 was used, both recovered 1 and product 2 were counted, while when [o-^{14}C]1 was used, only recovered 1 was counted. Three 5.000-mg weighings of each sample were counted, and each weighing was counted 10 times. Thus the assay per sample was an average of 3 × 10 counts. Compound 2 is yellow. Therefore, [^{14}C]benzoic acid was used as a standard for counting 2. A measure of quenching by 2 was obtained by counting benzoic acid in the absence and presence of 5.000 mg

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(26) Vogel, A. I. *Textbook of Practical Organic Chemistry*, 4th ed.; Longman: London, 1978; p 707.

(27) Jaffe, H. H.; Yeh, S. Y. *J. Am. Chem. Soc.* **1959**, *81*, 3274.

(28) Colombano, A. *Gazz Chim. Ital.* **1907**, *37*, 471.

(29) Garcia, H.; Primo, J. *Synthesis* **1985**, 901.

(30) Shine, H. J.; Kupczyk-Subotkowska, L.; Subotkowski, W. *J. Am. Chem. Soc.* **1985**, *107*, 6674; **1987**, *109*, 1286.

of unlabeled **2**. The quenching factor, 1.3027, was used to normalize the counts of samples of **2** from rearrangement.

Calculations of KIE were made as described earlier.[30]

Irradiation of 4-Methoxyphenyl Acetate (1), 2-Acetyl-4-methoxyphenol (2), and 4-Methoxyphenol for Spectroscopic Measurements. Solutions of these compounds were irradiated in the Rayonet reactor as described above. Samples (3 mL) were withdrawn at timed intervals for recording absorbance at 356 nm. Neither **1** nor 4-methoxyphenol absorb in this region. Data for irradiations of **1** in the absence and presence of propanethiol are given in Figure 1. They show the formation and slow decomposition of **2** in the absence of propanethiol and the formation and stability of **2** in its presence. Data for the prolonged irradiation of **2** alone and in the presence of propanethiol, 2,3-butanedione, and 4-methoxyphenol are given in Figure 2. Included in Figure 2 are data for the irradiation of 4-methoxyphenol alone. This compound was itself decomposed by prolonged irradiation at 300 nm, and the unknown product(s) of decomposition absorbed weakly at 356 nm.

The following absorbance data (λ_{max} [nm], ϵ) are pertinent: **1** (277, 1880; 223, 7030), **2** (356, 3860; 255, 6150; 224, 16,400), 4-methoxyphenol (292, 2990; 225, 5370). Absorbances recorded at 300 nm were as follows: for **1**, 0; for **2**, 500; for 4-methoxyphenol, 2250; for propanethiol, 0; for 2,3-butanedione, 25. Stratenus[18] has reported absorbances for ethanol solutions at particular intervals of wavelength, some of which correspond closely with our data, namely (λ_{max} [nm], ϵ) the following: **1** (275, 1846; 300, 0), **2** (360, 4063; 300, 357), **3** (290, 2880; 300, 2301).

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Registry No. 1, 1200-06-2; [*o*-^{14}C]-1, 108868-06-0; **2**, 705-15-7; [2-^{14}C]azoxybenzene, 104946-11-4; 4-hydroxy[2-^{14}C]azobenzene, 108834-59-9; 4-methoxy[2-^{14}C]azobenzene, 108834-60-2; 4-methoxy[2-^{14}C]phenol, 108834-61-3; ^{18}*O*-4-methoxyphenyl acetate, 108867-96-5; ^{18}*O*-phenol, 108834-62-4; 4-methoxyphenyl [1-^{13}C]-acetate, 92658-26-9; 4-methoxyphenol, 150-76-5; 4-methoxyphenyl [1-^{14}C]acetate, 16282-21-6; [2-^{14}C]azobenzene, 108834-63-5; 4-methoxy[2-^{14}C]aniline, 108834-64-6; [2-^{14}C]aniline, 83548-27-0; 4-methoxybenzenediazonium tetrafluoroborate, 459-64-3; oxygen-18, 14797-71-8; carbon-14, 14762-75-5; carbon-13, 14762-74-4.

Ring-Chain Tautomerism in 1,3-Oxazines

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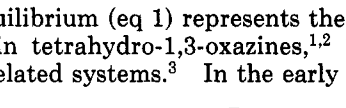
A comparative study on the ring-chain tautomerism of 49 2-(substituted-phenyl) tetrahydro-1,3-oxazines of seven different types, namely, tetrahydro-1,3-oxazines **3**, *r*-8a,*c*-2,*c*-4a- and *r*-8a,*c*-2,*t*-4a-1,3-perhydrobenzoxazines **5** and **7**, *r*-8a,*c*-2,*c*-4- and *r*-8a,*c*-2,*t*-4a-1,3-perhydrobenzoxazines **9** and **11**, 3,4-dihydro-2*H*-1,3-benzoxazines **12**, and 1,2-dihydro-4*H*-3,1-benzoxazines **13**, pointed out that in all cases the equilibria can be described with a simple equation,

$$\log K_X = (0.76 \pm 0.04)\sigma^+ + \log K_{X=H}$$

where K_X = [ring]/[chain] (X $\neq$ H). A factor *c* illustrating the sum of steric and electronic effects of substituents at C-4, C-5, and C-6 has also been introduced.

Ring-chain tautomerism has been studied extensively.[1b,c] The **1** ⇌ **2** equilibrium (eq 1) represents the ring-chain tautomerism in tetrahydro-1,3-oxazines,[1,2] 1,3-oxazolidines,[1,2] and related systems.[3] In the early reports the



1 **2** (1)

tautomeric equilibria were studied with the aid of molecular refraction, IR and UV spectroscopy.[1,2] These methods cannot result in exact tautomer ratios. It has been found that the products from 3-aminopropanol and carbonyl compounds appear in a higher ratio of cyclic vs. chain structures than those from 2-aminoethanol and carbonyl compounds.[4] In both cases the relative amount of the ring form was increased by C-alkylation of the amino alcohols.[4,5] McDonagh and Smith[6] published the first quantitative data for the ring-chain tautomerism of 2-substituted 3,4-dihydro-2*H*-1,3-benzoxazines. Later a clear correlation of log K/K_0 values of 2-aryl-substituted 1,3-oxazolidines to the Hammett σ^+ was found[7] but not to σ values as suggested earlier.[6b]

Since the 1,3-oxazolidine ring formation represents a unfavored 5-endo-trig process according to the Baldwin rules,[9] several investigations of this type of ring-chain

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[†] University of Turku.

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(1) (a) Cope, A. C.; Hancock, E. M. *J. Am. Chem. Soc.* **1942**, *64*, 1503. (b) Bergmann, E. D. *Chem. Rev.* **1953**, *53*, 309. (c) Valters, R.; Flitsch, W. *Ring Chain Tautomerism*; Plenum: New York, 1985.

(2) (a) Bergmann, E. D.; Gil-Av, E.; Pinchas, S. *J. Am. Chem. Soc.* **1953**, *75*, 358. (b) Holly, F. W.; Cope, A. C. *J. Am. Chem. Soc.* **1944**, *66*, 1875. (c) Watanabe, W. H.; Conlon, L. E. *J. Am. Chem. Soc.* **1957**, *79*, 2825. (d) Kovar, J.; Blaha, K. *Collect. Czech. Chem. Commun.* **1959**, *24*, 797. (e) Sobotkova, H.; Kovar, J.; Blaha, K. *Collect. Czech. Chem. Commun.* **1964**, *29*, 1898. (f) Belgodere, E.; Bossio, R.; Parrini, V.; Pepino, R. *J. Heterocycl. Chem.* **1980**, *17*, 1629. (g) Saeed, A. A. H.; Ebraheem, E. K. *Can. J. Spectrosc.* **1983**, *28*, 169.

(3) (a) Szilágyi, L.; Györgydeák, Z. *J. Am. Chem. Soc.* **1979**, *101*, 427. (b) Ponticelli, F.; Marinello, E.; Misalle, M. C. *Org. Magn. Reson.* **1982**, *20*, 138. (c) Dorman, L. C. *J. Org. Chem.* **1967**, *32*, 255.

(4) Bergmann, E. D.; Kaluszyner, A. *Recl. Trav. Chim. Pays-Bas* **1959**, *78*, 289.

(5) Pihlaja, K.; Aaljoki, K. *Finn. Chem. Lett.* **1982**, 1.

(6) (a) McDonagh, A. F.; Smith, H. E. *Chem. Commun.* **1966**, 374. (b) McDonagh, A. F.; Smith, H. E. *J. Org. Chem.* **1968**, *33*, 1. (c) McDonagh, A. F.; Smith, H. E. *J. Org. Chem.* **1968**, *33*, 8.

(7) (a) Paukstelis, J. V.; Hammaker, R. M. *Tetrahedron Lett.* **1968**, 3557. (b) Paukstelis, J. V.; Lambing, L. L. *Tetrahedron Lett.* **1970**, 299.

0022-3263/87/1952-3821$01.50/0