Tetrahedron Letters No.55, pp. 5803-5806, 1968. Pergamon Press. Printed in Great Britain.

OXYGEN ISOTOPE EFFECTS BY A NONCOMPETITIVE TECHNIQUE: THE TRANSITION-STATE CARBONYL STRETCHING FREQUENCY IN ESTER CLEAVAGE[1]

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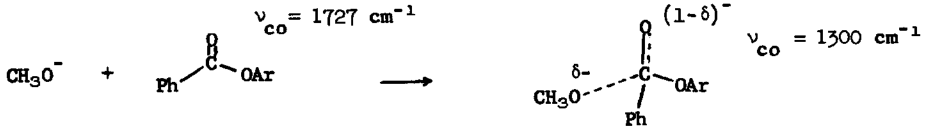
(Received in USA 19 July 1968; received in UK for publication 15 October 1968)

Kinetic isotope effects (4), which result only from force-constant changes on conversion of reactants into activated complex (5), constitute a method for structural elucidation of activated complexes analogous to the infrared spectroscopy of observable molecules. Hydrogen isotope effects are most commonly measured, but for structural analysis of activated complexes in organic reactions, heavy-atom effects should be at least as useful and have aroused considerable interest. These effects are of the order of a few percent in magnitude and have been determined in the past by competitive methods. We wish to report here the carbonyl-oxygen isotope effect for the methoxide-catalyzed methanolysis of aryl benzoates ($C_6H_5\overset{O^*}{\overset{\|}{C}}OAr$), determined by the measurement of individual rate constants for the O^{16} (99.8 atom-percent) and O^{18} (98.8 atom-percent) carbonyl-labeled esters.

The O^{18}-labeled esters were prepared in a dry box with nitrogen atmosphere by the ferric-chloride-catalyzed hydrolysis of benzotrichloride to benzoyl chloride (6), with consumption of a molar equivalent of D_2O^{18} (Bio-Rad Laboratories, 98.8-atom-percent O^{18}), followed by addition of the phenol and heating. The esters were taken up in chloroform, which was washed with water and evaporated; recrystallization was effected from anhydrous methanol. p-Bromophenyl benzoate as an example, exhibited an n.m.r. spectrum identical with that of the O^{16}-compound, had m.p. 102.0-102.7° (lit.(7), 102°) and its IR spectrum showed the intense O^{18}-carbonyl band at 1696 $cm.^{-1}$ and a small contribution (less than 2 percent) from the O^{18}-carbonyl band at 1726 $cm.^{-1}$ (Perkin-Elmer 421 grating spectrophotometer).

Kinetics were determined by the customary spectrophotometric technique, using the Cary Model 16 UV-visible spectrophotometer coupled to a Sargent Model SRL recorder to monitor absorbance at 305 mμ. Reactions were initiated in the thermostated cell holder by injection of excess base solution from a thermostated syringe into the ester solution. O^{16} and O^{18}-compounds were run alternately using the same base solutions for each. All runs were first order to within a standard deviation of the rate constant of 0.4 percent. First order rate constants were fitted by the least squares technique to the base concentrations, as shown in Table I for p-Bromophenyl benzoate. The second-order rate constants for the isotopic esters are $k_{16} = 1.9410 \pm 0.0059$ M^{-1} $sec.^{-1}$ and $k_{18} = 1.9072 \pm 0.0031$ M^{-1} $sec.^{-1}$, yielding a kinetic isotope effect of 1.018 ± 0.005 (all *errors quoted are standard deviations*). A *correction for the effect of the small* amount of O^{16} ester present in the O^{18} sample is less than the experimental error from other sources. Instead of fitting the O^{16}-ester and O^{18}-ester data to base concentration separately to obtain second-order rate constants, one can simply take the ratio of first-order rate constants at each base concentration. Such a procedure yields $k_{16}/k_{18} = 1.018$ with an average deviation of 0.007, a result identical with that from the least squares treatment.

If this oxygen kinetic isotope effect can be viewed as a simple secondary effect, then $k_{16}/k_{18} = \exp\left[hc(\Delta\nu^{r} - \Delta\nu^{\ddagger})/2kT\right]$, for all $\nu > 1000$ $cm.^{-1}$. Assuming $(\nu_{16}/\nu_{18})^{\ddagger} = (\nu_{16}/\nu_{18})^{r}$, we find the carbonyl stretching vibration frequency for the activated complex ($\nu_{16}^{\ddagger}$) to be 1300 ± 200 $cm.^{-1}$, decreased from the reactant value of 1727 $cm.^{-1}$ This finding is fully consistent with an activated complex for addition of methoxide ion to the carbonyl group, which is the rate-determining step for these reactions if they are two-step processes (8, 10).



A more detailed treatment of the isotope effect, including reaction-coordinate contributions by the carbonyl oxygen, will be presented later. The isotope effect is much more difficult to reconcile with a concerted displacement reaction at the carbonyl group (9), in the transition state for which the carbonyl stretching frequency might reasonably be expected to increase.

TABLE I

Rate Constants for Methoxide-Catalyzed Methanolysis of p-Bromophenyl Benzoate-carbonyl-O^{16} and p-Bromophenyl Benzoate-carbonyl-O^{18} in Methanol at 29.5°)[a]

$[CH_3O^-]$, M.	k_{16}^{obs}, sec.$^{-1}$	(k_{16}^{calc}, sec.$^{-1}$)[b]	k_{18}^{obs}, sec.$^{-1}$	(k_{18}^{calc}, sec.$^{-1}$)[c]
0.07544	0.1465	0.1457	0.1433	0.1432
0.06790	0.1295	0.1311	0.1287	0.1288
0.06035	0.1159	0.1164	0.1143	0.1144
0.05281	0.1029	0.1018	0.1007	0.1000
0.04526	--	--	0.0856	0.0857
0.03772	0.0731	0.0725	--	--
0.03395	0.0649	0.0652	0.0636	0.0641
0.03018	0.0577	0.0579	0.0565	0.0569
0.02640	0.0501	0.0505	0.0498	0.0497
0.02263	0.0430	0.0432	0.0427	0.0425
0.01886	0.0364	0.0359	0.0355	0.0353
0.01509	0.0283	0.0286	0.0278	0.0281
0.01132	0.0214	0.0212	0.0207	0.0209
0.00830	0.0156	0.0154	0.0152	0.0152
0.00604	0.0112	0.0110	0.0111	0.0108

a. Precision of temperature control is 0.01° and the temperature given is accurate to within ± 0.1°.

b. $k_{16}^{calc} = -0.0007 + (1.9410 \pm 0.0059)[CH_3O^-]$

c. $k_{18}^{calc} = -0.0007 + (1.9072 \pm 0.0031)[CH_3O^-]$

The same procedure has also been carried through for phenyl benzoate, which gives $k_{16}/k_{18} = 1.024 \pm 0.013$. This entire study of two esters consumed a quantity of labeled compounds valued at $1.20.

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1. This work was supported by the National Science Foundation and was carried out in part at the Computation Center of the University of Kansas.

2. Supported in part by an allocation from the Biomedical Sciences Support Grant of the University of Kansas.

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10. Since bending frequencies will probably increase on going to the near-tetrahedral activated complex, the value found for $\nu_{16}^{\ddagger}$ may be regarded as a maximum value.