Notes

Acknowledgment.—Acknowledgment is made to the donors of The Petroleum Research Fund, administered by the American Chemical Society, for support of this research.

Secondary Deuterium Isotope Effects in the Diphenylketene- α -Methylstyrene Cycloaddition

EUGENE I. SNYDER¹

Chemistry Department, East Tennessee State University, Johnson City, Tennessee 37601

Received June 19, 1970

The ketene-olefin cycloaddition has been probed mechanistically by several groups, especially Huisgen and coworkers. For unactivated double bonds (i.e., olefins unsubstituted by heteroatoms on a vinylic carbon) evidence favors a concerted cycloaddition, with asynchronous bond formation resulting in an activated complex with zwitterionic character.² The facility with which such a [2 + 2] concerted thermal cycloaddition occurs stands in contrast to most other olefin-olefin concerted thermal cycloadditions and has been ascribed³ to the presence of low-lying antibonding orbitals unique to the ketene functionality. The secondary deuterium isotope effects reported by Baldwin⁴ for the styrene-diphenylketene cycloaddition ($k_{\rm H}/k_{\rm D} = 1.23, 0.91$ for positions α and β to the phenyl, respectively, in styrene)

$$Ph_2C = C = O + PhCH = CH_2 \longrightarrow PhC - CH_2 \\ | \\ Ph_2C - C = O$$

are not obviously those which one would expect for a concerted cycloaddition, and in fact could be interpreted readily as indicating a two-step reaction. Similar isotope effects have been reported⁵ for the azo ester-vinyl ether cycloaddition $(k_{\rm H}/k_{\rm D} = 1.12, 0.83$ for positions α and β to the oxygen, respectively), a thermal reaction which probably is not concerted.^{6,7}

CHOEt EtO_2CN -NCO₂ $Et + CH_2$ -CHOEt \rightarrow EtO₂CN -NCO₂Et

In the hope of elucidating the concertedness of ketene cycloadditions, we measured the isotope effect in com-

(3) R. B. Woodward and R. Hoffmann, Angew. Chem., Int. Ed. Engl., 9, 781 (1969).

(4) J. E. Baldwin and J. A. Kapecki, J. Amer. Chem. Soc., 91, 3106 (1969). (5) E. K. von Gustorf, D. V. White, J. Leitlich, and D. Henneberg. Tetrahedron Lett., 3113 (1969).

(6) In a personal communication, R. Hoffmann has commented that he

could not spot any factor stabilizing the $2_s + 2_s$ addition for azo esters. (7) A referee has commented as follows. "If Koerner von Gustorf's non-concerted mechanism for one [2 + 2] cycloaddition is accepted, and if his $k_{\rm H}/k_{\rm D}$ = 1.12 and Baldwin's $k_{\rm H}/k_{\rm D}$ = 1.23 are readily interpreted as indicating a two-step reaction, then Huisgen's concerted mechanism for the ketene-styrene addition can't be accepted, as it is. Either both azo-olefin and ketene-olefin additions are concerted, or they are not, or either K. von Gustorf or Baldwin has made a large error in measuring $k_{\rm H}/k_{\rm D}$, or perhaps $k_{\rm H}/k_{\rm D} > 1$ means concerted in one situation and nonconcerted in another.

petitive reactions of α -methylstyrene and α -methylstyrene- d_3 . Seltzer previously used a methyl group

$$Ph_{2}C = C = O + PhC = CH_{2} \longrightarrow PhC = CH_{2}$$

$$Ph_{2}C = C = O + PhC = CH_{2} \longrightarrow PhC = CH_{2}$$

$$Ph_{2}C = C = O$$

adjacent to the bond making-breaking site as a probe of concertedness in the Diels-Alder reaction.⁸ The apriori expectations for the value of $k_{\rm H}/k_{\rm D}$ follow. (a) The reaction is concerted and insensitive to steric effects, $k_{\rm H}/k_{\rm D} \sim 1.0$. As the zwitterionic character of the activated complex increases so will the isotope effect, in analogy to the known effects of CH_3 vs. CD_3 at a cationic site.⁹ (b) The reaction is concerted but sensitive to steric effects which will be manifested by the smaller "size" of CD₃ vs. CH₃, $k_{\rm H}/k_{\rm D}$ < 1. (c) The reaction is nonconcerted, with initial attack of the ketene at the β position of the styrene. If the intermediate were a biradical then $k_{\rm H}/k_{\rm D} \sim 1.0^{.10}$ However, Huisgen seems to have eliminated² the possibility of a biradical, so that further consideration of this route is unnecessary. If the intermediate is zwitterionic with appreciable positive charge density at the benzylic carbon then $k_{\rm H}/k_{\rm D} > 1$, in the approximate range 1.3-1.5.

The experimental results are listed in Table I.¹¹ It is apparent that even on a 3-deuterium atom basis $k_{\rm H}/k_{\rm D}$ is experimentally indistinguishable from 1.0.

TABLE I

SECONDARY DEUTERIUM ISOTOPE EFFECTS

Run	$\mathrm{S_{H}/S_{D}}^{a}$	P_H/P_D^a	$k_{\rm H}/k_{\rm D}$ (for 3 deuteriums) ^{l}
1	2.22	2.36	$1.06 (1.06^{\circ})$
2	1.21	1.16	0.96

^a S_H/S_D = ratio of undeuterated to d_3 olefin; P_H/P_D = ratio of undeuterated to d_3 product. Both ratios were determined from deuterium analysis by the falling drop method. ^b See footnote 11 for error limits. ^c $P_{\rm H}/P_{\rm D}$ determined from nmr measurements, accurate to about 5%.

(9) E. A. Halevi, Progr. Phys. Org. Chem., 1, 109 (1965).

(11) After this work was completed, it became apparent to the author that measuring secondary deuterium isotope effects from total deuterium content is an inherently inaccurate method, as can be shown by a simple error analysis. The isotope effect, i, is given by

$$\left(\frac{P_{\rm H}}{P_{\rm D}}\right) / \left(\frac{S_{\rm H}}{S_{\rm D}}\right)$$

Total deuterium analysis measures the relative concentration of, say, da. species in product and substrate, so we can write

$$i = \left(\frac{1-D_1}{D_1}\right) / \left(\frac{1-D_2}{D_1}\right) = f(D_1,D_2)$$

where D_1 is the fraction of d_3 product and D_2 the fraction of d_3 reactant. The root mean square error in i, δi_{rms} , is

$$\delta_{\text{irms}} = \sqrt{\left[\frac{\partial f}{\partial D_1} \delta D_1\right]^2 + \left[\frac{\partial f}{\partial D_2} \delta D_2\right]^2}$$

where δD_1 , δD_2 are the uncertainties in D_1 , D_2 , respectively, and

$$\delta_{irms} = i \sqrt{\left[\frac{\delta D_1}{D_1(1-D_1)}\right]^2 + \left[\frac{\delta D_2}{D_2(1-D_2)}\right]^2}$$

Assuming an absolute error of 0.2% in the deuterium analysis corresponds to $bD_1 = 0.0067$ for PhCCDs==CH₂, $bD_2 = 0.013$ for d_3 product. For $i \sim 1$ and $D_1 \sim D_2 \sim 0.3$ or 0.5, then $\delta_{\rm irms} = 0.07$, which is a higher uncertainty than desirable. Obviously the uncertainty can be reduced appreciably if the ratios P_H/P_D, S_H/S_D, can be measured directly, and mass spectrometry probably is the method of choice for values of $i \sim 1$.

⁽¹⁾ Kraftco Corp., Research and Development Division, Glenview, Ill. 60025

⁽²⁾ For a relevant summary, see R. Huisgen, L. A. Feiler, and P. Otto, Chem. Ber., 102, 3444 (1969).

⁽⁸⁾ S. Seltzer, J. Amer. Chem. Soc., 87, 1534 (1965).

⁽¹⁰⁾ M. Feld, A. P. Stefani, and M. Szwarc, J. Amer. Chem. Soc., 84, 4451 (1964).

Unless the observed isotope effect results from a combination of opposing factors, they point to a concerted reaction with quite small charge accumulation.

Experimental Section

Deuterium analyses were performed by Mr. Josef Nemeth, Urbana, Ill. α -Methyl-styrene- d_3 , a gift from Dr. William Bayne,¹² was vacuum distilled prior to use. α-Methylstyrene, EKWL, was fractionated prior to use. Both samples were homogeneous upon glpc examination. Diphenylketene was prepared as described.18

Deuterium Isotope Effect Measurements.—Mixtures of Ph-CCH₃—CH₂ and PhCCD₅—CH₂ were prepared and their deu-terium content obtained. Mass spectral examination showed that over 95% of deuterium-containing species was d_8 ; subsequent calculations assumed only d_8 species. Both runs were performed simultaneously to minimize effects of temperature variation.

Run 1.—A solution of 1.384 g (11.6 mmol) of α -methylstyrene (9.30 atom percent excess deuterium, or 31.0% PhCCD₃=CH₂) and 0.348 g (1.79 mmol) of diphenylketene was stored in the dark under nitrogen at ambient temperature for 6 days. Excess olefin was distilled at 0.5 mm to afford 1.20 g (87%) of recovered α -methylstyrene. The residue was chromatographed on 42 g of silica gel 80-200 and eluted with 1.2% ether-Skellysolve B to afford 0.205 g (43%) of 3-methyl-2,2,3-triphenylcyclobutanone. A center cut was twice recrystallized from methanol to afford material of mp 77-78.14 Deuterium analysis showed 4.45 atom per cent excess deuterium, or 29.7% d3 species.

Run 2.-A solution of 1.384 g (11.5 mmol) of olefin (13.60 atom per cent excess deuterium or 45.3% PhCCD₃=CH₂) and 0.353 g (1.82 mmol) of diphenvlketene was reacted as above for 10 days. Chromatography followed by two recrystallizations from methanol and one from Skellysolve B-ether afforded the cyclobutanone, mp 96-97, 6.95 atom per cent excess deuterium or 46.3% ds product.

Istotope effect calculations were made using the relation

$$\frac{k_{\rm H}}{k_{\rm D}} = \left(\frac{{\rm P}_{\rm H}}{{\rm P}_{\rm D}}\right) / \left(\frac{{\rm S}_{\rm H}}{{\rm S}_{\rm D}}\right)$$

valid for competitive reactions run to small conversions (under 16% in our case). Ratios were obtained from deuterium analyses and relevant data are presented above. In run 1 the ratio $P_{\rm H}/P_{\rm D}$ was independently determined from nmr measurements (using undeuterated ketone as reference) as 0.70 ± 0.03 and $k_{\rm H}/k_{\rm D}$ was calculated using the ratio $S_{\rm H}/S_{\rm D}$ from deuterium analysis.

Registry No.—Diphenylketene, 525-06-4; α -methylstyrene, 98-83-9.

Acknowledgments. — This work was supported by the National Science Foundation. Acknowledgment is made to the donors of the Petroleum Research Fund for partial support of this research. The author thanks East Tennesse State University for the gracious hospitality accorded him during 1969-1970, and Dr. William Bayne for stimulating discussions.

(12) W. F. Bayne, Ph.D. Thesis, University of Connecticut, 1970.

Notes

Acidity of Hydrocarbons. XXXIV. **Rate of Proton Abstraction from** *p*-Trifluoromethyltoluene by Lithium Cyclohexylamide in Cyclohexylamine^{1,2}

A. STREITWIESER, JR.,* AND DAVID HOLTZ³

Department of Chemistry, University of California, Berkeley, California 94720

Received April 6, 1970

A study of the significance of the concept of fluorine anionic hyperconjugation in fluoro-substituted carbanions⁴⁻⁶ requires an accurate value for the base-catalyzed proton exchange of *p*-trifluoromethyltoluene (TFMT). Our earlier study of the protodetritiation of substituted toluene- α -t's with lithium cyclohexylamide (LiCHA) in cyclohexylamine (CHA) showed that several substituents followed the Hammett relationship with $\rho =$ 4.0;⁶ however, only an approximate rate was obtained for the *p*-trifluoromethyl substituent. TFMT decomposes LiCHA and necessitates the use of a competition method. We have now remeasured this reactivity by comparisons with both fluorobenzene-2-d(t) and triphenylmethane-d(t). In this method a mixture of the three compounds in cyclohexylamine is treated with a limited amount of LiCHA. The amount of isotope lost from the standard compounds before the destruction of catalyst by TFMT provides two independent measures of the relative rates of the latter reaction.⁶ Moreover, the use of both TFMT and TFMT- α - d_3 has permitted the determination of the first directly measured hydrogen-deuterium isotope effect, $k_{\rm H}/k_{\rm D}$, in the LiCHA-CHA system.

Experimental Section

Mass spectra were determined by Miss Sherri Firth using a modified consolidated Electrodynamics 21-103C mass spectrom-eter. Deuterium analyses were performed at $\gtrsim 10$ eV. Gas chromatographic (glpc) analyses were performed using an Aero-graph 1520 instrument. Tritium activities were determined by liquid-scintillation counting in low-potassium glass vials by the external standard ratio technique⁷ using a Nuclear Chicago Mark I Series Model 6860 scintillation counter equipped with a barium-113 δ source. Activities of samples were in the range 15,000-50,000 cpm. Background was ≤ 30 cpm. Counting efficiencies were 28-44%. It is believed that the accuracy of the tritium activity determinations is $\pm 1\%$.

p-Trifluoromethyltoluene- α - d_3 .—As adapted from the method of Schlosser,⁸ a mixture of 6.0 g (25.1 mmol) of p-trifluoromethylbenzyl bromide (prepared from the commercially available benzoyl chloride by reduction with lithium aluminum hydride, and conversion to the benzyl bromide with hydrobromic acid)⁹

(1) This research was supported in part by Grant GM-12855 of the National Institutes of Health, U. S. Public Health Service.

(2) Paper XXXIII: A. Streitwieser, Jr., and G. R. Ziegler, J. Amer. Chem. Soc., 91, 5081 (1969).

(3) Woodrow Wilson Fellow, 1964-1965; National Science Foundation Predoctoral Cooperative Fellow, 1965-1967; Eastman Kodak Science Award, 1966.

(5) A. Streitwieser, Jr., A. P. Marchand, and A. H. Pudjaatmaka, ibid., 89, 693 (1967).

(9) H. B. Hass and M. L. Bender, J. Amer. Chem. Soc., 71, 1768 (1949).

⁽¹³⁾ R. Huisgen and L. A. Feiler, Chem. Ber., 102, 3391 (1969).

⁽¹⁴⁾ The reported melting point of the cyclobutanone is $88.5-89.5^{\circ}$ (ref 11), although more recent preparations show mp 94-95° (R. Huisgen, personal communication). Comparison of our preparation with an authentic sample kindly supplied by Professor Huisgen showed identical $R_{\rm f}$ values on tlc (alumina, 2:1 Skellysolve B-benzene; one spot for both samples) and identical nmr spectra. However, our preparation showed additional weak absorptions in the ir fingerprint region. One further recrystallization of our preparation from Skellysolve B-ether afforded material of mp 95-96°, whose ir spectrum is superimposable upon that of the authentic sample.

^{*} To whom correspondence should be addressed.

⁽⁴⁾ A. Streitwieser, Jr., and D. Holtz, J. Amer. Chem. Soc., 89, 692 (1967).

 ⁽⁶⁾ A. Streitwieser, Jr., and H. F. Koch, *ibid.*, 86, 408 (1984).
 (7) "Liquid Scintillation Counting," Publication No. 711580, 1966, available from Nuclear Chicago Corp., Des Plaines, Ill. 60018.

⁽⁸⁾ M. Schlosser, Ber., 97, 3219 (1964).