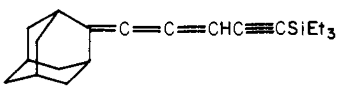
Reaction of 15 with Cyclohexene. Reaction of 1.29 mmol of triflate **15** with 1.61 mmol of *t*-BuOK and 19.5 mmol of cyclohexene in 200 mL of glyme gave only polymeric material with no cumulenic, allenic, or acetylenic absorption in the infrared.

Reaction of 15 with Et_3SiH. Reaction of 1.29 mmol of triflate **15** with 1.61 mmol of *t*-BuOK and 19.5 mmol of Et_3SiH in 200 mL of glyme gave 100 mg (25%) of **27** and 86 mg (34%) of **28**. Hydrocarbon **28** was present in all cases after the extended cumulene fraction of the chromatography prior to the elution of the other adducts, except in the case of **32** were there was significant coelution. Similar reaction of 0.29 mmol of triflate **15** with 0.36 mmol of *t*-BuOK and 29 mmol (100-fold excess) of Et_3SiH in 40 mL of glyme gave 15 mg (16.6%) of adduct **33**; no cumulene **27** was observed in this reaction. For **33**: ^{13}C NMR ($CDCl_3$, proton decoupled, rel. Me_4Si) δ 97.4, 139.3, 149.9, 173.1 (C=C=C=C). The difference in behavior between a large and a moderate excess (100 vs. 14) of silane is not understood. On the other hand with less than a tenfold excess of silane a significantly lower yield of product was observed.



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Reaction of 15 with Et_3GeH. Reaction of 1.81 mmol of triflate **15** with 2.26 mmol of *t*-BuOK and 9.95 mmol of Et_3GeH in 250 mL of glyme gave 69 mg (10.7%) of **29**, 3 mg (0.5%) of **30**, and 210 mg (32.7%) of **31** as yellow oils and 49 mg (13.8%) of **28**. Because of the small amount and sensitivity it proved to be impossible to fully isolate, purify, and spectrally characterize **30**.

Reaction of 15 with Et_3SnH. Reaction of 1.81 mmol of **15** with 2.26 mmol of *t*-BuOK and 10.1 mmol of Et_3SnH in 250 mL of glyme gave 117.5 mg (16.2%) of **32** as a yellow oil and 62.6 mg (17.6%) of **28**.

Attempted *t*-BuOK Catalyzed Isomerization of Cumulene 29. A solution of 0.17 mmol of *t*-BuOK in 5 mL of glyme was added over a 2-min period under argon to a solution of 0.085 mmol of cumulene **29** and *t*-BuNO in 10 mL of glyme at −78 °C. After 5 min of stirring at −78 °C the mixture was warmed to −50 °C then worked up by the standard procedure. TLC as well as spectroscopy indicated only recovered **29** with no isomerization to **30** or **31**. Hence this result, together with the fact that excess base was used in all reactions, indicate that the enyne and enediyne products observed (i.e., **24**, **25**, **30**, and **31**) are primary products and not the result of base-catalyzed isomerization.

Acknowledgment. This research was supported by the NSF (CHE 81-07629) and the donors of the Petroleum Research Fund, administered by the American Chemical Society. Extensive discussions with Professor D. H. Aue were most helpful.

Carbon Acidity. 58. Hydrogen Isotope Exchange Kinetics of Propylene with Lithium Cyclohexylamide

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Abstract: Rates for hydrogen isotope exchange with lithium cyclohexylamide (LiCHA) in cyclohexylamine-*N,N*-d_2 (CHA-d_2) and cyclohexylamine (CHA) are compared for propene and toluene. Benzyl hydrogens in toluene were found to be 6.2 times more reactive than allyl hydrogens in propene. Experimental primary isotope effects are also reported for propene: k^D(exptl)/k^T(exptl) = 2.9, k^H(exptl)/k^T(exptl) = 30, and k^H(exptl)/k^D(exptl) = 10.2. Derived internal return values show comparable values for propene and toluene. Analysis of polydeuteration rates shows that exchange is accompanied by complete equilibration of allyl positions. The high isotope effects and comparable acidities and internal return imply a transition state for propene which resembles that of toluene. An equilibrium pK_a on the CsCHA scale of ~43 is deduced for propene.

Studies of the stability of allylic anions, the simplest of all π-conjugated species, have become more numerous in recent years.[1,2] Allylic anions appear frequently as intermediates in base-catalyzed proton-exchange and olefin isomerization reactions in larger systems;[1,3] however, there are few studies involving the parent allyl anion derived from propene undoubtedly because propene is a gas at normal temperatures. Proton transfer involving propene has been reported in the gas phase by the flowing afterglow technique[4] and by ion-cyclitron resonance.[5] These measurements provide estimates of the stability of allyl anion relative to other anions and also estimates of the relative pK_a's of propene, toluene, and a number of other hydrocarbons in the gas phase; the proton affinity of allyl anion is about kcal mol^{-1} greater than benzyl anion.[6] In solution phase, deuterium exchange of propene in dimethyl sulfoxide-d_6 catalyzed by potassium *tert*-butoxide has been used to establish unequivocally the intermediacy of the π-allyl anion.[7]

We recently reported an investigation of hydrocarbon acidities in which allylic anions were generated from a series of cycloalkenes.[1] In this paper, we now turn our attention to the parent hydrocarbon, propene. We have again approached this problem by measuring hydrogen isotope exchange of allylic hydrogens in propene in the lithium cyclohexylamide (LiCHA)–cyclohexylamine (CHA) system. This study provides the first reliable estimate of the solution ion pair pK_a of propene since the kinetic properties are found to show important similarities to toluene.

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Propene had been assigned an approximate pK_a of 35.5 of Cram's MSAD acidity scale.[8] Breslow's electrochemical method indicates a pK in an electrode environment of 47–48.[9]

Experimental Section

Materials. MC&B spectroquality toluene and Matheson propene (99.5%) were used without purification. Toluene-*α-d*(*t*) (89.3% monodeuterated, 8 × 10^4 dpm/mg) was used from a previous preparation.[10] Distilled cyclohexylamine (CHA) was further purified by bulb-to-bulb distillation from lithium cyclohexylamide (LiCHA) preceding use. Cyclohexylamine-*N*,*N*-d_2 (CHA-d_2),[11] lithium cyclohexylamide-*N-d* (LiCHA-*d*),[1] and lithium cyclohexylamide[1] were prepared as described previously.

Propene-*3-d*(*t*). After removal of tetrahydrofuran (THF) from 24 mL of 1.1M allylmagnesium chloride in THF on a vacuum line, the solid allylmagnesium chloride was dried in vacuo. Deuterium oxide (6 mL) containing the contents of two 10λ capillaries of tritiated water was vacuum transferred to the allylmagnesium chloride. After the allyl Grignard was quenched, the water was frozen in a 2-propanol–liquid nitogen bath at –50 °C, and the propene was vacuum transferred to a flask containing 3A molecular sieves and later to a tared, evacuated gas bulb. Mass spectral analysis showed 92.3% monodeuteration and the absence of D_2O. The propene-*3-d*(*t*) had a tritium activity of 10^6 dpm/mg.

Kinetics in CHA-d_2. The kinetic solution was prepared in a cylindrical flask fitted with stopcock and standard taper joint. All manipulations were carried out on a vacuum line or in a glovebox to exclude adventitious air and moisture. Approximately 6 mmol of toluene (dried over 4A molecular sieves) and ~8 mmol of propene were transferred to a measured quantity of dry CHA-d_2 on a vacuum line. After addition of 2.4 mL of 0.58 M LiCHA-*d* solution, the reaction solution was quickly mixed and syringed into ten reaction bulbs (4-mL aliquots) fitted with long necks and stopcocks. The reaction bulbs were placed in a 50.0 °C constant temperature bath. Kinetic points were quenched at appropriate time intervals with 1 mL of water. Samples of both propene and toluene were vacuum transferred to mass spectral gas tubes while the reaction bulbs were submerged in a 2-propanol–water–dry ice bath maintained at –35 °C. The hydrocarbons were analyzed for deuterium incorporation by several scans on a CEC-21-130 mass spectrometer at low voltage (5–6 eV).

The intensities of the various species corresponding to propene (D_0), propene-*1-d* and -*3-d* (D_1), propene-d_2 (D_2), etc., were averaged and corrected for ^{13}C.

Kinetics in CHA. The kinetic solution was prepared in a manner similar to that described above. Samples of dry toluene-*α-d* and propene-*3-d*(*t*) (vide supra) were transferred to a cylindrical flask containing 46.0 mL of CHA. After addition of 16.0 mL of 0.69 M LiCHA, the solution was swirled and syringed in 4-mL aliquots into ten reaction bulbs. The bulbs were placed in a 50.0 °C constant temperature bath. The kinetics points, over a period of 18 days, were quenched by quickly chilling the reaction bulbs and adding 0.10 mL of water by syringe.

Samples of propene-*3-t* for tritium analysis were obtained by chromatographing 40 μL of reaction solution on a 10-ft VPC column of 20% Apiezon N on Chromosorb W at 60–70 °C. All of the propene effluent was passed through a right-angle tube, tipped with a fritted glass cap, into a vial of scintillation solution maintained at –68 °C. The tube was sealed inside the vial which was counted immediately in a Nuclear-Chicago Mark I liquid scintillation counter. Preliminary tests showed that propene loss was less than 0.5% when measured by using this procedure, provided that the samples were counted within 1 h after collection.

The analysis for tritium in the toluene-*α-t* samples was carried out after gas samples had been collected for deuterium analysis (vide infra). The quenched solutions were worked up by addition to 1.5 mL of decalin and ~20 mL of ice, followed by extraction of the CHA with 5 mL of concentrated hydrochloric acid. The resulting decalin solution was washed with water and dried over magnesium sulfate. The toluene was separated from the decalin by preparative VPC and was collected in 15 mL of spectral grade cyclohexane. The molar activity (dpm/mmol) was obtained by recording the spectrum of the toluene solutions on a Cary 118 spectrophotometer and by counting 10-mL aliquots of the spectral solutions on a Nuclear-Chicago Mark I liquid scintillation counter.

Determination of Base Concentration. Formal concentrations of LiCHA and LiCHA-d_2 were obtained by the procedure described previously.[1] Concentrations of the kinetically active LiCHA monomer was obtained by the eq 1 using Model 2.[12]

$$c = [\text{monomer}] \exp(500[\text{monomer}]) \qquad (1)$$

Analysis of Kinetic Data. Two important types of correction are necessary in the treatment of the raw kinetic data: correction for propene in the vapor above the solution and correction for hydrogen, deuterium, or tritium in the solvent. After correction of the raw data, the program LSKINI[13] was used to evaluate the pseudo-first-order rate constants.

Gas Solubility Corrections. The study of exchange kinetics of gaseous hydrocarbons is complicated by the fact that a significant quantity of the gas is not dissolved in the solution. Since base-catalyzed proton exchange takes place only in the solution phase, the rate of exchange will be altered by the lower concentration of the hydrocarbon in this phase. However, the hydrocarbon in the vapor phase may be considered to be in equilibrium with the solution because of the relatively long reaction times; hence, all of the hydrocarbon will ultimately be susceptible to exchange.

The calculation of the concentration of a dissolved hydrocarbon is greatly simplified if the solvent and solute form a regular solution.[14] Previous measurements in these laboratories have established that hydrocarbons form regular solutions in CHA and that the solubilities correlate normally with ΔE_b^v, the energy of vaporization at the boiling point, according to eq 2.[15] The solubility of propene was computed by

$$\Delta E_b^v = -1.156(-RT \ln x_2^{25\,°C}) + 6.035 \qquad (2)$$

using ΔE_b^v of 3.95 kcal mol^{-1}.[16,17] The solubility at 25 °C, 0.048, was extrapolated to a value of 0.032 at 50 °C by using an entropy of solution, –9.9 eu, derived from the solubility at 25 °C, eq 3,[15] and the temperature dependence of solubility, eq 4.[14] The number of moles of gas above the

$$\Delta \bar{S}_2 = 1.319(-R \ln x_2^{25\,°C}) - 17.8 \qquad (3)$$

$$\Delta \bar{S}_2 = R(\mathrm{d} \ln x_2/\mathrm{d} \ln T) \qquad (4)$$

liquid, n_g, and the number of moles in solution, n_s, compared to the total number of moles of propene present, n_t ($=n_s + n_g$), were calculated from eq 5, which was derived in a straightforward manner from the ideal gas

$$n_s^2 + (\mu V/RT + S - n_t)n_s - n_tS = 0 \qquad (5)$$

equation and Henry's law,[18] where S = moles of CHA, V = volume of free space above liquid, R = gas constant, T = temperature, and μ = Henry's law constant ($1/x_2$ at 1 atm). The fraction of propene in solution in the kinetic reaction bulbs ranged from 64% to 74%.

Solvent Corrections. In neither of the experiments described here is the exchangeable hydrogen isotope pool in the solvent effectively infinite. Depletion of exchangeable isotope during the course of the reaction results in an increasing probability that the isotope removed will be returned to the substrate. In order to take this into account, we corrected the kinetic data from the experiment in CHA-d_2 by the method described previously.[1] In the case of exchange of deuterium and tritium in substrates with protons from CHA, the procedure is somewhat different.[19,20] For the deuterium kinetics, the experimental rate constants were corrected by using eq 6,[19] where $Q = [(2b - a)^2 + 8abn/K]^{1/2}$, a =

$$k^D = (2b/Q)k^D(\text{exptl}) \qquad (6)$$

$[RH_{n-1}D]_0$, $b = [R'NH_2]_0$, and K = the exchange equilibrium constant taken as unity.[19] For tritium kinetics, the experimental constants were corrected by application of eq 7,[20] where $a = [RH_{n-1}T] + [RH_n] \simeq$

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$$k^{\mathrm{T}} = \frac{2b}{2b + na} k^{\mathrm{T}}(\mathrm{exptl}) \tag{7}$$

$[\mathrm{RH}_n]$ and $b = [\mathrm{R'NH_2}] + [\mathrm{R'NHT}] \simeq [\mathrm{R'NH_2}]$. These treatments differ because one isotope is present in macroscope amounts and the other is present in trace quantities. Both equations are approximations to a rather complex kinetic behavior in detail but suffice for the relatively small corrections necessary in our case.

Results and Discussion

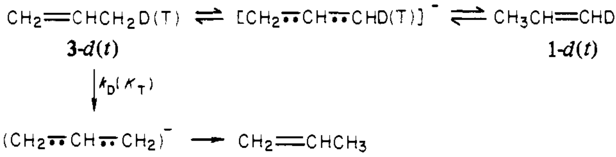
A summary of the experimental conditions and kinetic results are tabulated in Table I. Under the usual conditions for this type of exchange experiment, second-order rate constants may be calculated directly from the concentration of LiCHA monomer and the corrected psuedo-first-order rate constants. In the case of toluene, the derived second-order rate constants can be compared with previous measurements; the present value of $1.76 \times 10^{-2}\ \mathrm{M^{-1}\ s^{-1}}$ for k_2^{D} in CHA compares favorably with those reported earlier, $1.75 \times 10^{-2}\ \mathrm{M^{-1}\ s^{-1}}$ and $2.16 \times 10^{-2}\ \mathrm{M^{-1}\ s^{-1}}$.[11]

The other second-order rate constants for toluene, k_2^{H} in CHA-d_2 and k_2^{T} in CHA, could not be determined accurately from the present data. In the first case the base concentration was too low for accurate titration; in the second case the number of kinetic points available was small. However, the relative rates from these experiments, $k_1^{\mathrm{H}}(\mathrm{propene})/k_1^{\mathrm{H}}(\mathrm{toluene})$ in CHA-d_2, $k_1^{\mathrm{D}}(\mathrm{propene})/k_1^{\mathrm{D}}(\mathrm{toluene})$, and $k_1^{\mathrm{D}}/k_1^{\mathrm{T}}(\mathrm{propene})$ in CHA can be derived from the experimental results and are valid and useful. These relative rates compared with previously reported rate constants for toluene[11] permit the calculation of the corresponding second-order rate constants for propene. However, these ratios cannot be determined simply from the data in Table I but must be corrected first by a variety of statistical, solvent isotope, and equilibrium secondary isotope effects. These corrections will be reviewed in the next section.

Kinetic Isotope Effects. The rate of incorporation of deuterium from CHA-d_2 ($\mathrm{D_0} \rightarrow \mathrm{D_1}$) gives a value of k_{H} in that solvent. For comparison with k_{D} and k_{T} in CHA, the k_{H} data must be corrected for a solvent isotope effect, $k(\mathrm{CHA}\text{-}d_2)/k(\mathrm{CHA}) = 1.57$[11] and a statistical factor, σ_{H}, of 3 for both propene and toluene to account for the exchange probability of three equivalent methyl hydrogens in both compounds. The corrected rate constants become

$$k_1^{\mathrm{H}} = \frac{k(\mathrm{CHA})}{k(\mathrm{CHA}\text{-}k_2)} \frac{k_{\mathrm{H}}}{\sigma_{\mathrm{H}}} = \frac{k_{\mathrm{H}}}{(3)(1.57)} \tag{8}$$

Since k_{D} and k_{T} for toluene were measured in CHA with a substrate containing only one deuterium or tritium per molecule, no further corrections are necessary for these exchange rates for toluene. For propene, however, the situation becomes significantly more complex because of the rearrangement of propene-*3-d*(*t*) (**3**-*d*(*t*)) to propene-*1-d*(*t*) (**1**-*d*(*t*)) during the course of exchange (vide infra). This problem does not arise in the CHA-d_2 experiment because loss of undeuterated propene was followed. Because the primary isotope effect is relatively large, the system reaches equilibrium, eq 9, rapidly relative to the rate of deuterium or tritium exchange.



$$\mathrm{CH_2{=}CHCH_2D(T)} \rightleftharpoons [\mathrm{CH_2 \overline{\cdot\cdot} CH \overline{\cdot\cdot} CHD(T)}]^- \rightleftharpoons \mathrm{CH_3CH{=}CHD(T)}$$

3-*d*(*t*) **1**-*d*(*t*)

$$\downarrow k_{\mathrm{D}}(k_{\mathrm{T}})$$

$$(\mathrm{CH_2 \overline{\cdot\cdot} CH \overline{\cdot\cdot} CH_2})^- \longrightarrow \mathrm{CH_2{=}CHCH_3} \tag{9}$$

Since there is at least 1000-fold rate difference between allyl and vinyl hydrogen isotope reactivity (vide infra), a portion of the propene in solution is effectively inert; this portion depends on the equilibrium constant $K_{\mathrm{L}} = [\mathbf{3}\text{-L}] / [\mathbf{1}\text{-L}]$ and

$$k_1^{\mathrm{L}} = \frac{K}{K + 1} K^{\mathrm{L}}(\mathrm{exptl}) \quad \mathrm{L} \equiv \mathrm{H, D, or\ T} \tag{10}$$

The equilibrium constant K_{L} is dominated by the statistical factor of 1.5; that is, the isotope can be one of three hydrogens of the methyl group but one of only two in the terminal vinyl group. However, a secondary isotope effect is also significant because of the zero-point energy differences between methyl and vinyl hydrogen isotopes. The equilibrium isotope effect for deuterium was evaluated by using a treatment derived previously[21] from the Bigeleisen equation.[22,23]

Table I. Kinetic Results at 50 °C

compd	[hydrocarbon], M	$10^5 k_{(\mathrm{exptl})}$,[a] $\mathrm{s^{-1}}$	$10^5 k_1$, $\mathrm{s^{-1}}$	$10^3 k_2$, $\mathrm{M^{-1}\ s^{-1}}$
		CHA-d_2		
propene	0.133	23.0 ± 0.5	27.5	(123)[c]
toluene	0.128	149 ± 4	170	(756)[c]
		CHA		
propene-*3-d*	0.112	1.16 ± 0.02	1.12[b]	1.70[d]
propene-*3-t*		0.402 ± 0.039	0.394[b]	0.60[d]
toluene-*α-d*	0.109	12.0 ± 0.3	11.6[b]	17.6[d]
toluene-*α-t*		4.35 ± 0.24	4.27[b]	6.49[d]

[a] Experimental first-order rate constant corrected for gas solubility only. [b] Corrected for "back-reaction" of isotopes, eq 6 and 7. [c] Calculated from known rates of toluene[11] and experimental relative rates. [d] [LiCHA] is 0.177 M; concentration of monomer using Model 2 (eq 1; ref 12) is 6.58×10^{-3} M.

Table II. Corrected Rate Constants and Experimental Isotope Effects at 50 °C

	toluene	propene
$10^3 k_2^{\mathrm{H}}$, $\mathrm{M^{-1}\ s^{-1}}$	161[a]	26.1
$10^3 k_2^{\mathrm{D}}$, $\mathrm{M^{-1}\ s^{-1}}$	17.6	2.57
$10^3 k_2^{\mathrm{T}}$, $\mathrm{M^{-1}\ s^{-1}}$	6.5	0.87
$(k_{\mathrm{H}}/k_{\mathrm{T}})_{\mathrm{exptl}}$	24.8[b]	30
$(k_{\mathrm{D}}/k_{\mathrm{T}})_{\mathrm{exptl}}$	2.71[b]	2.9
$(k_{\mathrm{H}}/k_{\mathrm{D}})_{\mathrm{exptl}}$	9.15[b]	10.2

[a] From ref 11. [b] These results may be compared with the values 21.8, 2.58, 8.45, respectively, obtained previously.[11]

$$K_{\mathrm{H}}/K_{\mathrm{D}} \sim \exp(0.187/T)\sum_i \Delta\nu_{\mathrm{H}i} \tag{11}$$

The important frequency changes are methyl stretch (2900 $\mathrm{cm^{-1}}$) and degenerate bend (1300 $\mathrm{cm^{-1}}$) compared to vinyl stretch (3050 $\mathrm{cm^{-1}}$), in-plane bend (1100 $\mathrm{cm^{-1}}$), and out-of-plane bend (900 $\mathrm{cm^{-1}}$).[23] Equation 11 was derived from the empirical ratio of vibration frequencies, $\nu_{\mathrm{H}}/\nu_{\mathrm{D}} = 1.35$, and gives $K_{\mathrm{H}}/K_{\mathrm{D}} = 1.30$. The corresponding ratio for tritium, $\nu_{\mathrm{H}}/\nu_{\mathrm{T}} = 1.61$, gives analogously $K_{\mathrm{H}}/K_{\mathrm{T}} = 1.46$. Thus, the complete equilibrium constants for equilbrium 9 are $K_{\mathrm{D}} = 1.95$ and $K_{\mathrm{T}} = 2.19$. Table II summarizes the derived second-order constants and kinetic isotope effects corrected for the statistical and solvent isotope and equilibrium isotope effects as obtained for toluene and propene in the present study. The values for toluene compare favorably with those obtained previously[11] despite the expected higher probable error in the present kinetic result for toluene-*α-t*.

The primary kinetic isotope effects for propene are all rather high. The high isotope effects indicate that bond breaking is substantial at the transition state and that internal return is not important.

Internal Return. Internal return is expressed by k_{-1} in the proton-transfer mechanism.

$$\mathrm{RL} + \mathrm{B}^- \underset{k_{-1}^{\mathrm{L}}}{\overset{k_1^{\mathrm{L}}}{\rightleftharpoons}} \mathrm{R^-{\cdot}LB} \xrightarrow{k_{\mathrm{II}}} \mathrm{RH} \tag{12}$$

In the present case the base is a LiCHA ion pair and the intermediate is an allyllithium ion pair, which, depending on detailed structure, can return to the same labeled propene or the allylic rearranged propene. We have previously shown how the experimental isotope effect combined with the assumption of no isotope

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Table III. Rate Constants from Analysis of Polydeuteration in CHA-d_2

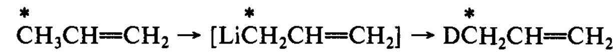
k_H	0.04 L mol^{-1} s^{-1}	k_{-H}/k_{-D}	9.96
k_{-H}	10^5-10^{11} L mol^{-1} s^{-1}	k_I	10^5–10^{12} s^{-1}
k_{-D}	10^4-10^{10} L mol^{-1} s^{-1}	$k_{I'}$	10^4–10^{11} s^{-1}
k_H/k_D	10.9	β	~1

effect in the solvent diffusion reaction k_{11} and the theoretical relationship between k_H/k_D and k_D/k_T permit the calculation of the fraction of internal return, a^L.[24]

$$a^L = k_{-1}{}^L/k_{11} \tag{13}$$

This method applied to the kinetic results reported previously for the exchange of toluene with LiCHA gives values at 50 °C for a^T, a^D, and a^H of 0.005, 0.012, and 0.12, respectively.[25] For propene the corresponding values are 0.007, 0.02, and 0.3, respectively. The values are all rather small except for protium exchange.

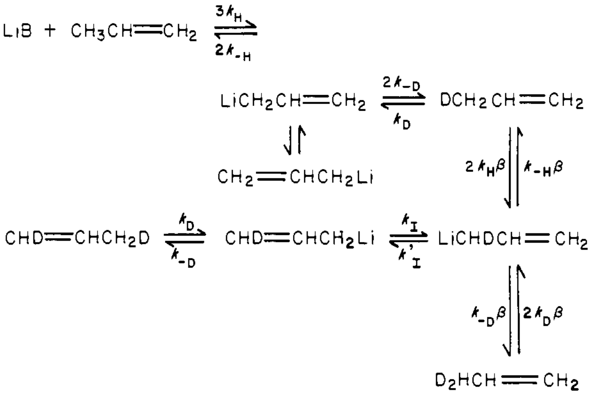
An independent measure of the magnitude of internal return to nonallylically rearranged substrate was obtained by following the introduction of additional deuterium in the exchange reaction of propylene with CHA-d_2. The technique is illustrated by the extreme case of exchange without allylic rearrangement (eq 14).



$$\overset{*}{C}H_3CH{=}CH_2 \rightarrow [Li\overset{*}{C}H_2CH{=}CH_2] \rightarrow D\overset{*}{C}H_2CH{=}CH_2 \tag{14}$$

The relative rate constants for $D_0 \rightarrow D_1$, $D_1 \rightarrow D_2$, and $D_2 \rightarrow D_3$ would then be 3:2:1 in the absence of secondary isotope effects, and D_4 would then not be formed. For completely equilibrated allyl anion intermediates the corresponding relative rates would be 3:2.4:1.8 and D_4 and D_5 would also be formed. Partial internal return would give intermediate values and the presence of secondary equilibrium isotope effects will modify these ratios.

In practice, we considered the complete set of exchange reactions with explicit consideration of allylic rearrangement as a separate kinetic step.



(15)

β is the secondary α-deuterium isotope effect and k_1 and k'_1 are the allylic rearrangment rate constants; the prime reflects another secondary isotope effect. The extension to D_3 and higher deuterated species is obvious. Complete kinetic expressions were desired for all of these reactions, and the resulting complex system of differential equations was solved by a modification of the procedure of Detar[26] as embodied in the computer programs REMECH and TSTMCH. Rate constants were varied systematically to obtain the best least-squares fit of calculated and experimental deuterium concentrations. The resulting rate constants are summarized in Table III, and the fit to the experimental deuterium contents of the kinetic points is shown in Figure 1.[27]

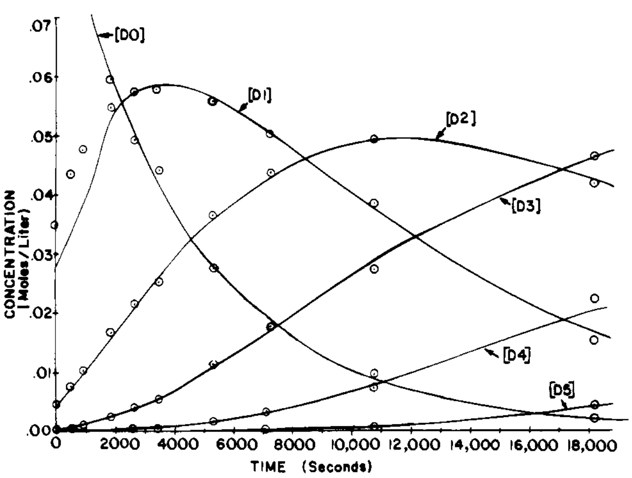


Figure 1. Comparison of experimental kinetic points with the concentrations of various deuterated propene species calculated from $k_H = 0.042$, $k_{-H} = 10^9$, $k_H/k_D = 10.9$, $k_{-H}/k_{-D} = 9.96$, $k_I = 6 \times 10^{10}$, and $\beta = 1$.

The value of k_H agrees with the more precise result in Table II and the primary isotope effects are also in agreement. The secondary isotope effect is small, too small to evaluate in this complex system. The rate constants for reaction of the carbanion-type intermediate with solvent were too large to evaluate by this method—a result totally anticipated. More important, the rate of allylic rearrangement was also indeterminantly large; that is, each replacement of isotope gives complete mixing of the α- and γ-carbons. The results establish that the allylic intermediate is effectively symmetrical, either because the intermediate has allylic symmetry as in an allyl anion–lithium cation ion pair or because an unsymmetrical intermediate, (e.g., $CH_2{=}CHCH_2Li$) isomerizes rapidly. By this criterion also, internal return is negligible.

Reaction Mechanism and Equilibrium Acidity. The above results strongly suggest that reaction of propylene with LiCHA produces an intermediate allyl anion–lithium cation species which achieves substantial equilibrium before reaction with solvent. The deuterium exchange of toluene with LiCHA has the rather low $\Delta S^{\ddagger}$ of −39 eu.[12] The high entropy demands of the reaction strongly suggests that additional solvent is localized at the transition state, undoubtedly by the lithium cation, and that the intermediate is a solvent separated or loose benzyl lithium ion pair. Note that (triphenylmethyl)lithium has been shown to be a solvent-separated ion pair in CHA.[28] Although temperature coefficient studies were not carried out with propene, the comparisons of isotope effects and internal return values strongly suggest that the intermediate allyllithium in this case is also solvent separated. The reaction mechanism appears to be closely similar for both hydrocarbons, and it seems reasonable to expect, therefore, that propene should belong to the same Brønsted family established previously for arylmethanes in CHA.[29] Application of the Brønsted slope of 0.31 to the 7-fold reactivity difference between toluene and propene gives a ΔpK_a difference of 2.7 in CHA. For toluene, pK_{CsCHA} is 41.2;[30] hence, for propene, $pK_{CsCHA} = 43.9$ (per hydrogen). A

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(25) The equations derived previously in ref 24 may be cast for convenience in the following form which uses $y = 3.344$ in $(k_D/k_T)^y = k_H/k_T$.

$$A + a^L(A - B) = [1 + \alpha^L(1 - C)]^\lambda$$

a^T: $\lambda = y = 3.344$; $A = (k^D(\text{exptl})/k^T(\text{exptl}))^\lambda/(k^H(\text{exptl})/k^T(\text{exptl}))$; $B = (k^D(\text{exptl})/k^T(\text{exptl}))^\lambda/K_T$; $C = k^D(\text{exptl})/k^T(\text{exptl})$. a^D: $\lambda = -2.344$; $A = (k^T(\text{exptl})/k^D(\text{exptl}))^\lambda/(k^H(\text{exptl})/k^D(\text{exptl}))$; $B = (k^T(\text{exptl})/k^D(\text{exptl}))^\lambda/K_D$; $C = k^T(\text{exptl})/k^D(\text{exptl})$. a^H: $\lambda = 1.427$; $A = (k^D(\text{exptl})/k^H(\text{exptl}))^\lambda/(k^T(\text{exptl})/k^H(\text{exptl}))$; $B = (k^D(\text{exptl})/k^H(\text{exptl}))^\lambda K_T$; $C = (k^D(\text{exptl})/k^H(\text{exptl}))K_D$. K_L is the distribution constant for the isotope between substrate and solvent; K_D and K_T for CHA are about 1.1–1.2.

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(27) The complete kinetic analysis and details of the computation are available as supplementary material.

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J. Am. Chem. Soc. 1981, 103, 6447-6455

corollary is that as in the case of arylmethanes, LiCHA exchange of propene involves a pyramidal transition state with only partial conjugation of the reaction center with the double bond. It could well be that conjugation in the propene transition state is more developed than for toluene because less substrate reorganization is involved. In that event, the effective Brønsted slope would be greater than 0.3 and the pK difference between propene and toluene is less than 2.7. Accordingly, the pK_{CsCHA} of propene is probably best represented as 43 ± 1.

The derived ΔpK_{CsCHA} for propene and toluene of ~ 2 agrees well with $\Delta pK = 1.9$–3.6 derived by Juan, Schwarz, and Breslow.[9] The latter estimate refers to an organoelectrolyte region of an electrode, but such an environment may not be too dissimilar from that in an ion pair. The close comparison of the acidities of propene and toluene in the two systems is probably more meaningful than a comparison of our propene pK_{CsCHA} with the absolute pK assigned as 47–48 in the electrochemical system, considering the uncertainties in the medium to which the latter number refers. The ion pair ΔpK for toluene and propene also compares with the gas-phase ΔpK of ≥ 1 estimated by Bohme et al.[4]

In kinetic exchange with LiCHA, propene is about 20–30 times more reactive than the cycloalkenes, cyclopentene through cyclooctene.[1] The primary hydrogens of propene are significantly more reactive than the secondary allylic positions of the cycloalkenes, a common result in kinetic acidities. The vinyl hydrogens of ethylene are about 1000 times less reactive than propene toward LiCHA;[31] hence, the present exchange experiments are not significantly complicated by concurrent vinyl exchange.

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Supplementary Material Available: A complete analysis and details of the computation (11 pages). Ordering information is given on any current masthead page.

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Unified Mechanism for Polyunsaturated Fatty Acid Autoxidation. Competition of Peroxy Radical Hydrogen Atom Abstraction, β-Scission, and Cyclization

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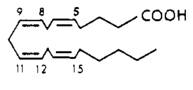
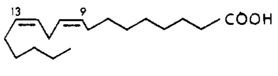
Abstract: The autoxidation of linoleic (18:2) and arachidonic (20:4) acids with several cosubstrates was investigated. Cumene, tetralin, 1,4-cyclohexadiene, and 9,10-dihydroanthracene in benzene were used as cosubstrates for the oxidation of linoleic acid. The distribution of products, trans,cis diene hydroperoxides and trans,trans diene hydroperoxides, was dependent on the ability of cosubstrates to donate hydrogen atoms to linoleate peroxy radicals. Arachidonic acid was oxidized in mixtures of benzene/1,4-cyclohexadiene with linoleic acid internal standard. Product distribution of six hydroperoxyeicosatetraenoic acids (HPETE) derived from arachidonic acid was established at different concentrations of 1,4-cyclohexadiene in the solvent mixture. A kinetic expression is derived that is useful in describing polyunsaturated fatty acid oxidation product mixtures. By the use of this kinetic derivation, the rate of cyclization of peroxy free radicals derived from arachidonic acid was determined.

Introduction

Interest in lipid oxidation[1-4] has been stimulated by discoveries that peroxide products of unsaturated fatty acid autoxidation have interesting biological properties. The enzymatic oxidation of arachidonic acid (**1**) plays a central role in a variety of biological events such as inflammation,[5] platelet aggregation,[6] asthma,[7] and anaphylaxis.[8] Random autoxidation of polyunsaturated fatty acids and esters also appears to be an important process[9] in vivo as is evidenced by the expiration of pentane and ethane, known fatty acid oxidation products, by organisms under free-radical stress. While the enzymatic oxidation of arachidonic acid (**1**) has received considerable attention, studies of the autoxidation of this important fatty acid have been fragmentary and incomplete.[10]



1, ARACHIDONIC ACID



2, LINOLEIC ACID, L-H

Product mixtures obtained in polyunsaturated fatty acid random autoxidation, on the other hand, are complex, and the primary processes leading to products have not been firmly established. Nevertheless, some kinetic and product studies have begun to address the important mechanistic questions in free-radical lipid oxidation and the following suggestions have been made.

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