in the AG and GG conformations were calculated by using the general dihedral angle driver method. As a calibration, the methyl rotation barrier in trimethylamine was calculated to be 4.37 kcal/mol. This is in excellent agreement with the experimental value (4.41 kcal/mol).[5] The various calculated barriers are compiled in Table II. The barriers range from 2.96 to 4.24 kcal/mol. Assuming an entropy of activation equal to zero, the highest calculated methyl rotation barrier gives a rate at 95 K that is about 4-5 times faster than that for the AG to GG conversion. It is possible that slowing methyl rotation contributes to additional exchange broadening of the ^1H DNMR line shape at or below 100 K.

Summary

Both the ^1H and $^{13}C\{^1H\}$ NMR spectra of isopropyldimethylamine decoalesce at very low temperatures and, at about 94 K, show two different subspectra. The major subspectrum (72-77%) is assigned to the C_1-symmetric enantiomers that have one isopropyl methyl group anti and the other gauche to the lone pair (AG and GA conformations). The minor subspectrum (23-28%) is assigned to the C_s-symmetric GG conformer that has both isopropyl methyl groups gauche to the lone pair; the methine proton is anti to the lone pair. At about 94 K, the AG (or GA) conformer is preferred over the GG form by a free energy difference of 0.07 ± 0.02 kcal/mol. Theoretical simulations of the exchange-broadened NMR spectra indicate a preferred (lowest barrier) AG to GG to GA conformational-exchange pathway. The free energy of activation for the AG (or GA) to GG process is 4.5 kcal/mol at 95 K. This is one of the lowest barriers measured by using NMR spectroscopy. The lower limit value of the free energy of activation for the AG to GA conversion is estimated to be 5.2 kcal/mol. Molecular mechanics calculations using Allinger's 1987 MM2 force field are in substantial agreement with the experimental results indicating that there is an enthalpy preference of 0.19 kcal/mol for the GG conformation and a barrier (ΔH^*) for the AG to GG process (5.37 kcal/mol) that is lower than that for the AG to GA conversion (7.84 kcal/mol). Calculated barriers for isolated methyl rotation range from 2.96 to 4.24 kcal/mol.

Experimental Section

NMR Spectra. The NMR spectra were recorded by using a Bruker WM-250 NMR system equipped with an Aspect 3000 computer. The magnet pole gap was modified to allow safe operation (no magnet O-ring freezing) down to 93 K. NMR sample temperature was varied by using a custom-built cold nitrogen gas delivery system used in conjunction with the Bruker BVT-1000 temperature control unit. Temperature measurement is accurate to ±3 K. NMR samples were prepared in precision 5- or 10-mm tubes and sealed after four freeze-pump-thaw cycles. All spectra are referenced to tetramethylsilane at 0 ppm.

Isopropyldimethylamine (IDMA). IDMA was prepared by using the procedure of Clark, Gillespie and Weisshaus[22] and purified on a 25% SF-96/5% XE-60 on Chromosorb WAW GLC column (20 ft × $^3/_8$ in.) at 413 K. NMR data: see DNMR Studies and Discussion.

Isopropyldi(methyl-d_3)amine. With cooling and stirring, 54 g (0.62 mol) of isopropylamine was neutralized by the slow addition of concentrated hydrochloric acid. The water was removed under vacuum, leaving the solid amine hydrochloride. The amine hydrochloride was dissolved in 50 mL of D_2O (99.9% isotopic purity, Cambridge Isotopes) and refluxed for 5 h under an efficient condenser equipped with a drying tube. The water was then removed under vacuum. This procedure was repeated seven times to give $(CH_3)_2CHND_3Cl$ that is 98.6% isotopically pure by NMR analysis. With cooling, the sample of $(CH_3)_2CHND_3Cl$ was neutralized (pH > 10) by the slow addition of 40% NaOD in D_2O (99.5% isotopically pure, Cambridge Isotopes). The resulting mixture was extracted with four 40-mL portions of anhydrous ether. The ether extracts containing $(CH_3)_2CHND_2$ were combined, dried over anhydrous Na_2SO_4, and filtered. Employing a modification of the procedure of Clark, Gillespie and Weisshaus,[22] we added 3.1 g (0.053 mol) of formic acid-d_2 (98% isotopically pure, 95% in D_2O, Cambridge Isotopes) with cooling to the ether solution of $(CH_3)_2CHND_2$. The ether, excess amine, and D_2O were removed first by careful distillation and then under vacuum to yield a viscous yellow oil. An additional 3.1-g (0.053-mol) sample of formic acid-d_2 and 100 mL of a 20% solution of formaldehyde-d_2 (98% isotopically pure, Cambridge Isotopes) were added to the yellow oil. The mixture was allowed to reflux for 24 h, acidified with 10 mL of concentrated HCl, and pumped under vacuum to yield a moist solid. With cooling, 40% NaOH in water was added dropwise to pH > 10. The aqueous layer was extracted with four 10-mL portions of ether and the ether dried over anhydrous Na_2SO_4. Isopropyldimethyl-$d_3$amine was purified on a 25% SF-96/5% XE-60 on Chromosorb WAW GLC column (20 ft × $^3/_8$ in.) at 413 K. ^1H NMR (CCl_4): δ 2.52 (1 H, septet, $^3J_{HH}$ = 6.1 Hz, CH), δ 0.96 (6 H, doublet, $C(CH_3)_2$), δ 2.08 (0.1 H, $N(CHD_2)_2$). Also see DNMR Studies and Discussion.

Acknowledgment. We are grateful to the University of Vermont Academic Computing Center for computational support.

Registry No. IDMA, 996-35-0.

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Picosecond Radical Kinetics. Rate Constants for Reaction of Benzeneselenol with Primary Alkyl Radicals and Calibration of the 6-Cyano-5-hexenyl Radical Cyclization

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Received April 27, 1992

Abstract: The cyclopropylcarbinyl radical ring opening was used as a radical clock to determine rate constants for benzeneselenol trapping in THF and in toluene. Hydrogen atom transfer trapping from PhSeH appeared to be partially diffusion controlled. An operational Arrhenius function for trapping in THF is log (k_T·M s) = 11.03 - 2.27/2.3RT. The recommended function for PhSeH trapping in other low-viscosity organic solvents is log (k_T·M s) = 10.87 - 2.10/2.3RT. The rate constant for trapping at 25 °C is 2.1 × 10^9 M^{-1} s^{-1}. The kinetic values are expected to apply for PhSeH trapping of simple primary alkyl radicals. As a check on this assumption, cyclization of the 6-cyano-5-hexenyl radical (**9**), produced from the corresponding PTOC ester radical precursor, was calibrated with PhSH and PhSeH trapping. The two trapping agents gave essentially equivalent results. The cyclizations of both (*E*)- and (*Z*)-**9** are described by log (k_r·s) = 11.0 - 3.8/2.3RT. This fast rearrangement (k_r = 1.6 × 10^8 s^{-1} at 25 °C) could prove to be useful as a radical clock for timing fast second-order processes.

Knowledge of the rates of radical reactions is important for mechanistic probe and radical clock studies. For very fast radical reactions, considerable progress in kinetic methodology has been reported in the past several years, especially for measurements

0002-7863/92/1514-8158$03.00/0

Table I. Calibration of PhSeH in THF

temp (°C)	[1][a]	$[PhSeH]_0$[b]	$[PhSeH]_f$[c]	(6 + 7)[d]	7/6[e]	k_r/k_T (M)[f]	10^{-9}M s·k_T[g]
50	0.026	0.038	0.012	92	3.230	0.0790	3.00
48	0.023	0.087	0.064	95	1.007	0.0757	2.92
48	0.023	0.130	0.107	100	0.635	0.0751	2.94
38	0.033	0.053	0.020	97	1.623	0.0577	2.68
30	0.036	0.130	0.094	81	0.430	0.0479	2.39
20	0.033	0.050	0.017	78	1.072	0.0344	2.23
20	0.033	0.100	0.067	72	0.423	0.0350	2.19
2	0.038	0.100	0.062	76	0.245	0.0195	1.78
2	0.038	0.053	0.015	64	0.633	0.0201	1.73
−20	0.038	0.076	0.038	61	0.178	0.0098	1.15
−21	0.022	0.050	0.028	65	0.257	0.0098	1.09
−44	0.022	0.041	0.019	59	0.127	0.00366	0.71
−45	0.026	0.060	0.034	52	0.078	0.00357	0.69

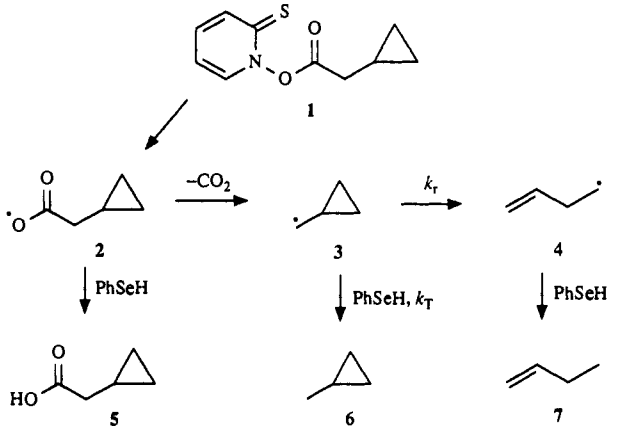
[a] Initial concentration of **1**. [b] Initial concentration of PhSeH. [c] Final concentration of PhSeH. [d] Percent yield of **6** plus **7**. [f] Ratio of rate constants for rearrangement (k_r) and trapping (k_T) determined from eq 2. [g] Rate constant for trapping determined from the k_r/k_T ratio and values for k_r from eq 1.

in and around room temperature. Direct studies of radical reaction rates employing laser pulses for radical generation are of obvious importance for absolute placement of rates on a kinetic scale, but there are limitations in direct methods. Expensive instruments can have temporal resolutions in the picosecond (or less) range, but the practical necessity of finding a radical source that can be converted to the desired radical rapidly usually limits direct methods to tens of picoseconds. Direct methods also typically require that radicals or their products contain a good chromophore for UV–vis spectroscopy, and the accuracy of unimolecular reaction kinetics can be limited. On the other hand, indirect competition methods, wherein one allows a bimolecular reaction with a known rate constant to compete against the reaction of interest, are inexpensive, can be employed with simple radicals, and in principle, can obtain temporal resolution in the picosecond range when the calibrated bimolecular trapping agent reacts with a rate constant approaching diffusion control and can be used at high concentrations. Another important advantage of indirect methods is that because the approach involves a partitioning of a radical between two reaction channels, it is not required that the process under study be the rate-limiting step in the overall sequence of radical production and subsequent reaction.

Our group has developed indirect kinetic methods for fast radical reactions based on the Barton PTOC esters.[2] These radical precursors have been shown to be among the most important entries to radicals for synthetic applications,[3] and they have a number of advantages in kinetic studies including ready access to highly strained radicals. Because PTOC esters will react in radical chain propagation steps with thiyl radicals, one may employ reactive thiols such as PhSH as trapping agents (the PTOC–thiol method); this permits kinetic studies of unimolecular reactions with rate constants as great as 1×10^{10} s^{-1} at room temperature.[2b]

Recently we communicated that the kinetic resolution of the PTOC–thiol method could be extended by employing benzeneselenol as a trapping agent.[4] PhSeH reacts with primary alkyl radicals about 20 times faster than PhSH[5] and twice as fast as the stable free radical 2,2,6,6-tetramethylpiperidine-*N*-oxyl[6] (Tempo), about an order of magnitude slower than diffusion in nonviscous organic solvents. With this velocity and one's ability to employ the selenol in concentrations exceeding one molar, PhSeH is the fastest pseudo-first-order radical trapping agent calibrated, with an ultimate resolution approaching 1 ps at room temperature. In this paper, we describe kinetic characterization of PhSeH trapping of primary alkyl radicals. The cyclopropylcarbinyl radical ring opening was used as the primary kinetic reference. A secondary reference reaction was cyclization of the 6-cyano-5-hexenyl radical which was calibrated in this work.

Scheme I



Calibration of Benzeneselenol Trapping

Ring opening of the cyclopropylcarbinyl radical is the most precisely characterized fast radical rearrangement despite the fact that the kinetics have not been measured directly. The results of kinetic studies employing three different methods (kinetic ESR spectroscopy,[7] PhSH trapping,[2b] and nitroxyl radical couplings[8]) and spanning >250 °C have been combined[2b] to give the Arrhenius function for ring opening in eq 1 wherein the log *A* value is in good agreement with that predicted for an essentially rigid molecule possessing two modes of reaction (cleavage of either of two cyclopropyl bonds) and in which the one degree of rotational freedom (methylene rotation) is lost in obtaining the transition state for ring opening.[7,9] The values from eq 1 should be considered as primary kinetic standards, and we have used this "radical clock"[10] to time PhSeH trapping reactions.[11]

$$\log (k_r \cdot s) = 13.15 - 7.05/2.3RT \qquad (1)$$

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(11) In our communication,[4] we used an Eyring function for the values for cyclopropylcarbinyl radical ring opening.[12] Recently, in an extensive study of various cyclopropylcarbinyl ring openings, Ingold's group used the Arrhenius function of eq 1 to describe these ring openings.[13] Therefore, we have now adopted eq 1 in order to standardize data related to the cyclopropylcarbinyl ring opening.
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Table II. Calibration of PhSeH in Toluene

temp (°C)	[1][a]	$[PhSeH]_0$[b]	$[PhSeH]_f$[c]	(6 + 7)[d]	7/6[e]	k_r/k_T (M)[f]	10^{-9}M s·k_T[g]
53	0.020	0.060	0.040	98	2.230	0.1110	2.36
48	0.020	0.130	0.110	100	0.765	0.0916	2.41
38	0.033	0.130	0.097	92	0.698	0.0789	1.97
30	0.033	0.065	0.032	85	1.330	0.0634	1.81
30	0.033	0.130	0.097	77	0.567	0.0641	1.79
20	0.030	0.040	0.010	74	1.680	0.0400	1.92
20	0.038	0.060	0.022	73	1.080	0.0427	1.80
0	0.023	0.043	0.020	72	0.702	0.0215	1.46
0	0.023	0.082	0.059	61	0.320	0.0224	1.41
0	0.033	0.080	0.047	73	0.381	0.0238	1.33
−21	0.023	0.072	0.049	59	0.169	0.0101	1.06
−22	0.023	0.060	0.037	60	0.214	0.0102	1.00
−44	0.020	0.040	0.020	68	0.140	0.00406	0.64
−45	0.020	0.050	0.030	61	0.098	0.00384	0.63
−45	0.020	0.060	0.040	57	0.078	0.00384	0.63
42	0.038	0.127	0.089	82	0.558	0.0599	2.99
42	0.038	0.254	0.216	73	0.271	0.0637	2.81
21	0.038	0.097	0.059	75	0.526	0.0405	1.97
21	0.038	0.146	0.108	72	0.270	0.0341	2.35
0	0.038	0.285	0.247	81	0.0743	0.0198	1.59
0	0.038	0.380	0.342	83	0.0540	0.0195	1.62
−25	0.038	0.097	0.059	72	0.0873	0.00668	1.27
−25	0.038	0.146	0.108	74	0.0665	0.00838	1.02
−43	0.038	0.070	0.032	65	0.0676	0.00329	0.84
−43	0.038	0.153	0.115	80	0.0249	0.00332	0.84

[a-g] See footnotes to Table I.

Scheme I shows the reactions of interest when the cyclopropylcarbinyl radical (3) is produced in a radical chain reaction from its PTOC ester precursor 1 in the presence of PhSeH. Decarboxylation of the initially formed acyloxy radical 2 gives cyclopropylcarbinyl radical (3) which subsequently is trapped by PhSeH or ring opens to the 3-butenyl radical (4) which, in turn, is also trapped by PhSeH. The initial decarboxylation reaction competes with acyloxy trapping by the reactive hydrogen donor which gives acid 5; the extent of this reaction is unimportant for the kinetic analysis although it can limit the overall precision by reducing the amount of radical 3 formed. The PhSe• radical formed in each of the trapping reactions further reacts with PTOC ester 1 in a chain propagation step; again, the rate of this process is not of kinetic significance. Another possible reaction, polar attack of the PTOC ester (an activated acyl compound) by PhSeH resulting in a "transacylation" reaction giving an acyl phenylselenide product,[14] can also reduce the precision by limiting the amount of cyclopropylcarbinyl radical; the extent of this reaction will be variable because the polar reaction will be important in the initial stages of the radical process during which adventitious radical chain inhibitors are depleted.

Table I contains results from studies of PhSeH trapping of radical 3 in THF. At the warmer temperatures, the total yields of hydrocarbons 6 and 7 were high, but the yields consistently dropped as the temperature was reduced. The initiating light flux in the experiments was essentially constant, and it is most likely that radical inhibitors were consumed at a constant rate irrespective of temperature. Because a polar transacylation reaction would slow as the reaction temperature was lowered, the reduced yield in hydrocarbon products at lower temperatures most likely resulted from increasingly competitive PhSeH trapping of the acyloxy radical in comparison to the decarboxylation reaction.

In these studies, low concentrations of the selenol were employed, and pseudo-first-order kinetics for trapping did not hold. The values for the ratios of the rate constants for rearrangement (k_r) and trapping (k_T) were determined from the ratio of products 5 and 6 by iterative solution of eq 2 which results from integration of the expression obtained by dividing the rate law for rearrangement (using a steady-state approximation for the radical) by the rate law for trapping. In eq 2, [1] is the initial concentration

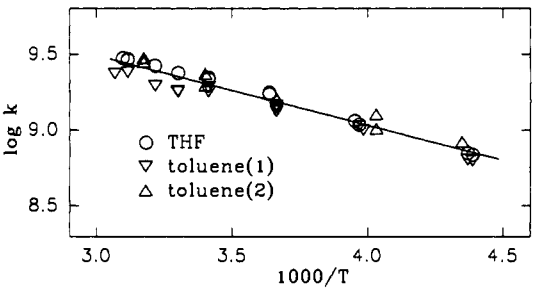

Figure 1. Arrhenius functions for PhSeH trapping. The toluene (1) points are taken from the first 15 entries in Table II, and the toluene (2) points are taken from the final 10 entries in Table II. The line represents eq 6.

of PTOC 1, 7/6 is the observed ratio of products, and $[PhSeH]_0$ and $[PhSeH]_f$ are the initial and final concentrations of selenol, respectively. If a pseudo-first-order kinetic analysis employing the mean concentration of selenol had been used, the ratios of rate constants would have differed by a few percent. In the final column of Table I, the trapping rate constants have been calculated from the experimental ratio of rate constants and the value of k_r from eq 1.

$$[1](7/6)(1 + 7/6)^{-1} = k_r/k_T\{\ln([PhSeH]_0 + k_r/k_T) - \ln([PhSeH]_f + k_r/k_T)\} \quad (2)$$

Table II contains results of similar studies of PhSeH trappings in solvent toluene. The first 15 entries comprise the data previously reported,[4] and the final ten entries are from a new set of studies. Agreement between these two sets of data is reasonable in the middle range of temperatures, but significant differences are seen in the high-temperature measurements with the newer data set more closely matching the results obtained in THF.

Previously, we had ascribed differences in the PhSeH trapping rate constants measured in THF and toluene to viscosity-dependent solvent effects.[4] However, the newer toluene studies suggest that diffusional solvent effects on PhSeH trapping in the two solvents are minor. This conclusion is in line with expectations because PhSeH trapping at room temperature is about an order of magnitude slower than diffusion in THF and toluene, and partial diffusional control of the reactions should result in only about a 10% diminution of the rate constants. In the newer data set in toluene, the concentrations of PhSeH were typically greater than those in the original data set, and it is possible that systematic

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errors in PhSeH concentration estimates resulted in greater errors in the lower concentration studies.

Figure 1 shows the results from Table I and II in graphical form. Arrhenius functions calculated from the THF data and the two sets of toluene studies are given in eqs 3–5, and an Arrhenius function calculated from all of the data is given in eq 6. Errors (2σ) for the last significant figures are for the functions and do not incorporate estimated errors in the cyclopropylcarbinyl ring opening rate constants. For studies conducted in THF, we recommended the use of eq 3. Given the levels of errors in eqs 4 and 5, it would appear that the combined function of eq 6 should be used to calculate the rate constant for PhSeH trapping in toluene and other low viscosity organic solvents.

$$\log (k_T \cdot s) = 11.03\ (7) - 2.27\ (9)/2.3RT \quad \text{(THF)} \quad (3)$$

$$\log(k_T \cdot s) = 10.72\ (11) - 1.99\ (14)/2.3RT \quad \text{(toluene (1))} \quad (4)$$

$$\log (k_T \cdot s) = 10.88\ (19) - 2.06\ (24)/2.3RT \quad \text{(toluene (2))} \quad (5)$$

$$\log (k_T \cdot s) = 10.87\ (14) - 2.10\ (17)/2.3RT \quad \text{(combined)} \quad (6)$$

Although eqs 3 and 6 should give good estimates of the rate constants for PhSeH trapping, the activation parameters from these equations are not meaningful. For example, thiophenol trapping of a primary radical has an activation energy of 1.74 kcal/mol,[5] and PhSeH trapping should have an even smaller activation energy. Because diffusional processes have activation energies of about 2.5 kcal/mol, partial diffusion control of the PhSeH trapping reaction will be more important at the lower temperature range of our measurements. This will lead to slightly curved temperature-dependent functions for PhSeH trapping which appear to be present in Figure 1.[15] One should note that when PhSeH is used to calibrate a new reaction and a linear approximation from eq 3 or 6 is applied, an Arrhenius plot of the new reaction data will be artificially curved in the opposite sense as those in Figure 1. However, solution of this new data by a linear function will lead to a cancelation in errors as long as the temperature range of the new study is similar to that we employed in the PhSeH calibration.[16]

Calibration of the 6-Cyano-5-hexenyl Radical Cyclization

The PhSeH trapping functions of eqs 3 and 6 provide rate constants for reactions with the cyclopropylcarbinyl radical. In general, fast hydrogen atom transfer agents such as PhSH react with the cyclopropylcarbinyl radical with rate constants essentially equal to those for reaction with a simple primary radical.[2b,5] It was expected that this would also be the case for PhSeH trapping, but a test with a primary radical was desired.

Cyclization of the 5-hexenyl radical to the cyclopentylmethyl radical, with a rate constant of $2 \times 10^5\ s^{-1}$ at 25 °C,[18] is much too slow to use as a radical clock for timing PhSeH trapping. However, 5-exo cyclizations of 5-hexenyl radicals substituted with electron-withdrawing groups on the alkene moiety appeared to be appropriately fast for PhSeH calibration. Specifically, cyclizations of 6-cyano-5-hexenyl and 6-cyano-6-methoxy-5-hexenyl

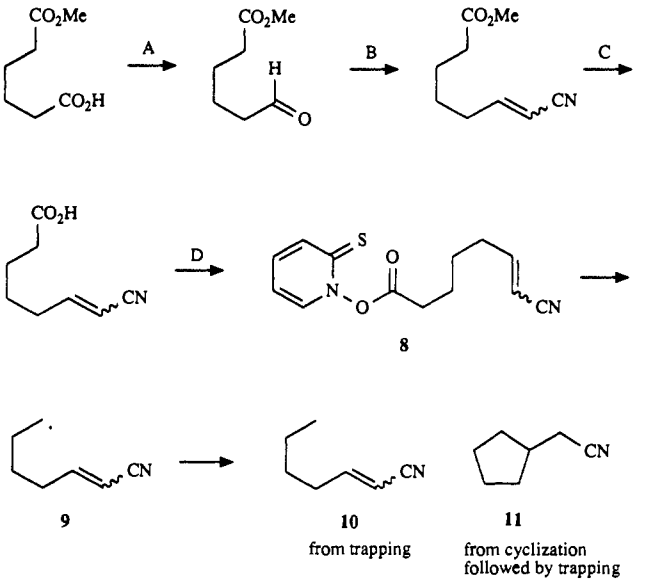

Figure 2. (A) (1) $BH_3 \cdot Me_2S$; (2) PCC; 66%. (B) *n*-BuLi, $(EtO)_2P(=O)CH_2CN$; 52%. (C) NaI, Me_3SiCl; 54%. (D) *N*-Hydroxypyridine-2-thione, DCC, catalytic DMAP; 55%.

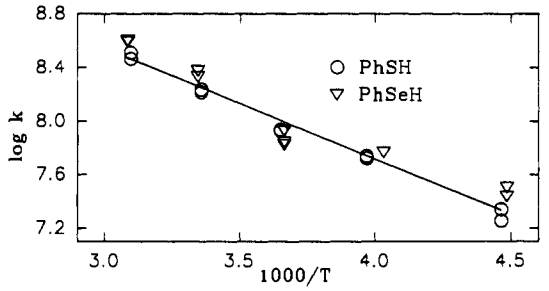

Figure 3. Arrhenius function for cyclization of radical **9**. The line represents eq 9.

radicals at 50 °C have been reported to be 200 and 400 times faster than that of the parent system.[19] As a test for the PhSeH trapping values, we have calibrated the 6-cyano-5-hexenyl radical cyclization against PhSH and PhSeH trapping.

Previously, radical **9** was produced from the corresponding bromide in a radical chain reduction with Bu_3SnH;[19] the kinetic calibration of the cyclization of radical **9** was at the limit of the tin hydride method. For our purposes here, the PTOC ester precursor **8** was required. The desired acid was available from the synthetic scheme shown in Figure 2. Precursor **8** was prepared from this acid by standard methods.[2b] The sample of **8** was a 1.2:1 mixture of the *E* and *Z* isomers.

When the mixture of isomers of PTOC ester **8** was allowed to react in the presence of either PhSH or PhSeH, the *E*:*Z* ratio of acyclic products **10** was, within experimental error, equal to the *E*:*Z* ratio of the initial PTOC ester. This confirms the previous observation that the rate constants for cyclizations of the isomers of radical **9** are essentially identical.[19] Thus, the electronic influence of the cyano group on the cyclization rate constant has no stereoelectronic component, and the small cyano group provides no steric barrier in the *Z* isomer. The practical significance of this observation is that there was no need to resolve the isomers of PTOC ester **8**.

Calibration of the cyclization of radical **9** in THF solvent over the temperature range −50 to 51 °C was accomplished by the PTOC–thiol method using both PhSH and PhSeH trapping as the basis reactions. The results are given in Table III. The values of k_T used to calculate k_r were obtained from the Arrhenius function for reaction of PhSH with a primary radical[20] and from

(15) When the data was solved with quadratic functions, the second-order terms were within one standard deviation of zero. Therefore, linear solutions, although approximate, are appropriate.

(16) This behavior was recently observed in kinetic measurements of the bond cleavages of the cubylcarbinyl radical which employed PhSeH trapping in THF.[17] The Arrhenius function for cubylcarbinyl cleavage calculated via a linear approximation of the slightly curved data had the expected log *A* value. The cubylcarbinyl results obtained provided a check on the PhSeH trapping rate constants in THF. Not only was the log *A* value for rearrangement consistent with theory, but low-temperature measurements of the rate of rearrangement using PhSeH and PhSH trapping as the basis reactions were in agreement with one another.

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Table III. Calibration of Radical 9 Cyclization

temp (°C)	[8][a]	trap	$[trap]_m$[b]	(10 + 11)[c]	11/10[d]	k_r/k_T (M)[e]	$10^{-8}s \cdot k_r$[f]
50	0.022	PhSH	0.695	83	2.30	1.71	2.91
50	0.013		1.17	78	1.52	1.90	3.23
25	0.025		0.42	74	2.69	1.21	1.64
25	0.020		0.55	73	2.14	1.26	1.71
1	0.038		0.67	88	1.14	0.82	0.86
1	0.034		0.81	88	0.95	0.83	0.87
1	0.028		1.01	89	0.75	0.81_5	0.85
−21	0.032		0.823	85	0.85	0.70	0.55
−21	0.025		1.091	83	0.61_5	0.67	0.53
−49	0.017		0.176	69	2.26	0.42	0.22
−49	0.013		0.23	65	1.45_5	0.35	0.18
51	0.023	PhSeH	0.56	81	0.222	0.124	3.89
51	0.018		0.70	82	0.181	0.127	3.99
26	0.022		0.40	84	0.228	0.091	2.13
26	0.017		0.52	83	0.194	0.101	2.36
0	0.017		0.24	75	0.217	0.052	0.84
0	0.013		0.32	76	0.127	0.041	0.67
0	0.043		0.74	74	0.072	0.053	0.86
0	0.033		0.97	74	0.044	0.043	0.70
−25	0.033		0.97	75	0.056	0.055	0.58
−50	0.028		0.40	71	0.107	0.043	0.27
−50	0.022		0.52	70	0.096	0.050	0.32

[a] Initial molar concentration of PTOC 8. [b] Mean concentration of trapping agent. [c] Percent yield of 10 plus 11. [d] Ratio of products. [e] Ratio of rate constants. [f] Rate constant for cyclization from ratio of rate constants and k_T values discussed in text.

eq 3. Pseudo-first-order analyses using the mean concentrations of the trapping agents were employed because the concentration of trap exceeded that of the PTOC precursor by more than an order of magnitude in each case.

Figure 3 shows the data for the cyclization of radical 9 in graphical form. Arrhenius functions for the cyclization determined against each trapping agent and the combined results are given in eqs 7–9 where the errors given are 2σ for the last significant figure. Despite the lack of precision in the PhSeH results, it is clear that the two trapping agents are calibrated essentially equivalently. Addition of the less precise PhSeH data to the PhSH data gave new activation parameters within the 95% confidence limits of eq 7 and increased the standard errors.

$$\log (k_r \cdot s) = 11.1\ (2) - 3.9\ (2)/2.3RT \quad \text{(PhSH)} \quad (7)$$

$$\log (k_r \cdot s) = 10.9\ (6) - 3.6\ (8)/2.3RT \quad \text{(PhSeH)} \quad (8)$$

$$\log (k_r \cdot s) = 11.0\ (3) - 3.8\ (4)/2.3RT \quad \text{(combined)} \quad (9)$$

The rate constant for cyclization of radical 9 at 25 °C is 1.6×10^8 s^{-1}. This reaction is somewhat faster than ring opening of the cyclopropylcarbinyl radical ($k_r = 9.4 \times 10^7$ s^{-1} at 25 °C). A previous determination[19] of the rate constant for cyclization of 9 employing the tin hydride method gave a value of 1.6×10^8 s^{-1} at 50 °C whereas eq 9 gives a value of 2.7×10^8 s^{-1} at 50 °C. Because the determination by the tin hydride method was at the limit of the method, the value from this work is expected to be more accurate. With such large rate constants for cyclization of 9 and given that radical 9 can be accessed from either the corresponding bromide or the homologated carboxylic acid via the PTOC ester, it is likely that the cyclization reaction will find applications as a radical clock in future studies of fast reactions.

Experimental Section

General. *N*-Hydroxypyridine-2-thione was obtained from the corresponding sodium salt (Olin) as previously described.[21] THF was distilled from sodium benzophenone under nitrogen immediately before use. Toluene was fractionally distilled under nitrogen and stored over molecular sieves. Thiophenol was distilled from $CaSO_4$ and stored over molecular sieves. Benzeneselenol was prepared and handled as previously described;[22] typically, samples were contaminated with Ph_2Se_2 (5–15%). ^1H and ^{13}C NMR spectra were obtained on Varian XL 200E and General Electric QE-300 spectrometers. Analytical GC was accomplished on Varian 2400 and 3400 chromatographs equipped with flame ionization detectors. Wide-bore capillary SE-30 and Carbowax columns (15 m, Alltech) were used for most separations. GC separations of methylcyclopropane and 1-butene were accomplished on 2 m × 6 mm Teflon columns containing active phases of $AgNO_3$ in ethylene glycol[23a] or diethylene glycol[23b] on Chromasorb P. Routine GC–mass spectral analyses were performed on a Hewlett Packard 5890 GC interfaced to a Hewlett Packard 5971 mass selective detector.

1-[[(Cyclopropylmethyl)carbonyl]oxy]-2(1*H*)-pyridinethione (1) was prepared as previously reported.[2b]

Methyl 6-oxohexanoate was prepared by the method of Brown et al.[24] by $BH_3 \cdot SMe_2$ reduction of adipic acid monomethyl ester (Aldrich) followed by pyridinium chlorochromate oxidation. Distillation gave the desired product in 66% yield: bp 85–87 °C (5 Torr); ^1H NMR ($CDCl_3$) δ 1.67 (m, 4 H), 2.34 (m, 2 H), 2.48 (m, 2 H), 3.68 (s, 3 H), 9.75 (s, 1 H); ^{13}C NMR ($CDCl_3$) δ 21.35, 24.30, 33.55, 43.33, 51.42, 173.59, 202.04.[25]

Methyl 7-cyano-6-heptenoate was prepared following the procedure of Park et al.[19] To a mixture of 22.0 mL of 1.3 M *n*-BuLi (28.6 mmol) and 10 mL of THF at 0 °C was added dropwise a solution of 5 g (28.2 mmol) of diethyl cyanomethylphosphonate (Aldrich) in 30 mL of THF. The ice bath was removed, and the mixture was stirred at room temperature for 1 h. To the resulting mixture was added dropwise a solution of 3.2 g (22.2 mmol) of methyl 6-oxohexanoate in 10 mL of THF. The mixture was stirred for 1 h and then treated with saturated aqueous NH_4Cl solution. The mixture was separated, and the aqueous phase was washed with ether. The combined organic phases were dried ($MgSO_4$), and the solvent was removed at reduced pressure. Chromatography on silica gel (15:85 ether–hexanes elution) gave 1.94 g (52%, oil) of methyl 7-cyano-6-heptenoate as a 55:45 mixture of the *E* and *Z* isomers as determined by ^1H NMR spectroscopy (signals at δ 6.47 and 6.70): ^1H NMR ($CDCl_3$) δ 1.51 (m, 2 H), 1.65 (m, 2 H), 2.33 (m, 4 H), 3.67 (s, 3 H), 5.28 (m, 1 H), 6.47 (d of t, J = 7.5, 10.8 Hz, 0.45 H), 6.70 (d of t, J = 7.0, 16.2 Hz, 0.55 H).[25]

7-Cyano-6-heptenoic acid was prepared by the method of Olah et al.[26] To a mixture of 1.03 g (6.2 mmol) of methyl 7-cyano-6-heptenoate and 2.77 g (18.5 mmol) of NaI in 20 mL of acetonitrile under nitrogen was added 2.35 mL (18.5 mmol) of Me_3SiCl. The mixture was heated at reflux for 100 h. Ether was added, and the acid was extracted into a 15% aqueous $NaHCO_3$ solution. The basic solution was acidified (HCl) and extracted with ether. Drying ($MgSO_4$) and removal of the solvent at

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reduced pressure gave 0.52 g (54%) of the desired acid as an oily mixture containing the *E* and *Z* isomers in a 55:45 ratio: ^{1}H NMR ($CDCl_3$) δ 1.52 (m, 2 H), 1.66 (m, 2 H), 2.39 (m, 4 H), 5.35 (m, 1 H), 6.47 (d of t, J = 7.6, 10.8 Hz, 0.45 H), 6.70 (d of t, J = 6.9, 16.5 Hz, 0.55 H); high-resolution MS calcd for $(M + 1)^+$ peak of $C_8H_{11}NO_2$ 154.0869, found 154.0870.[25]

1-[[(6-Cyano-5-hexenyl)carbonyl]oxy]-2(1*H*)-pyridinethione (8) was prepared by the standard method[2b] by reaction of the above acid with *N*-hydroxypyridine-2-thione and dicyclohexyl carbodiimide with catalytic (10 mol %) DMAP in benzene. The oily product was isolated as a 55:45 (*E*:*Z*) mixture of isomers by silica gel chromatography (1:1 ethyl acetate–hexanes elution) in 55% yield: ^{1}H NMR ($CDCl_3$) δ 1.60 (m, 2 H), 1.78 (m, 2 H), 2.28 (d of d, J = 5, 10 Hz, 1 H), 2.46 (d of d, J = 5, 10 Hz, 1 H), 2.71 (d of d, J = 4, 9 Hz, 2 H), 5.37 (m, 1 H), 6.48 (d of t, J = 7.3, 10.7 Hz, 0.45 H), 6.61 (m, 1 H), 6.70 (d of t, J = 6.9, 16.4 Hz, 0.55 H), 7.23 (m, 1 H), 7.55 (t, J = 5.7 Hz, 1 H), 7.64 (d, J = 7.9 Hz, 1 H).

2-Heptenenitrile (10) was prepared as previously reported.[19] The crude product was purified by column chromatography on silica gel (pentane elution). GC and ^{1}H NMR analyses showed a 60:40 (*E*:*Z*) ratio of isomers; the *Z* isomer eluted before the *E* isomer on a Carbowax GC column: ^{1}H NMR ($CDCl_3$) δ 0.87 (m, 3 H), 1.35 (m, 4 H), 2.15 (m, 1 H), 2.22 (m, 1 H), 5.27 (m, 1 H), 6.43 (d of t, J = 7.7, 10.8 Hz, 0.40 H), 6.66 (d of t, J = 6.9, 16.2 Hz, 0.60 H); MS of *Z* isomer, *m/e* (rel intensity) 109 (1, M^+), 108 (6), 94 (12), 80 (10), 69 (17), 68 (20), 67 (100), 56 (88); MS of *E* isomer, *m/e* (rel intensity) 109 (2, M^+), 108 (4), 94 (8), 80 (8), 69 (17), 68 (18), 67 (49), 56 (100).

Cyclopentylacetonitrile (11) was prepared as previously described.[19] The crude product was purified by chromatography on alumina (1:3, ethyl–pentane solution). ^{1}H NMR ($CDCl_3$) δ 1.31 (m, 2 H), 1.65 (m, 4 H), 1.89 (m, 2 H), 2.20 (m, 1 H), 2.39 (d, J = 7.0 Hz, 2 H); MS, *m/e* (rel intensity); 109 (1, M^+), 108 (15), 94 (9), 80 (13), 69 (100).

Kinetic Studies followed the general procedures previously reported[2b,21] with the exception that the trapping agents were added as stock solutions in the appropriate solvent that were prepared immediately before use. Following visible-light irradiation, the reaction tubes were cooled to −78 °C and opened immediately before GC analysis. Reactions of PTOC **1** were analyzed on the $AgNO_3$ columns; products were identified by the known GC retention times.[2b] Reactions of PTOC **8** were analyzed on the Carbowax column for quantification; products were identified by GC coinjection with authentic samples and by GC–mass spectrometry. Yields were determined relative to an internal standard of benzene or nonane (for PTOC **1** reactions) or dodecane (for PTOC **8** reactions). The GC response factors for **6** and **7** were assumed to be equal to one another and to the standard. The GC response factors for **10** and **11** were determined with authentic samples.

Acknowledgment. We thank the National Science Foundation (CHE-8816365 and CHE-9117929) for support. Xu Yue was a Robert A. Welch Undergraduate Scholar.

Spectroscopic Determination of Solute–Fluid Cluster Size in Supercritical N_2O

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Abstract: In supercritical fluids, near the critical point, there exists a region where the interactions between a solute and the surrounding solvent are such that the solvent molecules collapse about the solute. This enhancement of local solvent density, or solvent clustering, is an intriguing phenomena and may prove useful in separations, extractions, and reaction processes. We present here a means to experimentally determine the size of a solute–solvent cluster in the near-critical region using relatively straightforward spectroscopic techniques. In this work the solute, 6-propionyl-2-(dimethylamine)naphthalene (PRODAN), is fluorescent. Therefore, we can use fluorescence anisotropy and lifetime measurements to determine the rotational correlation time of PRODAN in supercritical N_2O. The recovered rotational correlation time is in turn related to the volume of the rotating species if the viscosity of the medium is known. Two limiting cases describing the observed rotational diffusion are considered. In the first, we assume a situation with minimal interaction between the solute and solvent. Second, we investigate the case where the solute and solvent interact strongly. Analysis of the experimental data within this framework allows us to determine the lower and upper volume limits of a solvent cluster. By using the sensitivity of the PRODAN emission spectrum, to the local solvent environment, we determine the density directly surrounding the solute (i.e., the local density). In the region near the critical point, the local density of N_2O about PRODAN is enhanced approximately 2.5-fold compared to the bulk. From the experimental local solvent density and cluster volumes, one has a means to calculate the average number of excess solvent molecules making up a cluster. Based on the two limiting cases, average cluster sizes between 25 and 103 N_2O molecules occur near the critical pressure, and decrease with increasing pressure.

Introduction

Supercritical fluids have properties which are intermediate of gases and liquids.[1-3] Gas-like viscosity and diffusivity coupled with liquid-like solvation power yield a medium that is an appealing alternative to conventional solvents used in chromatography[1-6] and industrial extraction processes.[7-9] Applications in these areas have blossomed over the past decade, preceding a detailed understanding of the underlying solvation processes (i.e., solute–solvent interactions).

The discovery of an interesting phenomenon[10,11] which occurs very near the critical temperature (T_c) and pressure (P_c) has sparked much interest in understanding the molecular-level interactions between solutes and supercritical fluids. In this work, Eckert and co-workers[10,11] found that, at infinite dilution, the partial molar volume of the solute (naphthalene, camphor, or

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