to four of the reactors in the amounts of 0.058, 0.114, 0.231, and 0.478 mmol. The closed reactors were immersed in a thermostatic oil bath held at 170 °C for 20 h. Products were washed from the reactors with *tert*-butylbenzene. Capillary gas chromatographic analysis of the products confirmed that the ratios of tetralin to tetralin-d_{12} remained essentially unchanged over the course of the reaction. In this analysis, tetralin was cleanly separated from tetralin-d_{12}. Toluene was isolated from the reaction mixture using preparative packed-column gas chromatography and collected in glass-wool-packed U-tubes immersed in a dry ice/acetone bath. The ratio of toluene to toluene-d_1 was determined by measuring the relative intensities at masses 92.0626 and 93.0689 with a Kratos MS-50 high-resolution mass spectrometer at an ionizing voltage of 70 eV with resoltuion of at least 1:50 000. The method was shown to be precise and accurate by analyzing samples collected from the gas chromatography of authentic toluene-α-d, of known deuterium content. High resolution is necessary to separate the peaks due to toluene and toluene-d, from close lying neighbors. In the spectrometer, the parent ions decompose to form tropylium ion. Monodeuteriotropylium ion has a mass of 92.0608. The parent ion of toluene containing natural abundance ^{13}C has a mass of 93.0659. The results of this experiment are plotted in Figure 1. Experiments at lower temperatures required longer reaction times for complete decomposition of dibenzylmercury. At 110 °C, the time allowed was 67 days.

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Absolute Rate Constants for Hydrogen Atom Abstraction by Benzyl Radical from Thiophenol, Tributylstannane, Tributylstannane-*d*, and Dicyclohexylphosphine and for the Cyclization of the 2-Allylbenzyl Radical[1]

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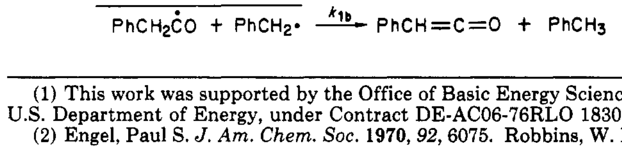
Absolute rate constants for the abstraction of hydrogen atom from thiophenol, tributylstannane, and tributylstannane-*d* in hexane and tributylstannane and dicyclohexylphosphine (DCPH) in cyclohexane were determined by competition of the abstraction reaction of benzyl radical, produced by the photolysis of dibenzyl ketone, with self-termination using termination rate constants of Fischer et al. in cyclohexane. For tributylstannane in cyclohexane, $\log (k_{abs}/M^{-1}\ s^{-1}) = (8.647 \pm 0.172) - (5.584 \pm 0.238)/\theta$, and for DCPH, $\log (k_{abs}/M^{-1}\ s^{-1}) = (8.001 \pm 0.184) - (6.278 \pm 0.26)/\theta$, $\theta = 2.303RT$ kcal/mol. A rate expression for benzyl radical termination in hexane was developed by combining values of $k_{abs}/(k_t)^{1/2}$ from the competition of benzyl abstraction from Bu_3SnH vs. termination using the values of k_{abs} obtained in cyclohexane. The resulting expression for self-termination of benzyl in hexane, $\ln (2k_t/M^{-1}\ s^{-1}) = (25.98 \pm 0.36) - (1803.58 \pm 199.4)/RT$, is in satisfactory agreement with the termination rates predicted by using the Smoluchowski equation for rate control by translational diffusion ($\ln (2k_t) = 26.53 - 2065.6/RT$). For benzyl in hexane, values of $k_{abs}/(k_t)^{1/2}$ combined with the experimental expression for termination gave, for reaction with thiophenol, $\log (k_{abs}/M^{-1}\ s^{-1}) = (8.273 \pm 0.180) - (3.790 \pm 0.24)/\theta$ and, for the reaction of benzyl and tributylstannane-*d*, $\log (k_{abs}/M^{-1}\ s^{-1}) = (8.712 \pm 0.410) - (6.155 \pm 0.56)/\theta$. Relative rate expressions (k_{re}/k_{abs}) for the cyclization of the 2-allylbenzyl radical vs. abstraction from tributylstannane, thiophenol, and DCPH were combined with the absolute rate expressions for abstraction from these donors to give, for the cyclization of 2-allylbenzyl radical to 2-indanylmethyl radical, the expression $\log (k_{re}/s^{-1}) = (11.14 \pm 0.30) - (16.28 \pm 0.53)/\theta$.

The photolysis of dibenzylketone provides a convenient source of benzyl radicals for the study of hydrogen abstraction from reactive hydrogen donors. The excited singlet state of dibenzyl ketone precedes the shorter lived triplet state[2] leading to teh phenylacetyl–benzyl geminate cage pair (eq 1).



$$PhCH_2C(=O)CH_2Ph \xrightarrow{h\nu} [PhCH_2C(=O)CH_2Ph]^* \underset{k_{-1a}}{\overset{k_{1a}}{\rightleftharpoons}} \overline{PhCH_2\dot{C}O + PhCH_2\cdot} \xrightarrow{k_{1b}} PhCH{=}C{=}O + PhCH_3 \quad (1)$$

Ninety-nine percent of the geminate pairs, which do not undergo internal return (k_{-1a}), produce free benzyl radical[3] following the decarbonylation step (eq 2). Less than 0.3%

$$PhCH_2\dot{C}O \xrightarrow{k_2} PhCH_2\cdot + CO \qquad (2)$$

of the geminate pairs produce phenylketene and toluene (k_{1b}) in low-viscosity solvents. The decarbonylation rate is represented by $\log (k_2/s^{-1}) = (12.0 \pm 0.3) - (6.9 \pm 0.4)/\theta$, $\theta = 2.303RT$ kcal/mol.[4] In the absence of hydrogen donors, benzyl radicals terminate to form bibenzyl (eq 3) or transient semibenzenes (eq 4).[3] The semibenzenes have

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(1) This work was supported by the Office of Basic Energy Sciences, U.S. Department of Energy, under Contract DE-AC06-76RLO 1830.

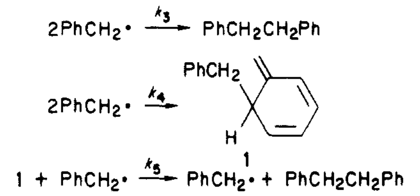
(2) Engel, Paul S. *J. Am. Chem. Soc.* **1970**, *92*, 6075. Robbins, W. K.; Eastmann, R. H. *Ibid.* **1970**, *92*. 6076. Robbins, W. K.; Eastmann, R. H. *Ibid.* **1970**, *92*, 6077.

(3) Langhals, H.; Fischer, H. *Chem. Ber.* **1978**, *3*, 543-553.

(4) (a) Lunazzi, L.; Ingold, K. U.; Scaiano, J. C. *J. Phys. Chem.* **1983**, *87* (4), 529-30. (b) Turro, N. J.; Gould, I. R.; Bareta, B. H. *Ibid.* **1983**, *87* (4) 531-2.

0022-3263/86/1951-0019$01.50/0

been detected by means of their CIDNP and have been trapped with strong acids as tolylphenylmethanes in yields of up to 19% of the total of termination products. In the absence of acid, the semibenzenes are quantitatively converted to bibenzyl at all temperatures, presumably by the chain sequence involving benzyl radical (eq 5).[3] The essentially quantitative material balance reported by Langhals and Fischer[3] implies that the semibenzenes are not trapped by abstraction of the doubly allylic aliphatic hydrogen, since this would lead to the formation of toluene and 1-phenyl-2-(4-benzylphenyl)ethane and other isomers from the coupling of 2- or 4-(phenylmethyl)benzyl with benzyl radical and a reduction in yield. Addition of benzyl radical to semibenzenes thus appears to be significantly faster than the abstraction reaction. From these considerations, the product bibenzyl is associated with the total termination rate constant, k_t, where $k_t = k_3 + k_4$.



(3)

(4)

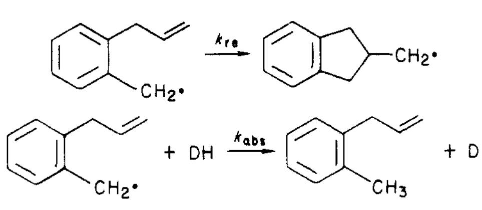
(5)

In the presence of fast hydrogen donors, a portion of the benzyl radicals can be intercepted to produce toluene (eq 6). Fischer and co-workers have developed rate constants

$$\mathrm{PhCH_2\cdot} + \mathrm{DH} \xrightarrow{k_6} \mathrm{PhCH_3} + \mathrm{D\cdot} \tag{6}$$

by ESR[5] and optical spectroscopy[6,7] for the termination of benzyl in cyclohexane and have demonstrated that benzyl termination is diffusion-controlled and satisfactorily described by the Smoluchowski treatment of translational diffusion. These termination rate constants for benzyl are the most accurate termination rates available and are suitable as standards for competitive reactions for the determination of absolute rates of hydrogen atom abstraction reactions.

In previous work[8] we developed a rate expression for the rearrangement of 2-allylbenzyl to 2-indanylmethyl and 2-tetralyl radicals in competition with abstraction from Bu_3SnH[8] and, more recently, from thiophenol, phenols, dicyclohexylphosphine, and arylalkyl donors[9] (eq 7 and 8).



(7)

(8)

For five-member ring closure forming 2-indanylmethyl, Bu_3SnH gave $\log[(k_{re}/k_{abs})/\mathrm{M}] = (2.32 \pm 0.16) - (10.47 \pm 0.36)/\theta$. For thiophenol and dicyclohexylphosphine (DCPH), $\log[(k_{re}/k_{abs})/\mathrm{M}] = (2.983 \pm 0.133) - (12.832 \pm 0.263)/\theta$ and $(3.197 \pm 0.04) - (9.895 \pm 0.075)/\theta$, respectively (Table II). No satisfactory absolute rates (k_{abs}) exist for the reaction of benzyl with Bu_3SnH, PhSH, or DCPH which could be combined with values of k_{re}/k_{abs} to give k_{re} (eq 7). The objective of the present study was to provide a suitable series of absolute rate expressions for atom transfer to benzyl which in turn would yield a rate expression for the radical clock reaction. Thus, we present a competitive study of the abstraction of hydrogen atom from Bu_3SnH, Bu_3SnD, PhSH, and DCPH by benzyl in competition with self termination of the benzyl radical. Values of $k_{abs}/(k_t)^{1/2}$ were combined with values of k_t of Fischer et al.[5-7] to give absolute rate constants for benzyl abstraction from which rate expressions for exo and endo cyclization reactions of 2-allylbenzyl (eq 7) can be estimated. The cyclization of the 2-allylbenzyl radical to the 2-indanylmethyl radical is an example of a radical "clock".[10] Intramolecular clock reactions such as those of eq 7 can be used to determine the rates of competing intermolecular reactions (eq 8). The 2-allylbenzyl rearrangement is a particularly valuable clock reaction, since it provides a method of determining difficult to obtain rates of benzyl radical reactions with aralkyl hydrogen donors.[9]

Experimental Section

General Data. NMR spectra were determined with a Varian FT-80. GCMS spectra for isotope analysis were determined with a Hewlett-Packard Model 5985 GCMS system operating at 10 eV.

Reagents. Dibenzyl ketone (Aldrich) was recrystallized four times from hexane at −25 °C (>99.9% purity, free of toluene and bibenzyl) and stored at −25 °C in the dark. Burdick and Jackson HPLC grade hexane and Fisher cyclohexane were used as received. Thiophenol (Aldrich) was distilled under ultrapure nitrogen to give >99.8% purity with ≤0.2% phenyl disulfide as the only impurity. Alfa dicyclohexylphosphine and tributylstannane were distilled under vacuum (>99.9% purity), and Alfa tributylstannane-*d* (>99.5% d) was used as received.

Kinetic Experiments. Photolysis of Dibenzyl Ketone and Bu_3SnH in Cyclohexane. Samples from a stock solution of 1.9×10^{-2} M dibenzyl ketone, 1.01×10^{-4} M *tert*-butylbenzene (internal GC standard), and Bu_3SnH, 1.5×10^{-3} M in hexane, were freeze–thaw degassed and sealed in 5-mm diameter quartz tubes for photolysis. The samples were photolyzed in a thermostated, vacuum-jacketed quartz chamber in a 2.5-cm diameter target area with the light from a 1000-W Hanovia No. 977B0010 Hg/Xe lamp and Kratos Model LPS255HR power supply passing through a high intensity monochromator (Kratos GM252) with 3.00-mm entry and exit slit widths. The samples were photolyzed at 337 nm for 10–1100 s (±0.5 s) at 10–50 °C (±0.5 °C) for cyclohexane and −25 to +50 °C for hexane, with less than 1% consumption of ketone and typically 5% consumption of donor, in order to maintain a constant concentration and distribution of radical species. Unphotolyzed samples were frequently analyzed by GC to confirm the absence or establish any background concentrations of toluene and bibenzyl. Samples were opened under nitrogen atmosphere and toluene, bibenzyl, and unreacted Bu_3SnH concentrations were determined by using a Hewlett-Packard Model 5880A gas chromatograph equipped with a 30-m J&W Scientific DB-5 column in the purged splitless injection mode. The linearity of production of both bibenzyl and toluene with time was confirmed by photolyzing samples for 60, 120, 180, and 240 s. Least-squares treatment of the concentrations of toluene and bibenzyl vs. time gave excellent linear correlations and near-zero intercepts. The effect of varying illumination intensity was also examined. The yields of products increased at higher intensity, but the rate constants from the ratios of products were invariant. Care was taken to assure that the absorbance of the samples was sufficiently low that irradiation intensity varied by less than 5% from the front to the back of the samples and that strongly asorbing photolytically labile products, i.e., phenyl disulfide, were not permitted to accumulate to a significant extent, which would

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Table I. Arrhenius Parameters and Rate Constants for the Reaction of Benzyl Radicals and Donors[a]

donor	log (A/M^{-1} s^{-1})	E_a, kcal/mol	k_{abs}(25 °C), M^{-1} s^{-1}	solv
Bu_3SnH[b]	8.647 ± 0.172	5.584 ± 0.238	3.586×10^4	cyclohexane
DCPH	8.001 ± 0.184	6.278 ± 0.260	2.512×10^3	cyclohexane
Bu_3SnH[c]	(8.647 ± 0.172)[c]	(5.584 ± 0.238)[c]	(3.586×10^4)[c]	hexane
Bu_3SnD[d]	8.712 ± 0.410	6.155 ± 0.560	1.5871×10^4	hexane
	(8.739 ± 0.25)[e]	(6.338 ± 0.32)[e]	(1.24×10^4)[e]	(decane)[e]
PhSH[d]	8.273 ± 0.140	3.790 ± 0.240	3.129×10^5	hexane
PhSD[f]	8.49	4.89	8.03×10^4	

[a] Errors are two standard deviations of slope and intercept from a linear least-squares regression (95% confidence). [b] Calculated from experimental values of $k_{abs}/(k_t)^{1/2}$ using k_t values calculated from $\ln(2k_t) = 26.1959 - 2497.55/RT$.[5] [c] Abstraction rates (k_{abs}) assumed identical in hexane and cyclohexane, and experimental values of $k_{abs}/(k_t)^{1/2}$ in hexane were used to calculate k_t from cyclohexane k_{abs} values, giving $\ln(2k_t) = (25.98 \pm 0.18) - (1803.58 \pm 94.7)/RT$. [d] Values of k_{abs} calculated from experimental $k_{abs}/(k_t)^{1/2}$ values with k_t values from the expression $\ln(2k_t) = 25.98 - 1803.58/RT$. [e] The values in parentheses are calculated by using A_H/A_D and $E_D - E_H$ values of ref 19. [f] From k_H/k_T data of ref 27, after conversion to k_H/k_D using the Swain equation.[18]

have changed the distribution of radical concentrations during the course of the photolyses.

DCPH in Cyclohexane. A solution of 1.9×10^{-2} M dibenzyl ketone, 4.7×10^{-3} M DCPH, and *tert*-butylbenzene (GC standard) in cyclohexane were photolyzed for typically 10–25 min and analyzed as for the Bu_3SnH experiments above.

Bu_3SnH, Bu_3SnD, and PhSH in Hexane. Solutions containing 7.40×10^{-4} M PhSH, 1.5×10^{-3} M Bu_3SnH, or 1.55×10^{-3} M Bu_3SnD and 2×10^{-2} M dibenzyl ketone were photolyzed from −30 to +50 °C, with all other procedures identical with cyclohexane.

To verify that the hydrogen abstracted by benzyl radical comes from the donor, GCMS analyses of Bu_3SnD experiments were carried out. $PhCH_2D$ (99.0% label, determined by careful NMR integration) was prepared by reduction of benzyl chloride in neat Bu_3SnD. The GCMS spectrum (10 eV) gave (m/z (abundance)) 91 (0.4), 92 (7.8), 93 (100), 94 (8.0), and 95 (0.4) compared to unlabeled toluene 91 (6.7), 92 (100), 93 (8.0), and 94 (0.3). GCMS examination of a room-temperature Bu_3SnD photolysis experiment gave, for toluene (10 eV) (m/z (abundance)) 91 (0.9), 92 (12.0), 93 (100.0), 94 (7.8), and 95 (0.3). A computer program was written to generate linear combinations of the experimental molecular ion clusters of the standards for GCMS analysis. This revealed the mixture to contain 97% $PhCH_2D$ and 3% $PhCH_3$. Since the rates of abstraction of all donors used were comparable to the rates of the Bu_3SnD experiments, negligible hydrogen abstraction from extraneous sources such as the transient semibenzenes can be assumed. The results of Langhals and Fischer[3] revealed that semibenzene formation occurs in about 15% of benzyl terminations. In our experiments, the final concentrations of bibenzyl were around 5×10^{-4} M. This established the maximum concentration of semibenzenes at less than 8×10^{-5} M, compared to donor concentrations of about 1.4×10^{-3} M. Thus, unrealistically high rate constants for abstraction by benzyl from the semibenzenes would be required to compete with abstraction from the donors, and for the present reactive donors, it can be safely ruled out.

Densities of cyclohexane and hexane were calculated by the method of Gunn and Yamada[11] for correction of donor and product concentrations.

Results

Table I presents Arrhenius parameters for abstraction by benzyl radical from donors. Detailed kinetic data are presented in the supplementary section (Tables IV–VIII). Figure 1 presents a representative Arrhenius plot of the kinetic data for the reaction of benzyl and DCPH.

In addition to the course of reaction of benzyl radicals as depicted in eq 1–6, termination processes involving combination of benzyl with the donor derived radical (D·) as shown in eq 9 may be expected to occur, in a fashion similar to that depicted for benzyl in eq 4. For simplicity, only one isomer is shown. A steady-state treatment of eq 3–5 and 9–12 gives eq 13. Since $k_{10b} >> k_{-10a}$ and $k_{12c} >> k_{12b}$ due to the high endothermocity of processes k_{10a} and k_{12b}, eq 13 reduces to eq 13a.

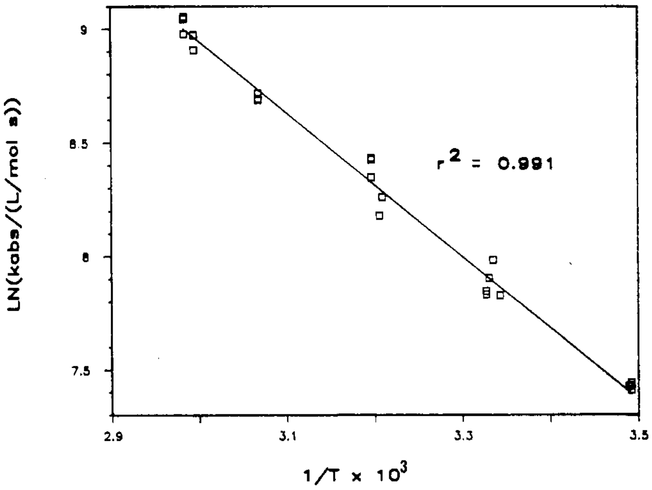
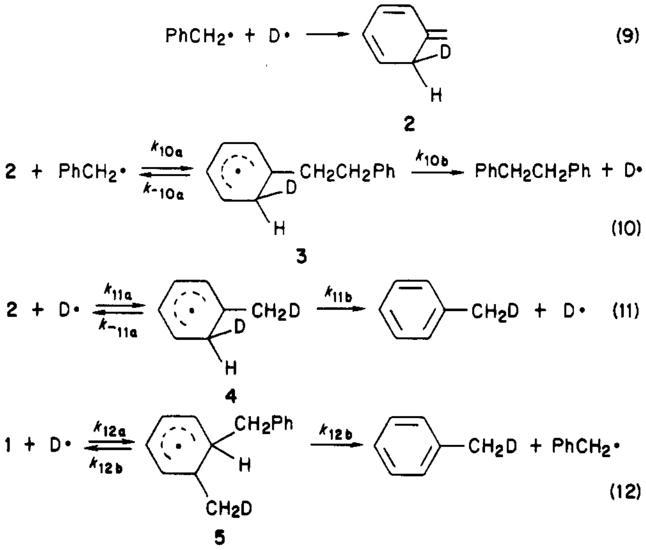


Figure 1. Arrhenius plot for the reaction of benzyl radical with DCPH.



$$\frac{d[PhCH_2CH_2Ph]}{dt} = k_3[PhCH_2\cdot]^2 + k_4[PhCH_2\cdot]^2 + \frac{k_{10b}k_{10a}[\mathbf{2}][PhCH_2\cdot]}{k_{-10a} + k_{10b}} + \left\{\frac{k_{12b}k_{12a}}{k_{12b} + k_{12c}} - k_{12a}\right\}[\mathbf{1}][D\cdot] \quad (13)$$

$$\frac{d[PhCH_2CH_2Ph]}{dt} = (k_3 + k_4)[PhCH_2\cdot]^2 + k_{10a}[PhCH_2\cdot][\mathbf{2}] - k_{12a}[\mathbf{1}][D\cdot] \quad (13a)$$

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[11] Reid, R. C., Prausnitz, J. M.; Sherwood, T. K. "The Properties of Gases and Liquids", 3rd ed.; McGraw-Hill: New York, 1977; pp 60–61.

Evaluation of eq 13a reveals the first term to be much greater than the second term and the third term to be at most 5% of the first term, allowing further simplification of eq 13a to eq 14.[12,13] Evaluation of each term of eq 13a is possible by using the integrated forms of eq 14 and 15 and experimental or estimated k_{abs} and k_t values, because under the present experimental conditions, radical concentrations ($PhCH_2\cdot$, D·) are constant.[13] Thus, the formation of bibenzyl is accurately described by eq 14, and

$$\frac{d[PhCH_2CH_2Ph]}{dt} \sim (k_3 + k_4)[PhCH_2\cdot]^2 = k_t[PhCH_2\cdot]^2 \qquad (14)$$

rate constants k_t correspond to the rate constants determined by Fischer et al.[5] The rate of formation of toluene is given in eq 15. For constant donor and benzyl concentrations, integrating and combining eq 14 and 15 gives eq 16 and 17. Thus, GC analysis of a reaction mixture

$$d[PhCH_3]/dt = k_{\text{abs}}[PhCH_2\cdot][DH] \qquad (15)$$

$$\frac{[PhCH_3]}{[PhCH_2CH_2Ph]^{1/2}} = \frac{k_{\text{abs}}[PhCH_2\cdot][DH]\Delta t}{k_t^{1/2}[PhCH_2\cdot]\Delta t^{1/2}} \qquad (16)$$

$$k_{\text{abs}}/k_t^{1/2} = [PhCH_3]/[PhCH_2CH_2Ph]^{1/2}[DH](\Delta t)^{1/2} \qquad (17)$$

photolyzed to short extent of conversion of donor and dibenzyl ketone for a time Δt provides a simple procedure for the determination of $k_{\text{abs}}/(k_t)^{1/2}$. Similar approaches have been used to obtain alkyl radical abstraction rates from the gas-phase photolysis of ketones in the presence of donors.[15]

The termination rate constants of Fischer et al.[5] for benzyl in cyclohexane were used for calculations of the first entry (Bu_3SnH) in Tabel I: $\ln(2k_t) = 26.2 - 2497.6/RT$. When Bu_3SnH experiments were repeated in hexane, the values of k_{abs} were assumed to be identical in cyclohexane and hexane, and the experimental values of $k_{\text{abs}}/(k_t)^{1/2}$ obtained were used to calculate k_t values. This provided an expression for the total self-termination of benzyl in hexane, $\ln(2k_t) = 25.98 - 1803.6/RT$. This expression was in turn used to convert experimental values of $k_{\text{abs}}/(k_t)^{1/2}$ for PhSH and Bu_3SnD in hexane to values of k_{abs}.

Discussion

Although no rate constants exist for the reaction of benzyl radical with Bu_3SnH, Chatgiliaglu, Ingold, and Scaiano[16] have estimated an upper limit of 3×10^5 M^{-1} s^{-1} for k_{abs} at 25 °C. The present value (Table I) of 3.59×10^4 M^{-1} s^{-1} would have been a factor of 10 too slow for convenient observation by kinetic laser flash spectroscopy.[16] The value of $\log A_{\text{abs}} = 8.65$ for Bu_3SnH and benzyl lies within the range of log A values for the reactions of *tert*-butyl (8.43), isopropyl (8.71), *n*-butyl (9.06), and methyl radicals (9.39) with Bu_3SnH.[16] From the Bu_3SnD experiments, $k_H/k_D = 2.26$ at 25 °C, compared to Lewis' value of $k_H/k_D = 3.24$ for benzyl,[17] obtained by the application of the Swain equation to k_H/k_T data.[18] Data of Strong, Brownawell, and San Filippo for the reduction of benzyl bromide in dodecane gives $k_H/k_D = 2.89$ at 25 °C, $E_D - E_H = 0.754$ kcal/mol, and $A_H/A_D = 0.810$. The results of Table I give $E_D - E_H = 0.57$ and $A_H/A_D = 0.99$. The Bu_3SnD data of the present work were gathered primarily to settle the question of abstraction from semibenzenes. A smaller number of data points were used to obtain the Bu_3SnD data, with higher error than other donors of Table I. Although our results for k_H/k_D agree within experimental error with those of Strong et al.[19] combining our Bu_3SnH results with their $E_D - E_H$ and A_H/A_D values results gives a more accurate rate expression for abstraction by benzyl from Bu_3SnD, $\log (k_{\text{abs}}/M^{-1}\ s^{-1}) = 8.74 - 6.34/\theta$. The k_H/k_D values for benzyl may be compared with k_H/k_D values for methyl (2.3),[16] ethyl (1.9),[16] and octyl (2.0)[19] radicals. Because of the high exothermicity of all of the hydrocarbon radical–Bu_3SnH reactions, a less pronounced increase in k_H/k_D is expected on going to the less reactive benzyl radical, since the transition state for abstraction remains substantially unsymmetrical. A recent evaluation of thermochemical data places the Sn–H bond strength of $(CH_3)_3SnH$ at 74 kcal/mol.[20] For benzyl + Bu_3SnH, $\Delta H° \simeq -14$ kcal/mol.[21] Thus, absolute rates for the reactions of methyl, ethyl, *n*-butyl, *tert*-butyl, isopropyl, cyclohexyl,[16] neopentyl, cyclopropyl, vinyl, and phenyl[22] as well as benzyl with Bu_3SnH are now available as standards for mechanistic studies.

Thiols and thiophenol have long been known to be rapid radical scavengers.[23] Absolute rate data for the reaction of benzyl radical and thiols are not available,[24] although Burkhart[25,26] has reported a value of $k_{\text{abs}}/(k_t)^{1/2}$ of 0.51 $M^{-1/2}$ $s^{-1/2}$ for the reaction of benzyl and thiophenol at 25 °C in cyclohexane. Using Fischer's[5] value of $(k_t)^{1/2} = 4.53 \times 10^4$ $M^{-1/2}$ $s^{-1/2}$, $k_{\text{abs}} = 2.31 \times 10^4$ M^{-1} s^{-1}, a factor of 14 slower than the present results. Combining k_H/k_D values

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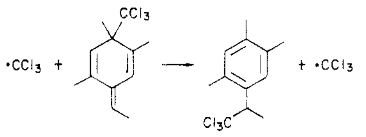
(12) Since semibenzenes **1** and **2** and the related intermediates **3**, **4**, and **5** have not been observed, the chain decomposition pathways proposed in eq 5, 10, 11, and 12 are of course speculative. Radical chain decompositions of semibenzenes have precedent; e.g.



See: Wilt, J. W. In "Free Radicals"; Kochi, J. K., Ed.; Wiley: Sons, New York, 1973; pp 464–465 and references therein.

(13) For example, from a 10-s photolysis of PhSH and dibenzyl ketone, $[PhCH_3] = 4.5 \times 10^{-5}$ M, $[PhCH_2CH_2Ph] = 1 \times 10^{-5}$ M, $[PhSSPh] = 3 \times 10^{-5}$ M, $[PhCH_2SPh] = 1.5 \times 10^{-5}$ M, $[PhCH_2\cdot] = 2 \times 10^{-8}$ M, and $[PhS\cdot] = [D\cdot] = 1.9 \times 10^{-8}$ M. The assumptions that 15% of cross-termination reactions (e.g., forming $PhCH_2SPh$) result in semibenzenes and that the semibenzenes do not accumulate to detectable concentrations relative to the normal cross-termination product lead to estimates of concentrations of $\mathbf{1} < 2 \times 10^{-6}$ M and $\mathbf{2} < 10^{-7}$ M, respectively. By comparison with the rate of polystyrene polymerization (ref 14a), k_{10a} is unlikely to be greater than 10^4 M^{-1} s^{-1}. The rate constant k_{12a}, by comparison with addition of PhS· to α-methylstyrene (ref 14b), may be as high as 1×10^8 M^{-1} s^{-1}. Thus $(k_3 + k_4)[PhCH_2\cdot]^2 = 2 \times 10^{-6}$ mol s^{-1}, $k_{10a}[PhCH_2\cdot][\mathbf{2}] \leq 10^{-10}$ mol s^{-1}, and $k_{12a}[PhS\cdot][\mathbf{1}] \leq 10^{-7}$ mol s^{-1}. Thus, the second term of eq 13a is negligible, and the third term is at most about 5% of the first term and can also be neglected. Similar analyses lead to the same conclusion for DCPH and Bu_3SnH.

(14) (a) The rate of polymerization of styrene is 145 M^{-1} s^{-1} at 60 °C. Ingold, K. U. In "Free Radicals"; Kochi, J. K., Ed.; Wiley-Interscience: New York, 1973; p 92 and references therein. (b) Ito, O.; Matsuda, M. *J. Org. Chem.* **1982**, *47*, 2261–4.

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Table II. Relative Rate Expressions (k_{re}/k_{abs}) for Reactions of 2-Allylbenzyl with Donors[a] (k_{abs}) vs. Cyclization to the 2-Indanylmethyl Radical (k_{re})

donor	log $[(A_{re}/A_{abs})/M]$	$E_{abs} - E_{re}$, kcal/mol
PhSH	2.983 ± 0.133	−12.832 ± 0.263
Bu_3SnH	2.320 ± 0.160	−10.470 ± 0.360
DCPH[b]	3.197 ± 0.038	−9.895 ± 0.071

[a] From ref 9. Errors are 2σ (95% confidence level). [b] Dicyclohexylphosphine.

for benzyl + thiophenol-*d* reported by Pryor and Kneipp[27] with the present values provides an expression for deuterium abstraction by benzyl from thiophenol-*d*: $\log k_D = 8.49 - 4.89/\theta$. The reaction of triphenylmethyl with thiophenol has been reported to be much slower than benzyl: $\log k_{abs} = (7.423 \pm 0.36) - (9.060 \pm 0.18)/\theta$.[28]

Phosphines are reactive hydrogen atom donors.[29,30] While no rate constants are known for the reaction of phosphines with the benzyl radical, Pellon found that chain transfer constants for methyl methacrylate and styrene polymerization in the presence of octylphosphine were 1.62×10^3 M^{-1} s^{-1} and 5.22×10^2 M^{-1} s^{-1} at 60 °C.[29] Thus, polystyryl radical abstracts hydrogen from octylphosphine about 15 times more slowly than benzyl radical abstracts hydrogen from DCPH (Table I).

In Table I we have assumed that the rate of abstraction of hydrogen by benzyl from Bu_3SnH is identical in cyclohexane and hexane. Thus, from the experimental values of $k_{abs}/(k_t)^{1/2}$, values of k_t were calculated to give the expression $\ln (2k_t) = (25.98 \pm 0.18) - (1803.58 \pm 95.7)/RT$ for the termination of benzyl in hexane. The accuracy of this expression was checked by calculating the dependence of $\ln (2k_t)$ vs. $1/RT$ using the von Smoluchowski equation (eq 18) for diffusion-controlled reactions.[31-33] Parameters

$$2k_t = (8\pi/1000)\sigma\rho D_{AB}N \tag{18}$$

for eq 18 were chosen following Schuh and Fischer,[31] resulting in the expression $\ln (2k_t)_{calcd} = 26.53 - 2065.6/RT$. The values from this expression are within 10% of the experimental values, supporting the assumption that the abstraction rate constants for benzyl radical are identical within experimental error in hexane and cyclohexane. Typical differences in calculated and experimental termination rate constants range from 5 to 25%.[31]

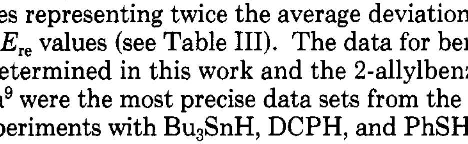
Absolute Rate Expressions for the Exo and Endo Cyclizations of the 2-Allylbenzyl Radical

Table III. Independent Arrhenius Expressions for the 2-Allylbenzyl → 2-Indanylmethyl Rearrangement from Data of Tables I and II

donor	log (A_{re}/s^{-1})	E_{re}, kcal/mol
Bu_3SnH	10.97	16.05
PhSH	11.26	16.62
DCPH	11.20	16.20
av	11.14 ± 0.30[a]	16.29 ± 0.60[a]

[a] Cited error is twice the average deviation.

With use of the above absolute rate expressions for benzyl abstraction, rate expressions for the 2-allylbenzyl radical exo (eq 7) and endo (eq 19) rearrangements can now be estimated. The absolute rate expressions of Table I are combined with the radical rate expressions of Table II[8,9] to yield three independent estimates of $\log (k_{re})$ (Table III). Thus, the rearrangement of the 2-allylbenzyl radical is represented by $\log (k_{re}/s^{-1}) = (11.14 \pm 0.30) - (16.28 \pm 0.53)/\theta$ by averaging the three expressions for k_{re}, with uncertainties representing twice the average deviations of $\log A_{re}$ and E_{re} values (see Table III). The data for benzyl + DCPH determined in this work and the 2-allylbenzyl–DCPH data[9] were the most precise data sets from the two types of experiments with Bu_3SnH, DCPH, and PhSH. It was thus satisfying that the average expression for $\log (k_{re})$ was near the value for the combined DCPH experiments. From the known[8] relative rates of exo to endo cyclization reactions of 2-allylbenzyl, $\log (k_{re}/k_{19}) = 0.14–2.0/\theta$, the rearrangement of 2-allylbenzyl to 2-tetralyl (eq 19) can now be represented by $\log (k_{24}/s^{-1}) = (11.06 \pm 0.3) - (18.28 \pm 0.6)/\theta$.



(19)

In the above calculations for the exo and endo cyclization barriers, it is assumed that benzyl and 2-allylbenzyl abstract at identical rates. Stabilization of the benzylic radical by the allyl group will reduce DH° of 2-allyltoluene by somewhat less than 0.4–0.9 kcal/mol compared to toluene, since bond dissociation energies of substituted toluenes vary about 3 kcal/mol per unit change in Hammett σ.[34] This effect will contribute a small and probably negligible increase in E_{abs}. The steric effect is also likely to cause a negligibly small increase in E_{abs}, since the heteroatom of the donor (Sn, S, P) is removed from nearest approach to a hydrogen of the allyl group in the most favorable conformation by around 3.5 Å. Results from studies of alkyl radical abstraction[16,22] from Bu_3SnH also suggest minor effects of branching at sites β to the radical center because the donor heteroatom is removed to some distance from the radical center. These considerations suggest that electronic and steric substituent effects of the 2-allyl substituent should be small. A third source of error comes from combining relative rates for PhSH and Bu_3SnH (Table I) determined in phenyl ether[9] with k_{abs} results obtained in cyclohexane and hexane. (The most accurate paired results, for DCPH, were determined in hexane and dodecane.[9]) Although solvent effects for the reactions of benzylic radicals and PhSH and Bu_3SnH have not been determined, Tanner[35] has shown that changing from benzene to acetonitrile leads to less than a 10% increase in rates of halogen abstraction from benzylic halides by the tributyltin radical. We expect solvent effects to exert small rate enhancements, for the presumably polar

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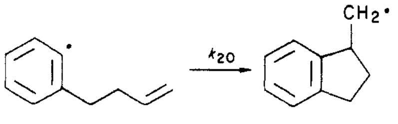
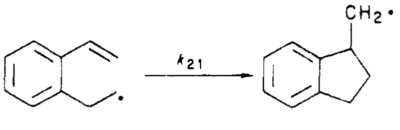
transition states of abstraction (especially PhSH), but the agreement of the overall average of Bu_3SnH, DCPH, and PhSH Arrhenius parameters with the DCPH results (Table III) indicates that the effects are small compared to experimental error. The largest source of error lies probably in the extrapolation of the results of Table I, determined at a mean temperature of 35 °C, to the results of Table I, determined at a mean temperature of 150 °C. The use of three pairs of rate expressions should reduce the extrapolation error.

The Arrhenius parameters for the 2-allylbenzyl cyclization can be compared to those for the cyclizations of two structurally related radicals. The 2-(4-butenyl)phenyl → 1-indanylmethyl cyclization exhibited log A = 11.2 and E_a = 3.6 (eq 20),[36] and the 2-(2-vinylphenyl)ethyl → 1-indanylmethyl rearrangement (eq 21)[8] exhibited log A = 10.6 ± 0.4 and E_a = 7.29 ± 0.6. Both rearrangements exhibit log A values which are higher than for 5-hexenyl (log A = 10.42), E = 6.85.[16] This is due mainly to the elimination of an additional RCH_2–CH_2R rotation due to introduction of the benzo structure into the 5-hexenyl system. For the 2-allylbenzyl radical, the log A_{re} value 11.14 is higher than 5-hexenyl and 2-(2-vinylphenyl)ethyl, as expected from the essentially frozen benzylic CH_2 rotation. We had expected the more rigid 2-allylbenzyl radical to exhibit a slightly higher A factor for cyclization than the 2-(4-butenyl)phenyl radical. However, errors for the two systems are large enough to accommodate the expected difference in log A of about 0.2–0.3. Detailed statistical mechanical calculations for these systems would be interesting, since, by contrast with the ground state, a tighter transition state might be expected for 2-allylbenzyl (see below). Statistical mechanical calculations based on MINDO/3-UHF structural parameters are reported to give A factors for 5-hexenyl analogues which are essentially in agreement with experiment.[37]



(20)



(21)

The 2-allylbenzyl exo cyclization barrier of 16.28 kcal/mol is substantially greater than typical 5-hexenyl-like cyclizations, which exhibit exo cyclization barriers of 7 ± 1.5 kcal/mol.[16,38] The major contribution to the greater barrier for exo cyclization of 2-allylbenzyl will be the geometric requirement of rotation of the benzylic CH_2 until the benzylic p orbital is nearly orthogonal to the aromatic π-system during the formation of the indan ring. Localizing the benzylic radical spin density will contribute 10.1 ± 2 kcal/mol, the resonance energy of the benzyl radical,[39] to the radical cyclization barrier. The remaining components of the barrier consist of van der Waals interactions between hydrogen atoms and other repulsive steric interactions, strain derived from unfavorable bond angles in the cyclopentene-like portion of the evolving indanylmethyl ring system, and torsional strain from distortion of the olefinic bond. It is generally accepted that homolytic addition to olefins requires approach of the SOMO of the attacking radical to the π^* region of the olefin.[40] In 5-hexenyl and related cyclizations, this rather strictly defined reaction pathway results in significant bond angle deformation in the transition structure. Beckwith and Schiesser[41] have determined the relative contributions of van der Waals interactions, bond bending (ring strain), and torsional strain (distortion of the olefin bond) to 5-hexenyl and related cyclization barriers in an MNDO-UHF and MM2 theoretical study. Strain effects were found to predominate in determining exo–endo regioselectivity in the 5-hexenyl cyclization, outweighing thermodynamic and steric effects to produce the less stable cyclopentylmethyl radical in preference to the cyclohexyl radical.

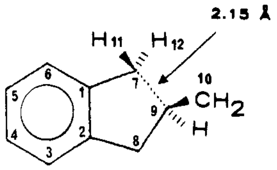


Figure 2. MNDO transition-state structure for the exo cyclization of the 2-allylbenzyl radical.

To reveal the extent to which localization of spin density at the benzylic carbon and development of strain in the evolving cyclopentene ring system has occurred at the transition state, we have carried out an MNDO[42] study of the exo cyclization of 2-allylbenzyl.[43] The transition state was located by stretching the C7–C8 bond (Figure 2) of the 2-indanylmethyl radical. The C7–C8 separation at the transition state was found to be 2.15 Å, compared to 2.2 Å predicted by MNDO for the C1–C5 distance in the 5-hexenyl exo cyclization, and 2.25 Å for the 2-(4-butenyl)phenyl cyclization.[41] Thus, MNDO predicts a progressively more product-like transition state as the reactivity of the attacking radical center decreases. The calculations revealed the dihedral (twist) angles 11-7-1-6 and 12-7-1-6 to be 69° and −77°, respectively (Figure 2). The plane defined by C1, C7, and the bisector of the 11-7-12 angle is tilted by only 4° from the plane of the aromatic ring, demanding complete loss of benzylic resonance energy in the transition state of the cyclization. The bond angles 7-1-6 and 8-2-3 are 123° at the transition state, compared to 127.3 and 129.5° in the 2-indanylmethyl radical, suggesting that the bond angle deformations in the 2-indanylmethyl radical are only partially developed at the cyclization transition state. Details of these calculations will be reported elsewhere.[43]

The Arrhenius parameters of this work have provided new rate expressions for the reaction of the benzyl radical with heteroatom donors, as well as providing the rate constants for the 2-allylbenzyl rearrangement, a valuable benzylic radical clock reaction. In a companion study, the 2-allylbenzyl radical clock is utilized to determine relative

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and absolute rate constants for hydrogen atom abstraction from arylalkyl, deuterated arylalkyl, and heteroatom donors.[9]

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Supplementary Material Available: Detailed kinetic data are provided in Tables IV–VIII of the microfilm edition (10 pages). Ordering information is given on any current masthead page.

Preparation of Optically Active 1,2-Diols and α-Hydroxy Ketones Using Glycerol Dehydrogenase as Catalyst: Limits to Enzyme-Catalyzed Synthesis due to Noncompetitive and Mixed Inhibition by Product

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Glycerol dehydrogenase (GDH, EC 1.1.1.6, from *Enterobacter aerogenes* or *Cellulomonas sp.*) catalyzes the interconversion of analogues of glycerol and dihydroxyacetone. Its substrate specificity is quite different from that of horse liver alcohol dehydrogenase (HLADH), yeast alcohol dehydrogenase, lactate dehydrogenase, and other alcohol dehydrogenases used in enzyme-catalyzed organic synthesis and is thus a useful new enzymic catalyst for the synthesis of enantiomerically enriched and isotopically labeled organic molecules. This paper illustrates synthetic applications of GDH as a reduction catalyst by the enantioselective reduction of 1-hydroxy-2-propanone and 1-hydroxy-2-butanone to the corresponding *R* 1,2-diols (ee = 95–98%). (*R*)-1,2-Butanediol-2-d_1 was prepared by using formate-d_1 as the ultimate reducing agent. Comparison of (*R*)-1,2-butanediol prepared by reduction of 1-hydroxy-2-butanone enzymatically and with actively fermenting bakers' yeast indicated that yield and enantiomeric purity were similar by the two procedures. Reactions proceeding in the direction of substrate oxidation usually suffer from slow rates and incomplete conversions due to product inhibition. The kinetic consequences of product inhibition (competitive, noncompetitive, and mixed) for practical synthetic applications of GDH, HLADH, and other oxidoreductases are analyzed. In general, product inhibition seems the most serious limitation to the use of these enzymes as oxidation catalysts in organic synthesis.

The NAD(P)(H)-dependent oxidoreductases are useful in the synthesis of chiral synthons. Horse liver alcohol dehydrogenase (HLADH)[1,2] has been most thoroughly explored; lactate dehydrogenase and L-leucine dehydrogenase have also been used.[3,4] The practicality of these systems for organic synthesis has increased with the recent development of effective procedures for enzyme immobilization and nicotinamide cofactor regeneration.[5-7] This manuscript describes the use of another commercially available oxidoreductase, glycerol dehydrogenase (GDH, EC 1.1.1.6), to reduce α-hydroxy ketones to chiral 1,2-diols. Previous studies have shown that chiral 1,2-diols having the same absolute configuration obtained here are obtained by reduction of α-hydroxy ketones using fermenting bakers' yeast.[8,9] We compare these enzymatic and fermen-

Table I. Relative Rates of Reduction of α-Hydroxy Ketones by GDH/NADH[a]

substrate	relative rate[b] *C.s.*	relative rate[b] *E.a.*	K_m, mM *C.s.*	K_m, mM *E.a.*
dihydroxyacetone	100	100	0.3	0.5
(*R*)-2,3-dihydroxypropanal	270			
(*S*)-2,3-dihydroxypropanal	130			
1-hydroxy-2-propanone[c]	30	20		0.04
1-hydroxy-2-butanone[c]	15	20		
2-oxopropanal	13			
2-hydroxycyclobutanone	290			
2-hydroxycyclopentanone	140		10	
2-hydroxycyclohexanone	14			
3-hydroxy-2-butanone	45		3	4

[a] Abbreviations: *C.s.*, *Cellulomonas sp.*; *E.a.*, *Enterobacter aerogenes*. Reactions were conducted at pH 7.6, 25 °C. Details of reaction conditions are given in the Experimental Section. The products of these reactions were not isolated, nor were their structures explicitly established. Compounds which did not react under these conditions include 1,2-cyclohexanedione, 2,3-butanedione, 2-propanone, 1-chloro-2-propanone, acetaldehyde, 2-hydroxy-4,4-dimethylcyclohexanone, and 4-hydroxy-3-hexanone. [b] The concentration of substrate in each experiment was 100 mM unless indicated otherwise. [c] The concentration of the substrate was 0.2 mM in these determinations of relative rate. Lower rates were observed at higher concentrations of substrate (100 mM).

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