Rate constants for the reaction of cumylperoxyl radicals with Bu₃SnH and (TMS)₃SiH

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Received (in Liverpool, UK) 13th December 1998, Accepted 18th January 1999

The rate constants for the reaction of a cumylperoxyl radical with Bu₃SnH and (TMS)₃SiH were determined at 72.5 °C to be 1600 and 66 M^{-1} s⁻¹, respectively, by using inhibited hydrocarbon oxidation methodologies.

In the last two decades, radical chain reactions have proven to be valuable in synthetic organic chemistry.^{1a} The majority of such chain processes have been carried out by using Bu₃SnH or (TMS)₃SiH, which are the most widely used reagents under reduction conditions.¹ For a synthetically useful radical chain reaction the intermediates must be *disciplined*. The concept of discipline² in free radical reactions is strictly connected with the kinetic information of each individual step, although upon first consideration, the importance of the kinetic knowledge might be less apparent in planning a synthetic strategy.

The reaction of peroxyl radicals with organic substrates is one of the most important classes of reactions in chemistry,³ being the key step of several processes, e.g. autoxidation of synthetic polymers, lipid peroxidation and DNA damage. The use of alkylperoxyl radicals in synthesis is limited to a few procedures.^{4,5} In one of them, the conversion of halides to alcohols has recently been approached by tin hydride reduction under aerobic conditions.⁵ The reaction sequence that has been suggested is shown in Scheme 1. Examples in which the alkyl radical rearranges itself prior to the reaction with molecular oxygen are reported,⁵ although in some cases the reaction is sluggish and gives undesired products.⁶ Nakamura and coworkers were able to run these experiments under conditions where hydroperoxides were isolated in good yields.7 In one case, the (TMS)₃SiH mediated halide to alcohol transformation was reported to give a moderate yield.7 In all these transformations, the reaction of a peroxyl radical with a tin or silicon hydride is crucial. Kinetic information regarding this step is not available. In their recent mechanistic studies on model DNA damage, Greenberg and co-workers8 arbitrarily assumed the rate constants for the ROO• radical with Bu₃SnH to be 5×10^3 M^{-1} s⁻¹ at 55 °C in THF. Following these considerations, the knowledge of the rate constants for the reaction of peroxyl radicals with Bu₃SnH and (TMS)₃SiH turns out to be necessary for better synthetic planning as well as a reference reaction for mechanistic studies.

Herein we report the rate constants of a cumylperoxyl radical with (TMS)₃SiH and Bu₃SnH which have been determined by using inhibited hydrocarbon oxidation methodologies.^{9,10} In particular, two different kinetic approaches were used for the



two reducing agents, depending on the presence or absence of an induction period when they are used as antioxidants. Scheme 2 shows that the initiation and propagation steps are identical for the two methods, whereas the termination steps are different.

Providing that conditions can be found in which *termination* 1 is applied, the rate constant for H-atom abstraction from the silane by cumylperoxyl radicals can be obtained from eqn. (1),⁹

$$\frac{(-d[O_2]/dt)_0}{(-d[O_2]/dt)} - \frac{(-d[O_2]/dt)}{(-d[O_2]/dt)_0} = \frac{fk_{\text{SiH}}[(\text{TMS})_3\text{SiH}]_0}{(2k_i R_i)^{1/2}}$$
(1)

where $(-d[O_2]/dt)$ and $(-d[O_2]/dt)_0$ represent the initial rate of oxidation of cumene with or without $(TMS)_3SiH.$ [‡] The stoichiometric factor *f*, which is the number of cumylperoxyl radicals trapped by each molecule of silane, is assumed to be equal to 2.§ The inhibition of thermally initiated (0.021 M of AIBN at 345.5 K) oxidation of pure cumene by $(TMS)_3SiH$ (concentration range of 1.84×10^{-4} to 6.13×10^{-4} M) is found to be the case. Fig. 1 shows that the oxidation rate of cumene decreases upon increasing the concentration of silane without an induction period. On the other hand, Fig. 1 also shows the linear regression analysis of eqn. (1), whose slope provides $2k_{SiH}/(2k_t R_i)^{1/2}$ to be 7.1×10^2 m⁻¹. Since the rate of radical production¹

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Initiation
Production of R \cdot at a rate = R_{i}
Propagation
R' + O_2 \xrightarrow{fast} ROO'
                        <sup>k</sup><sub>p</sub> → ROOH + R
ROO' + RH -
Termination 1
2 ROO \cdot \xrightarrow{2k_t} non-radical products
ROO + (TMS)<sub>3</sub>SiH
                                         ROOH
                                                        (TMS)<sub>3</sub>Si
                                                    +
                        (TMS)<sub>3</sub>Si
                                          fast
                                                     non-radical
                           or
(f-1) ROO* +
                                                     products
                      (TMS)<sub>3</sub>SiOO
Termination 2
ROO \cdot + Bu_3SnH \xrightarrow{k_{SnH}} ROOH
                                                  + Bu<sub>2</sub>Sn<sup>4</sup>
                        Bu<sub>3</sub>Sn '
                                        fast
                                                  non-radical
(f-1) ROO *
                                                  products
                      Bu<sub>2</sub>SnOO
                      R = PhCMe_2
                           Scheme 2
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Fig. 1 Plots of (O) $-d[O_2]/dt$ and (\bullet) $(-d[O_2]/dt)_0/(-d[O_2]/dt) - (-d[O_2]/dt)/(-d[O_2]/dt)_0 vs. [(TMS)_3SiH]; [AIBN] = 0.021 M at 345.5 K.$

and the termination for cumylperoxyl radicals¹² are $R_i = 1.09 \times 10^{-6}$ M s⁻¹ and $2k_t = 3.2 \times 10^4$ M⁻¹ s⁻¹, respectively, we calculated $k_{\text{SiH}} = 66.3 \text{ M}^{-1} \text{ s}^{-1}$ at 345.5 K.

The inhibition of thermally initiated (0.0172 M of AIBN at 345.5 K) oxidations of pure cumene by Bu₃SnH (concentration range of 1.07×10^{-3} to 3.20×10^{-3} M) shows an induction period (τ). *Termination 2* in Scheme 2 describes the inhibition mechanism and the initial rate of oxidation (before exiting from the induction period), given by eqn. (2), of peroxyl radicals

$$(-d[O_2]/dt) = \frac{k_p[RH]_0 R_i}{fk_{snH}[Bu_3SnH]_0}$$
(2)

trapped by each molecule of Bu₃SnH. The use of Boozer *et al.*'s induction period method,¹³ of which an example is illustrated in Fig. 2 (*i.e.* suppression of the oxygen uptake by the presence of Bu₃SnH) allows the determination of the τ values. Then the stoichiometric factor f can be obtained from $f = R_1 \tau/[Bu_3SnH]_0.^{9,10}$ All the data are summarized in Table 1. From the slope of the linear plot between $-d[O_2]/dt$ and $1/[Bu_3SnH]_0$, the



Fig. 2 Oxygen consumption during the AIBN-initiated (0.0172 m) oxidation of cumene in the presence of 2.64 \times 10⁻³ m of Bu₃SnH at 345.5 K.

Table 1 Kinetic data for the oxidation of cumene in the presence of ${\rm Bu}_3{\rm Sn}{\rm H}^a$

$(d[O_2]/dt)^{b/M} s^{-1}$	[Bu ₃ SnH] ₀ /м	v	τ∕min	f
10.94×10^{-6}	1.07×10^{-3}	11.8	10	0.52
7.01×10^{-6}	1.64×10^{-3}	7.5	15	0.51
$3.15 imes 10^{-6}$	2.64×10^{-3}	3.4	21	0.44
4.67×10^{-6}	3.20×10^{-3}	5.0	20	0.35
a [AIBN] = 0.0172 m	M, $R_{\rm i} = 0.89 \times 10^{-10}$	⁶ м s ⁻¹ at	345.5 K. ^b	$d[O_2]/dt =$
$(d[O_2]/dt)_{exp} - R_i$	· ·			

 $k_{\rm p}$ [RH]₀ $R_i/fk_{\rm SnH}$ was found to be 11.6 × 10⁻⁹ s⁻¹.§ Taking $k_{\rm p}$ = 1.3 M⁻¹ s⁻¹,¹² [RH]₀ = 7.188 M, R_i = 0.89 × 10⁻⁶ M s⁻¹,¹¹ and an average of f = 0.46, we calculated $k_{\rm SnH}$ = 1559 M⁻¹ s⁻¹ at 345.5 K.

In summary, the rate constants of 66 and 1600 M⁻¹ s⁻¹ at 345.5 K were obtained for the reaction of cumylperoxyl radicals with (TMS)₃SiH and Bu₃SnH, respectively. Therefore, the alkylperoxyl radicals abstract a hydrogen atom from the tin hydride 24 times faster than from the silane. (TMS)₃SiH is a notably less reactive hydrogen donor than Bu₃SnH, mainly due to the *ca*. 5 kcal mol⁻¹ difference in bond dissociation energies.¹⁴ For comparison, primary alkyl radicals and acyl radicals abstract hydrogen from the silane five and 16 times slower, respectively, than from the tin hydride at the same temperature and in much faster processes.¹⁴

Notes and references

[†] This relation can be used when the initial oxidation rate and the initiation rate remain essentially constant under the experimental conditions.

[‡] This is possible if the reactions in *termination 1* dominate the systems and if the products of these reactions are not active towards initiation.

§ Since the chain length of oxidation [*i.e.* $v = (-d[O_2]/dt)_{exp}/R_i]$ is less than 12, the initial rate of oxidation is corrected for oxygen absorption by the initiator, and nitrogen evolution from the initiator, *i.e.* $-d[O_2]/dt = (-d[O_2]/dt)_{exp} - R_i$, where the $(-d[O_2]/dt)_{exp}$ is the experimental initial rate of cumene oxidation.

- (a) For example, see: D. P. Curran, N. Porter and B. Giese, Stereochemistry of Radical Reactions, VCH, Weinheim, 1995; W. B. Motherwell and D. Crich, Free Radical Chain Reactions in Organic Synthesis, Academic Press, London, 1992; (b) For reviews on (TMS)₃SiH, see: C. Chatgilialoglu, Acc. Chem. Res., 1992, 25, 188; C. Chatgilialoglu, C. Ferreri and T. Gimisis, in The Chemistry of Organic Silicon Compounds, ed. S. Rappoport and Y. Apeloig, Wiley, London, 1998, vol. 2, pp. 1539–1579.
- 2 A terminology introduced by Barton. For example, see: D. H. R. Barton, Aldrichim. Acta, 1990, 23, 3; D. H. R. Barton and S. I. Parekh, Half a Century of Free Radical Chemistry, CUP, Cambridge, UK, 1993.
- 3 For some representative reviews, see: K. U. Ingold, Acc. Chem. Res., 1969, 2, 1; N. A. Porter, in Organic Peroxides, ed. W. Ando, Wiley, Chichester, 1992; C. von Sonntag and H.-P. Schuchmann, Angew. Chem., Int. Ed. Engl., 1991, 30, 1229; C. Walling, in Active Oxygen in Chemistry, ed. C. S. Foote, J. C. Valentine, A. Greenberg and J. F. Liebman, Blackie, London, 1995, pp. 24–65.
- 4 For example, see: G. L. Hill and G. M. Whitesides, J. Am. Chem. Soc., 1974, 96, 870; D. H. R. Barton, D. Crich and W. B. Motherwell, J. Chem. Soc., Chem. Commun., 1985, 1066; H. C. Brown, M. M. Midland and G. W. Kabalka, Tetrahedron, 1986, 42, 5523.
- 5 E. Nakamura, T. Inubushi, S. Aoki and D. Machii, J. Am. Chem. Soc., 1991, **113**, 8980; S. Moutel and J. Prandi, *Tetrahedron Lett.*, 1994, **35**, 8163; S. Mayer and J. Prandi, *Tetrahedron Lett.*, 1996, **37**, 3117; M. Sawamura, Y. Kawaguchi, K. Sato and E. Nakamura, *Chem. Lett.*, 1997, 705; M. Sawamura, Y. Kawaguchi and E. Nakamura, *Synlett*, 1997, 801.
- 6 For example, see: D. L. Boger and J. A. McKie, J. Org. Chem., 1995, 60, 1271.
- 7 E. Nakamura, K. Sato and Y. Imanishi, Synlett, 1995, 525.
- 8 K. A. Tallman, C. Tronche, D. J. Yoo and M. M. Greenberg, J. Am. Chem. Soc., 1998, 120, 4903.
- 9 E. T. Denisov and I. V. Khudyakov, *Chem. Rev.*, 1987, **87**, 1313; E. T. Denisov, *Liquid-Phase Reaction Rate Constants*, Plenum, New York, 1974; N. M. Emanuel, E. T. Denisov and Z. K. Maizus, *Liquid Phase Oxidation of Hydrocarbons*, Plenum, New York, 1967.
- 10 J. A. Howard, Y. Ohkatsu, J. H. B. Chenier and K. U. Ingold, *Can. J. Chem.*, 1973, **51**, 1543; J. H. B. Chenier, S. B. Tong and J. A. Howard, *Can. J. Chem.*, 1978, **56**, 3047; S. Korcek, J. H. B. Chenier, J. A. Howard and K. U. Ingold, *Can. J. Chem.*, 1972, **50**, 2285.
- J. P. Van Hook and A. V. Tobolsky, J. Am. Chem. Soc., 1958, 80, 779;
 E. Niki, Y. Kamija and N. Ohta, Bull. Chem. Soc. Jpn., 1969, 42, 3220.
- 12 D. G. Hendry, J. Am. Chem. Soc., 1967, 89, 5433.
- 13 C. E. Boozer, G. S. Hammond, C. E. Hamilton and J. N. Sen, J. Am. Chem. Soc., 1955, 77, 3233.

14 C. Chatgilialoglu, Chem. Rev., 1995, 95, 1229.

Communication 8/08894B