Determination of the rate constants of the addition of primary alkyl radicals to allylstannanes

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The rate constants and the activation parameters of the addition of primary alkyl radicals to allyldibutyl-4,7,10-trioxaundecylstannane **1** and (2-ethoxycarbonylprop-2-enyl)dibutyl-4,7,10-trioxaundecylstannane **2** were determined by studying their respective free radical reactions with (2-bromo-1,1-dimethylethyl)benzene and 6-bromohex-1-ene at different temperatures.

Introduction

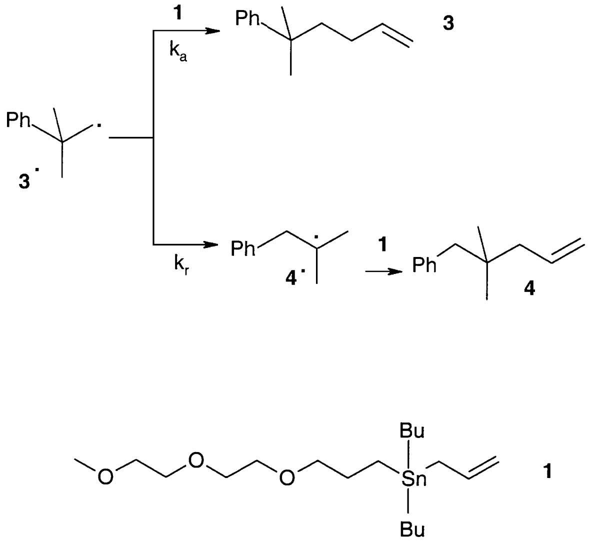
Allylstannanes are among the most widely used reagents to replace bromine atoms by allyl groups.[1] However, the difficulty of separation of organic reaction products from the stannic compounds is an important limitation. Although several chemical transformations of a trialkyl- or triaryl-tin halide in a more easily eliminable compound from the reaction medium were used, none of them appeared fully satisfactory, as we reported in a previous article.[2] Several substitutes for allyltri-*n*-butyltin were proposed to overcome this problem. Thus, the allyltin moiety has been immobilized on a polymer to readily eliminate the tin compounds after reaction by precipitation and simple filtration.[3] Other new compounds were designed in our laboratory, including allylic monoorganotins[4] and allyltrialkyltins having a polar tail.[5] All of them gave good results from the point of view of separation, however no comparison with the allyltri-*n*-butylstannane has been made with regards to the reactivity. As cascades of free radical reactions are used more and more frequently in synthesis, it appeared important to determine the reactivity of the allyltin having a polar tail, allyldibutyl-4,7,10-trioxaundecylstannane **1**, that we designed to replace the allyltri-*n*-butyl stannane. This is the primary objective of this work, part of a larger program devoted to the study of the free radical reactivity of substitutes of tin reagents involving free radical reactions by the use of clock radicals.[6] The kinetic results will be compared with those obtained by Curran *et al.*[7] for the allyltri-*n*-butyltin. The availability of (2-ethoxycarbonylprop-2-enyl)dibutyl-4,7,10-trioxaundecylstannane **2**, an allyltin with an activated double bond and a polar tail,[5] prompted us to extend this kinetic study.

Results

Kinetic study of the addition of primary alkyl radicals to allyldibutyl-4,7,10-trioxaundecylstannane 1

The absolute rate constants for the rearrangement of certain radicals are known and can therefore be used to serve as a reference in competition with the reaction to calibrate. Several clock radicals were proposed by Griller and Ingold[6] for this purpose. Assuming a value in the range of 10^4 l mol^{-1} s^{-1} for the rate constant of addition of a primary alkyl radical to the double bond of **1** (k_a), similar to the one of allyltributyltin,[7] the neophyl [2-methyl(2-phenyl)propyl] rearrangement was selected as a clock reaction. Then, the rate constant k_a could be calculated from the concentrations of the reaction products (Scheme 1). Indeed, the kinetic analysis of the reaction mechanism led to the following differential equation:

$$d[\mathbf{3}]/d[\mathbf{4}] = (k_a/k_r)[\mathbf{1}]$$



Scheme 1

For measurements of the concentrations of the reaction products performed at low consumption of **1** ([**1**] = [**1**]$_0$), the integration of the differential equation led to the following relation:

$$[\mathbf{3}]/[\mathbf{4}] = (k_a/k_r)[\mathbf{1}]_0$$

The value of k_a/k_r can then be easily calculated from the measured concentrations [**3**] and [**4**], determined using gas chromatography. The reaction of (1,1-dimethyl-2-bromoethyl)-benzene with **1** was performed with several different concentrations (0.1, 0.2, 0.3 and 0.4 mol l^{-1}) of **1** at different temperatures

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Table 1 Experimental values of the rate constant k_a of addition of primary alkyl radicals to the double bond of allyldibutyl-4,7,10-trioxaundecylstannane **1** at several temperatures

T/K	$k_a/10^3$ l mol^{-1} s^{-1}
393[a]	63.1
	64.3
	57.6
	65.0
353[a]	13.1
	10.0
	11.9
	9.1
313[a]	1.36
	1.6
	1.49
	1.72
273[b]	0.229
	0.258
	0.214
	0.266

[a] Measurements in benzene. [b] Measurements in decane.

Table 2 Experimental values of the rate constant k_b of addition of primary alkyl radicals to the double bond of (2-ethoxycarbonylprop-2-enyl)dibutyl-4,7,10-trioxaundecylstannane **2** at several temperatures

T/K	$k_b/10^5$ l mol^{-1} s^{-1}
393[a]	15.0
	16.0
	12.3
	13.5
353[a]	9.75
	9.55
	8.39
	10.25
313[a]	2.98
	2.27
	3.29
	2.89
273[b]	0.578
	0.513
	0.509
	0.639

[a] Measurements in benzene. [b] Measurements in decane.

in the range 0 to 120 °C. The rate constant of addition, k_a, could then be calculated at the various temperatures (Table 1) taking into account that the rate constant of the neophyl rearrangement[8] (k_r) is:

$$\log (k_r/\mathrm{s}^{-1}) = 11.6 - (49.4/\theta) \text{ with } \theta = 2.303RT \text{ in kJ mol}^{-1}$$

The plot of log k_a *versus* $1/T$ gave a good agreement with an Arrhenius relationship ($r^2 = 0.99$) between these two variables leading to the following values for the activation parameters: log (A/l mol^{-1} s^{-1}) = 10.2 ± 0.4, E_a = 41.2 ± 2.6 kJ mol^{-1}.

For the reactions performed at 0 °C, decane was used in place of benzene which freezes at this temperature. It was verified at 80 °C that, as shown previously for the dibutyl-4,7,10-trioxaundecylstannane,[2] there was no solvent effect upon the reaction selectivity.

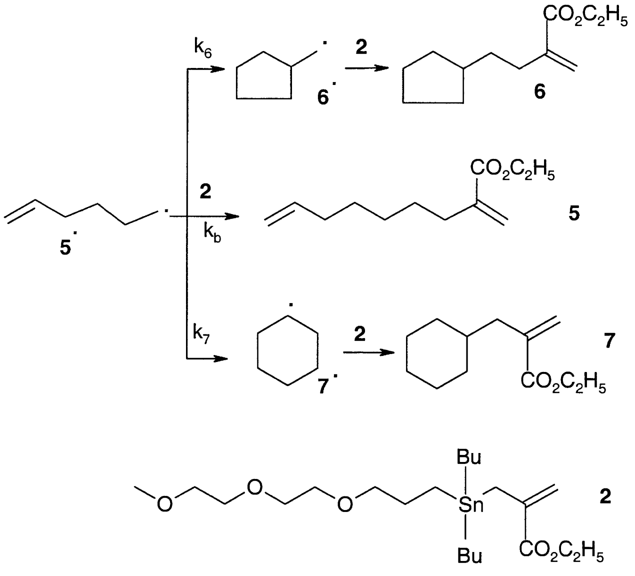
Kinetic study of the addition of primary alkyl radicals to (2-ethoxycarbonylprop-2-enyl)dibutyl-4,7,10-trioxaundecylstannane 2

On the basis that the rate constant of addition of alkyl radicals to the double bond of **2** (k_b) is of the same order of magnitude as that for addition to methacrylic acid,[9] we selected the hex-5-enyl radical rearrangement as a clock reaction.[6] Assuming a concentration of the allyltin **2** close to its initial value (less than 10% conversion), the classical kinetic treatment of the competition, depicted in Scheme 2, led to the following equation:

$$([\mathbf{6}] + [\mathbf{7}])/[\mathbf{5}] = (k_6 + k_7)/k_b[\mathbf{2}]_0$$

The ratios of the rate constants $(k_6 + k_7)/k_b$ were determined at each temperature from the values of the concentration of the reaction products **5**, **6**, and **7** measured by GC for the reaction performed with different initial concentrations (0.1, 0.2, 0.3 and 0.4 mol l^{-1}) of **2**. The knowledge of k_6[10] and k_7[11] [log (k_6/s^{-1}) = 10.4 − 28.6/θ and log (k_7/s^{-1}) = 9.9 − 36.0/θ with $\theta = 2.303RT$ in kJ mol^{-1}] allowed the calculation of the values of k_b (Table 2). In the case of the reactions performed at 0 °C, benzene was replaced by decane as above.

The plot of log k_b *versus* $1/T$ showed a good Arrhenius relationship ($r^2 = 0.99$) between these two variables leading to the determination of the activation parameters of the addition of primary alkyl radicals to **2**: log (A/l mol^{-1} s^{-1}) = 9.2 ± 0.3, E_a = 23.1 ± 1.9 kJ mol^{-1}.



Scheme 2

Discussion

The rate constant of addition of primary alkyl radicals to the double bond of **1** at 80 °C, about 1.3 × 10^4 l mol^{-1} s^{-1}, is not significantly different from the estimated value for the homologous reaction involving allyltri-*n*-butylstannane[7] (4 × 10^4 l mol^{-1} s^{-1}). This shows that **1** is a good substitute for allyltri-*n*-butylstannane, with the advantage of an easier separation from the organic reaction products. The influence of the polar tail on the reactivity of an "acrylic stannane" is difficult to determine because there is no previous measurement of the rate constant of addition of primary alkyl radicals to such unsaturated stannanes.

Taking into account the competition for the primary alkyl radicals between the addition to the allylstannane (**1** or **2**) and to the corresponding allylated derivatives (**3**, **4** or **5**, **6** and **7**), it would be of interest to compare the rate constants determined in this study with those given for the addition of primary alkyl radicals to 1-alkenes. The review of Fischer and Radom is a reference for reaction rates of addition of alkyl radicals to double bonds.[12] To our knowledge, there is no available value for such reactions of addition relative to primary radicals. Although it may be questionable to compare the reactivity of methyl, *tert*-butyl and primary alkyl radicals with a vinylic

Table 3 Rate constants of addition of alkyl radicals to double bonds of **1**, **2**, 1-alkenes and methyl methacrylate (MMA)

	k/l mol^{-1} s^{-1}
$R_{prim}^{\bullet}$ + **1**	1×10^3
$Me^{\bullet}$ + 1-alkene[12]	7.6×10^3
t-$Bu^{\bullet}$ + 1-alkene[12]	1.1×10^3
$R_{prim}^{\bullet}$ + **2**	1.5×10^5
$Me^{\bullet}$ + MMA[12]	4.9×10^5
t-$Bu^{\bullet}$ + MMA[12]	6.6×10^5

double bond, one can see in Table 3 that the values of the rate constants of addition are of the same order of magnitude at, or near, room temperature. The same conclusion can be drawn from the comparison involving methacrylic derivatives and alkyl radicals (Table 3). Similar values are also obtained at about 70 °C for the rate constants of addition of hex-5-enyl radicals to methacrylic acid[9] and **2** (about 7×10^5 l mol^{-1} s^{-1}). These results do not agree with the experimental results.[5] Indeed, in the course of the reaction of allylstannanes with bromoalkanes, despite the existence of such a competition, the allylated derivatives were produced with fair yields.[5] According to Curran *et al.*,[7] allylstannanes must be at least one order of magnitude more reactive toward alkyl radicals than simple alkenes to explain the experimental results. The good agreement between the various determinations of the rate constants of addition of primary alkyl radicals to the different allylstannanes is in favour of the validity of these measurements by clock reactions.

Estimation of the rate constant at different temperatures can readily be made using the Arrhenius equation. Fischer and Radom[12] have suggested a value for log (A/l mol^{-1} s^{-1}) of 8.5 ± 0.5 in the addition of primary alkyl radicals to a terminal double bond. The values of log (A/l mol^{-1} s^{-1}) obtained in the present work, respectively 10.18 and 9.19, are quite a way from this recommended value. The determination of the activation parameters of a reaction by the measurement of rate constants on a relatively small domain of temperature could lead to erroneous results, even with relatively accurate values of the rate constants, which could be the case here. Therefore, we decided to reconsider the treatment of our results (values of Tables 1 and 2) including this value [$1/T = 0$, log (k/l mol^{-1} s^{-1}) = log (A/l mol^{-1} s^{-1}) = 8.5] in the linear regression of log k_a and log k_b *vs.* $1/T$. On the basis of this analysis, we would like to recommend the following Arrhenius relationships to estimate the rate constant of the addition of primary alkyl radicals to **1** and **2**:

$$\log (k_a/\text{l mol}^{-1}\,\text{s}^{-1}) = 8.6 \pm 0.9 - (32.1 \pm 5.9)/\theta \text{ with } \theta = 2.303RT \text{ in kJ mol}^{-1}$$

$$\log (k_b/\text{l mol}^{-1}\,\text{s}^{-1}) = 8.5 \pm 0.3 - (19.1 \pm 2.6)/\theta \text{ with } \theta = 2.303RT \text{ in kJ mol}^{-1}$$

Conclusion

The replacement of a butyl by a 4,7,10-trioxaundecyl group on the tin atom of an allyltributylstannane does not significantly change the rate of addition of a primary alkyl radical to a double bond. Therefore, compounds **1** and **2** should be useful in the replacement of the halogen atom in alkyl bromide by prop-2-enyl and 2-ethoxycarbonylprop-2-enyl entities, affording a facile separation of the pure organic products from the stannic compounds. The knowledge of the rate of the addition reactions to the double bonds of these stannanes will allow integration of these sequences in cascade synthetic reactions.

Experimental

^{1}H NMR spectra were recorded at 250 MHz in $CDCl_3$ solutions with $Si(CH_3)_4$ as an internal standard using a BRUKER AC 250 spectrometer. ^{13}C NMR spectra were recorded at 62.9 MHz. Data are reported as δ-values (ppm) and coupling constants (J/Hz).

GC studies were performed with a VARIAN 3400 coupled to a SPECTRAPHYSIC CHROMJET integrator. The capillary column used was DB1 type (5% Ph), 30 m in length, 0.25 mm inner diameter with a film thickness of the stationary phase of 0.25 µm, while the carrier gas was nitrogen (0.5 bar as flow rate).

GC-MS were recorded with a Varian Saturn GC/MS 4D coupled with a Varian 3400 CX gas chromatography apparatus.

Solvents were used without purification when the degree of purity was high enough or distilled according to the appropriate procedure.

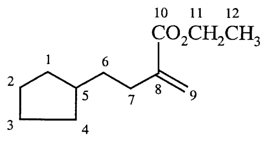
Syntheses

Allyldi-*n*-butyl-4,7,10-trioxaundecylstannane **1** and (2-ethoxycarbonylprop-2-enyl)di-*n*-butyl-4,7,10-trioxaundecylstannane **2** were prepared according to a procedure described previously.[5] (2-Bromo-1,1-dimethylethyl)benzene was synthesized from the commercially available chloride *via* the reaction of its Grignard reagent with bromine. 6-Bromohex-1-ene was purchased from Aldrich. Bromomethylcyclopentane was prepared from cyclopentylmethanol with phosphorus tribromide.

5-Methyl-5-phenylhex-1-ene **3** was obtained by condensation of allylbromide with the Grignard reagent made from 1-chloro-2-methyl-2-phenylpropane.[13]

4,4-Dimethyl-5-phenylpent-1-ene **4** was prepared according to a literature procedure.[14]

The free radical reaction of (2-ethoxycarbonylprop-2-enyl)-di-*n*-butyl-4,7,10-trioxaundecylstannane (1.8 g, 3.55 mmol) and bromomethylcyclopentane (0.5 g, 3.06 mmol), initiated by BEt_3–O_2 at room temperature, produced ethyl 2-(2-cyclopentylethyl)prop-2-enoate **6** using a procedure described previously.[5] The product was isolated after chromatography over silica (petroleum ether–ether 95 : 5) with a yield of 60%. This compound was previously prepared in a different way.[15]



^{1}H NMR δ (250 MHz, $CDCl_3$, Me_4Si): 6.1 and 5.4 (2s, 2 H, C^9H_2), 4.2 (q, J 7.1, 2 H, $C^{11}H_2$), 2.3 (t, J 7.0, 2 H, C^7H_2), 1.2 (t, J 7.1, 3 H, $C^{12}H_3$), 1.8–0.7 (m, 11 H, cycle H and C^6H_2); ^{13}C NMR δ ($CDCl_3$): 167.3 (C^{10}), 141.3 (C^8), 123.8 (C^9), 60.4 (C^{11}), 39.7 (C^5), 25.1, 31.0, 32.5 and 34.9 (C^1, C^2, C^3, C^4, C^6 and C^7), 14.1 (C^{12}).

Ethyl 2-(cyclohexylmethyl)prop-2-enoate **7** was prepared earlier by our group.[16]

Synthesis of ethyl 2-methylenenon-8-enoate **5** was achieved by the reaction of (2-ethoxycarbonylprop-2-enyl)di-*n*-butyl-4,7,10-trioxaundecylstannane **2** used in excess with 6-bromohex-1-ene according to the following procedure.

In a flask containing (2-ethoxycarbonylprop-2-enyl)di-*n*-butyl-4,7,10-trioxaundecylstannane **2** (3 g, 5.91 mmol), 6-bromohex-1-ene (0.19 g, 1.18 mmol) in 2 ml of anhydrous benzene and 2 ml of a molar solution of triethylborane in hexane were simultaneously added over 3 hours using two syringe pumps. Chromatography over a silica column (petroleum ether–ether 98 : 2) did not allow separation of ethyl 2-methylenenon-8-enoate **5**, the major product, from ethyl 2-(2-cyclopentylethyl)prop-2-enoate **6**. The former was identified by GC-MS: m/z 123 ($[CH_2{=}CH(CH_2)_5C{=}CH_2]^+$, 90%), 95

($[CH_2=CH(CH_2)_3C=CH_2]^+$, 34%), 81 ($[CH_2=CH(CH_2)_2CH=CH_2]^+$, 100%).

Kinetic studies

The kinetic studies were performed according to the following procedure.

A solution of 0.5 mmol of (2-bromo-1,1-dimethylethyl)-benzene, 0.05 mmol of AIBN and 0.35 mmol of a suitable GC reference in anhydrous benzene was made up to 5 ml in a volumetric flask and a sample of 1 ml was placed in a Schlenck tube. A 0.1 M solution of **1** in anhydrous benzene was similarly prepared, and a 1.0 ml sample in a small tube was carefully placed in the Schlenck tube. The contents of the Schlenck tube were degassed by three freeze–pump–thaw cycles, heated to the desired temperature for 5 min and then mixed. After a suitable time (10–60 min) the mixture was analysed by GC.

The activation parameters of the addition of primary alkyl radicals to the double bonds of **1** and **2** were obtained from the linear regression of log k *vs.* $1/T$ using EXCEL 2000 for the PC (confidence level of 95%).

Acknowledgements

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