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Reactions of allyloxy(methoxy)carbene in solution. Carbene rearrangement and Claisen rearrangement of the carbene dimer

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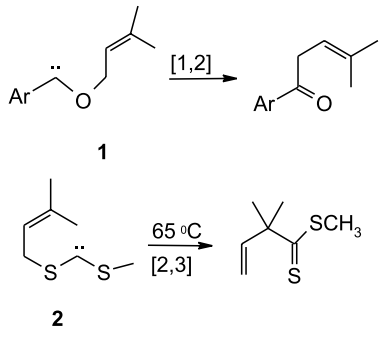
Abstract—Allyloxy(methoxy)carbene, with and without deuterium in the α-position of the allyloxy group, was generated in benzene at 50 and at 110 °C. At the higher temperature, the carbene fragmented to allyl and methoxycarbonyl radicals that subsequently coupled. At the lower temperature, most of the carbene dimerised. The structure of the major product and the distribution of deuterium indicated that the dimer underwent Claisen rearrangement at 50 °C to methyl 2-allyloxy-2-methoxy-4-pentenoate. Facile rearrangement of the dimer was supported by the results of a computation which placed the barrier at about 18 kcal mol^{-1}.

1. Introduction

Both [1,2]- and [2,3]-sigmatropic rearrangement of allylic, heteroatom carbenes, as well as radical-pair formation, are known. In 1977 and 1978, Iwamura and co-workers[1] ascribed rearrangement of aryl(4,4-dimethylallyloxy)carbenes (**1**) to a [1,2] shift, Scheme 1. In 1972, Baldwin and Walker[2] showed that *S*-methyl-(3,3-dimethylallyl)carbene (**2**) undergoes a clean [2,3] sigmatropic rearrangement to a dithiocarboxylic acid methyl ester at 65 °C, Scheme 1. In the same year, Hoffmann and co-workers[3] published a detailed study of the gas phase thermolysis of **3a** and **3b**, at 250 °C, Scheme 2. They concluded that a sequential carbene (**4**)/radical pair (**5**) mechanism best accounted for their results.



Scheme 1.

We had shown[4] that two phenyl-substituted allyloxy-(methoxy)carbenes (e.g., **6**) fragment to radical pairs in benzene at 110 °C, Scheme 3. Carbene **6**, and the isomeric species with Ph at the terminus of the double bond, favored the product from apparent 1,2-migration. Although it was evident that some, but not all, of the product could have come from concerted 1,2-rearrangement, it was unclear whether the product distribution reflected some sigmatropic rearrangement or whether it could also be explained in terms of a concurrent radical-pair mechanism, with a cage effect operating in solution. Very rapid radical-pair coupling, in systems that do not involve a molecule, such as N_2, between the initially-formed radicals, might occur without complete rotational equilibration, favoring re-attachment at the allylic site originally bonded to oxygen. Such coupling would be indistinguishable from concerted [1,2]-migration. [1,2]-Migration is theoretically unfavorable in comparison with [2,3]-sigmatropic rearrangement, but it can eclipse the latter if steric demand is high.[1]

In the gas phase study of Hoffmann and co-workers, a cage effect could not operate and it was pointed out that the high temperature (250 °C) favored the radical-pair mechanism on the grounds of entropy.[3]

We decided to examine the rearrangement of allyloxy-(methoxy)carbene with precursors **7a–d** (Scheme 4), from which **4a** and **4b** can be generated in solution at 110 °C (**7a**,

Keywords: Allyloxy(methoxy)carbene; Carbene dimer; Claisen; Rearrangement.
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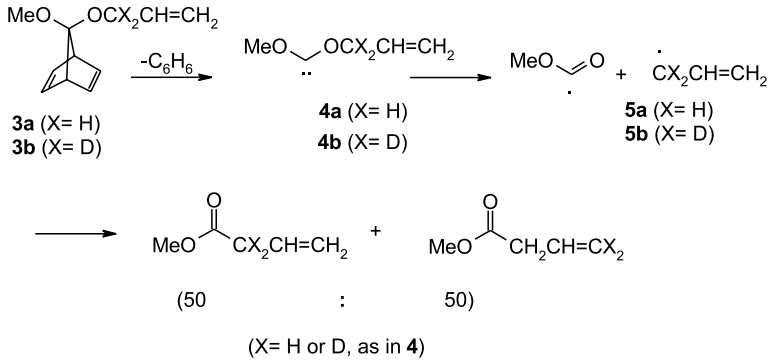
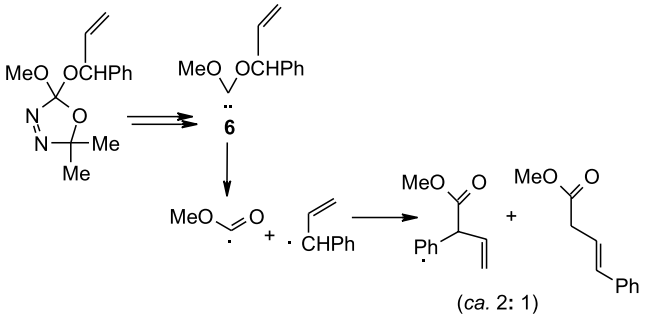
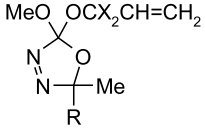


Scheme 2.



Scheme 3.



7a: R= Me, X= H)
b: R= Me, X= D)
c: R= p-MeOC$_6$H$_4$, X = H)
d: R= p-MeOC$_6$H$_4$, X= D)

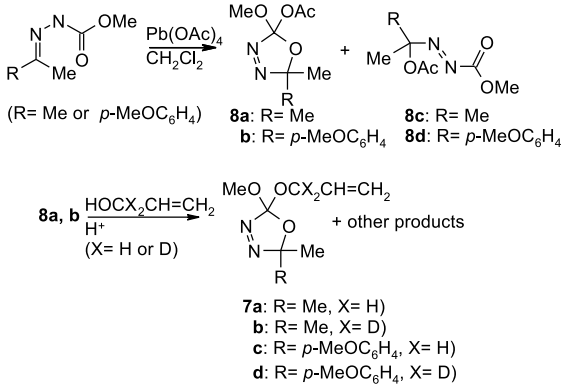
Scheme 4.

7b) or 50 °C (**7c**, **7d**). Sigmatropic rearrangement, as observed by Baldwin and Walker,[2] might well become a competitive (or exclusive) process for **4**, especially at the lower temperature, given that fragmentation should be less likely than was the case with the phenyl-substituted allyloxycarbenes, such as **6**, which were studied previously.[4]

Results of that study, as well as Claisen rearrangement of 1,2-diallyloxy-1,2-dimethoxyethene under relatively mild conditions, are reported.

2. Methods, results, and discussion

2-Allyloxy-2-methoxy-5,5-dimethyl-Δ^3-1,3,4-oxadiazoline (**7a**) and the dideuterio analogue (**7b**), as well as the corresponding 5-methyl-5-(*p*-methoxyphenyl) compounds, **7c** and **7d** were prepared by the route[5] shown in Scheme 5. Compound **7a** was thermolysed at 110 °C, in ordinary



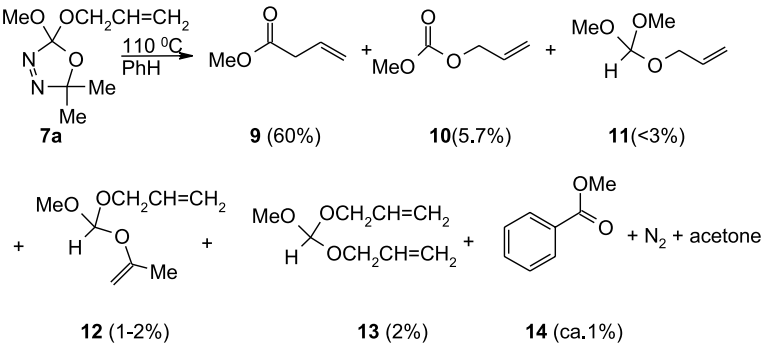
Scheme 5.

benzene and in carefully dried benzene, in a sealed tube to determine the effects of adventitious water. *tert*-Butyl alcohol, or the stable free radical TEMPO, were added in separate experiments to ascertain whether both a carbene and radicals could be trapped. After 24 h, the solutions were analyzed by gas chromatography.

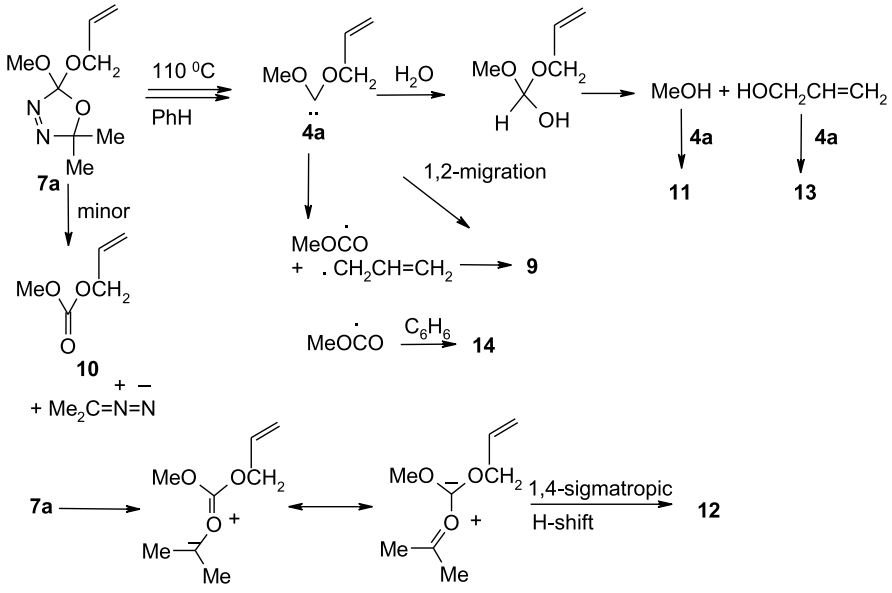
3. Thermolysis of 7a in ordinary benzene

A solution of **7a** in dry benzene at 110 °C for 24 h gave one major product and several minor products noticeable by GC. Thinking that some of those could be caused by adventitious water, we ran the reaction in ordinary benzene which gave, in addition to a solvent peak, six fractions large enough to be collected by GC. Yields from reactions in ordinary benzene are not relevant because such reactions were used only to identify the minor components that were always detectable by GC. Fraction one, not collected, contained benzene and, presumably, acetone and other volatile products. Fractions 2–7 were methyl 3-butenoate (**9**), methyl 2-propenyl carbonate (**10**), allyl dimethyl orthoformate (**11**), allyl methyl 2-propenyl orthoformate (**12**), diallyl methyl orthoformate (**13**) and methyl benzoate (**14**). Yields in Scheme 6 pertain to reaction in dry benzene (distilled from CaH_2); conditions for detecting but not isolating **11** and **13**.

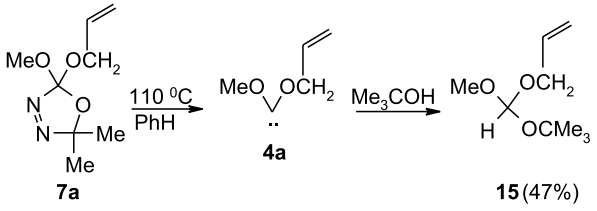
Probable origins of products **9**–**14**, orthoformates **11** and **13** coming from capture of the carbene by adventitious water, are shown in Scheme 7. Formation of carbonates, such as **10**, is a known process in the thermolysis of oxadiazolines



Scheme 6.



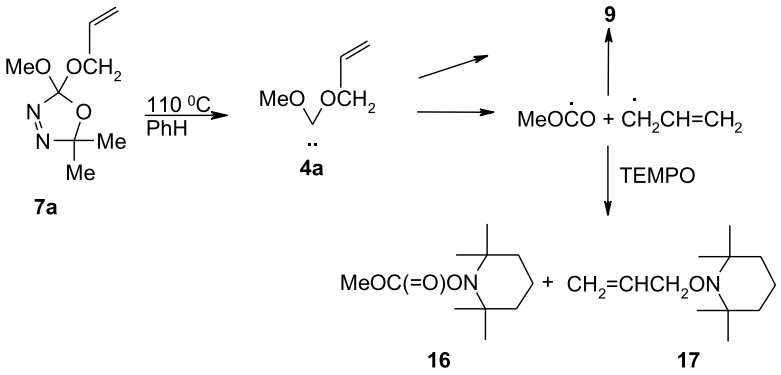
Scheme 7.



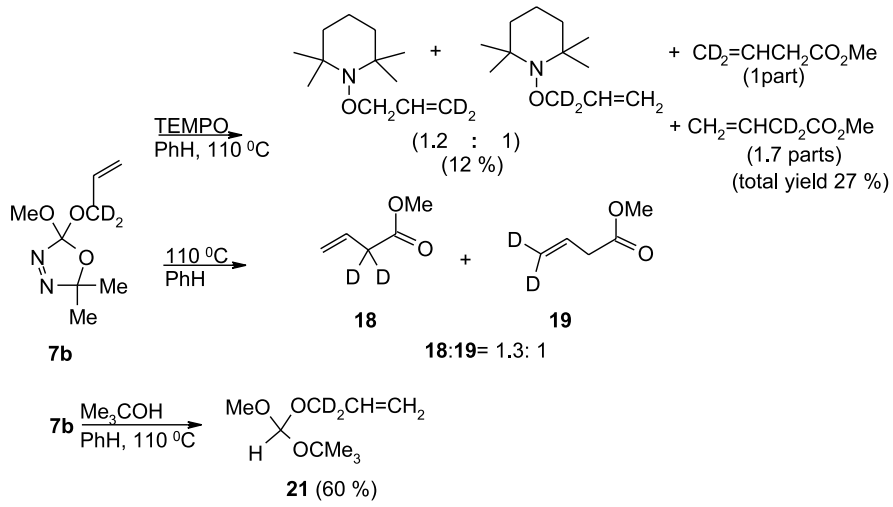
Scheme 8.

analogous to **7a**[6] and the [1–4] sigmatropic shift to afford **12** is a known reaction of carbonyl ylides, particularly in acetoxy analogues.[7,8] Methyl benzoate (**14**) is formed by attack of the methoxycarbonyl radical on benzene.

Thermolysis of **7a** in the presence of *tert*-butyl alcohol gave allyl *tert*-butyl methyl orthoformate (**15**), in support of the intermediacy of carbene **4a**, Scheme 8.



Scheme 9.

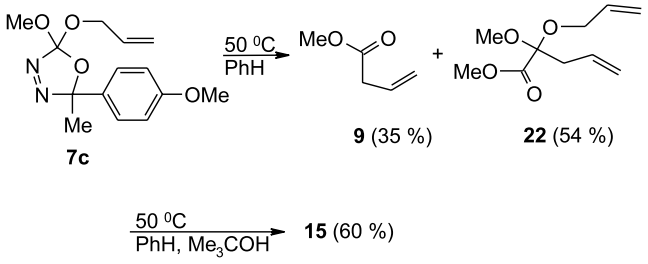


Scheme 10.

Thermolysis of **7a** in the presence of TEMPO and collection by GC afforded the known adducts of the methoxycarbonyl[4b,9] and allyl[10] radicals, **16** and **17**, respectively, Scheme 9. Yields of **16** and **17** were 13 and 18%, respectively. Methyl 3-butenoate (**9**, 17%) was also obtained.

Thermolysis of **7b** at 110 °C gave **18** (1.3 parts) and **19** (1 part), Scheme 10. With added TEMPO, adducts of deuterated allyl and TEMPO (12%, 1 part α- to 1.2 parts γ-deuterated) were obtained as well as deuteriated methyl butenoates (27%, 1.7 parts α- to 1 part γ-deuteriated). Thermolysis of **7b** in the presence of *tert*-butyl alcohol gave **21** (60%), in which all of the deuterium was alpha.

In contrast, at 50 °C, **7c** gave methyl-3-butenoate (**9**) (35%) and **22** (54%), while in the presence of *tert*-butyl alcohol it afforded **15** (60%), Scheme 11. Under the same conditions, **7d** gave **18**, **19**, and **24**, Scheme 12. In the presence of TEMPO, **7c** and **7d** afforded only trace amounts of adducts **16** and **17** (presumably D-labeled from **7d**).

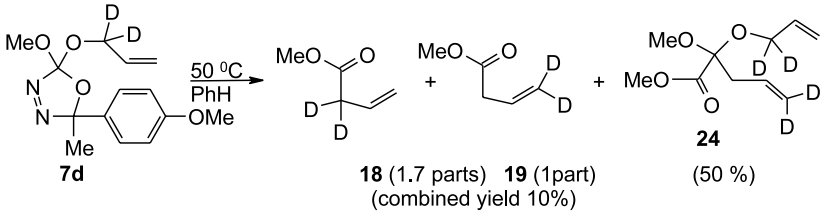


Scheme 11.

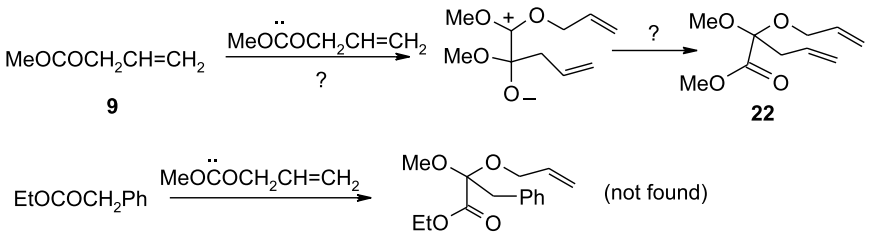
We interpret the high temperature results as follows. First, we can dismiss compounds **10**–**14**, Scheme 6, because they are really minor when dry benzene is used and we know their origins (Scheme 7). Second, we know that allyloxy(methoxy)carbene is formed from **7a**,**b** because that carbene can be captured by *tert*-butyl alcohol. Third, a part of the carbene from **7a** undergoes scission to a radical pair if it is not trapped quickly, as indicated by the finding of methyl benzoate (Scheme 6) and the TEMPO adducts of the methoxycarbonyl and allyl radicals (Scheme 9). The low yields of the TEMPO adducts suggests that methyl 3-butenoate (**9**) arises largely by sigmatropic or 1,2-migration in the carbene. Efficient, in cage radical coupling, relative to radical separation, cannot be ruled out because TEMPO would not trap radicals that are not separated by diffusion.

Thermolysis of **7b** in the presence of TEMPO (Scheme 10, top) gave a 1.7:1 ratio (α- to γ-deuteriated) of ester products rather than the 1:1 ratio observed by Hoffmann et al.[3] in their gas-phase study. This result implies that in concerted processes [1,2]- is favored over [2,3]-rearrangement. The allyl fragments captured by TEMPO are nearly equally deuteriated at the α- and γ-positions, as expected. Those adducts are expected to form in 1:1 ratio and we cannot explain the apparent 1.2:1 ratio obtained from the ^{2}H NMR spectra.

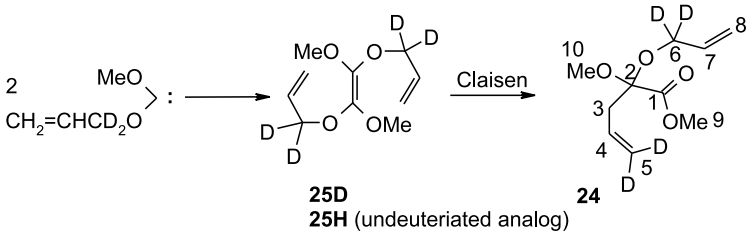
In the absence of TEMPO, where radical processes compete (Scheme 10, center) the ester ratio was down from 1.7:1 to 1.3:1, implying that the portion of ester from radical coupling is formed in a ratio closer to the 1:1 ratio expected from radicals separated by diffusion. If we assume that



Scheme 12.



Scheme 13.



Scheme 14.

TEMPO captures essentially all of the diffusion-separated radicals, then 1.7:1 represents the ratio of the methyl 4-butenoates arising from in-cage coupling, or the net effect of 1,2-migration superimposed on in-cage coupling. A cage effect, favoring coupling of the methoxycarbonyl- and the allylic radical at the allyl site originally bonded to the carbene oxygen, had been observed before,[4] in a system more likely than **7b** to react by the radical pair mechanism. The analysis cannot be more detailed because we do not know what fraction of the radicals is not scavenged by TEMPO but leads to methyl 3-butenoate without ever becoming free. Alternatively, there could be some 1,2-migration in the carbene, in competition with radical-pair formation. What is certain is that there is a radical pair component and that sigmatropic rearrangement, as observed by Baldwin[2] for a thio analogue, can be ruled out as the major mechanism because it would have led primarily to **19**.

At the lower temperature available with **7c**, fragmentation of carbene **4a** to radicals was barely detectable, as indicated by the negligible yields of TEMPO adducts. The carbene was still formed, as indicated by the formation of **9** as well as the trapping with *tert*-butyl alcohol, Scheme 11. We were surprised to find **22**, a strikingly-new product that we had never seen at the higher temperature required to thermolyze **7a**. A simple rationale for compound **22**, based on the precedented ring expansion when strained carbonyl compounds are treated with dimethoxycarbene,[11] is shown in Scheme 13. That result might follow if fragmentation (and rearrangement) of the carbene were slow at 50 °C, permitting it to accumulate sufficiently to attack **9** by addition to carbonyl carbon. Although the mechanism had attractive features, it would be surprising if the nucleophilic carbene **4a** were to add efficiently to the carbonyl group of **9**. This simple explanation lost credence when it was found that inclusion of ester **9** at the outset actually decreased the yield of **22**. Moreover, inclusion of ethyl phenylacetate did not lead to even a trace of the product of carbene attack on that ester, Scheme 13.

These results led us to look for a new mechanism for the formation of **22**. One could arrive at that structure by means of a Claisen rearrangement of the dimer of **4a**, which is an allyl vinyl ether twice over, Scheme 14. The dimer was not observed, but that is not surprising in view of the large substituent effects on rearrangement rates. For example, an alkoxy substituent at C-2 can lead to facile rearrangement at about 35 °C.[12] Coupling of two α-deuteriated carbenes, followed by Claisen rearrangement, would lead to **24** with α-deuterium in the allyloxy group and γ-deuterium in the allyl group, as shown in Scheme 14. That was shown to be the case with the ^{1}H NMR spectrum. Whereas the ^{1}H NMR spectrum of **22** has the α-CH_2 signal of the $OCH_2CH{=}CH_2$ group at 3.96 and 4.06δ, the spectrum of **24** did have any absorption at that position, indicating that the allyloxy group in **24** was $OCD_2CH{=}CH_2$. Moreover, whereas **22** has the terminal vinyl signals of the $CCH_2CH{=}CH_2$ group at 5.12 and 5.14δ, that of **24** did not absorb in that region, indicating that its C-allyl group was $CH_2CH{=}CD_2$. The rest of the signals from **24** were in agreement with that structure, taking into account the effects of deuterium. These results are in keeping with coupling of the carbene to generate a tetraalkoxyethene and sigmatropic Claisen rearrangement of the latter. Coupling of dialkoxycarbenes that do not rearrange fast has been observed before[13] and all that is required in this case is that both concerted rearrangement and fragmentation to radical pairs be slow at 50 °C.

4. Computational studies

The Claisen rearrangement of carbene dimer **25H** to **22** was modeled with Gaussian 03[14a] at the DFT level of theory using the Becke3PW91 functional.[14b,c] The optimized equilibrium geometry of **25H** and transition state **25H-TS** for its rearrangement were obtained at the B3PW91/6-31+G(d) level using the default convergence criteria.

Frequency calculations were performed to characterize **25H** and **25H-TS**. The latter, as expected, exhibited one

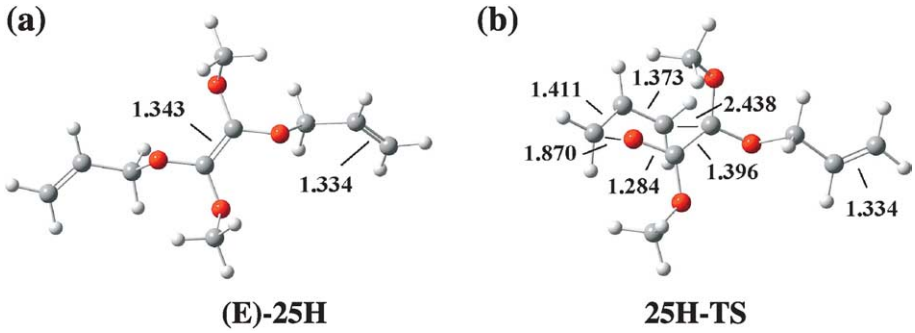


Figure 1. Geometrical structures of (a) (*E*)-1,2-diallyloxy-1,2-dimethoxyethene (**25H**) and (b) transition state (**25H-TS**) for [3,3] Claisen rearrangement of (*E*)-**25H** with selected inter-nuclear distances in angstroms.

Table 1. Thermochemical data for [3,3] Claisen rearrangement of (*E*)-1,2-diallyloxy-1,2-dimethoxyethene at the B3PW91/6-31+G(d) level

Compound	E_{elec}[a]	E_o (E_{elec}+ZPE)[a]	H[a,b] (E+RT)	G[a,c]
25H	−691.213958	−690.964018	−690.945705	−691.012480
25H-TS	−691.184465	−690.936315	−690.918880	−690.981539
Barrier (kcal mol^{-1})	18.50	17.38	16.84	19.41

[a] In hartrees.
[b] Corrected to 298.15 K. $E=E_o+E_{vib}+E_{rot}+E_{trans}$.
[c] Corrected to 298.15 K. $G=H-TS$.

imaginary frequency (−432.0 cm^{-1}). Moreover, animation of the vibration showed that it connected the reactant to the product. The conformations of (*E*)-**25H** and **25H-TS** (the transition state for the [3,3] sigmatropic rearrangement) that were used in calculating the barrier are displayed in Figure 1 and the thermochemical data are listed in Table 1. The Claisen transition state **25H-TS** is chair-like, but it is quite unsymmetrical. The C–C bond (2.438 Å) being formed is significantly longer than the C–O bond (1.870 Å) being broken. That barrier is in the region of 17–18 kcal mol^{-1} and is in good accord with the facile reaction observed experimentally; formation and rearrangement of the dimer in benzene was complete (NMR) at 50 °C in 24 h.

5. Conclusions

The reactions exhibited by allyloxy(methoxy)carbene in solution are very temperature dependent. At 110 °C, a fraction of the carbene fragments to a radical pair that couples to afford methyl 3-butenoate. Alpha deuteriated carbene ($MeOCOCD_2CH{=}CH_2$) rearranges with a preference for methyl 2,2-dideuterio-3-butenoate, suggesting incomplete rotational equilibration (a cage effect) in the radical pair and/or some competition from a 1,2-rearrangment.

At 50 °C, fragmentation to a radical pair is not important (an entropic effect) and it appears that unimolecular reactions are slow enough to permit the carbene to dimerise. A major product (**22**) is one attributed to Claisen rearrangement of the carbene dimer (**25**). The low barrier (17–18 kcal mol^{-1}) computed at the DFT level provides support for the conclusion that **22** is formed via Claisen rearrangement of the carbene dimer **25**.

6. Experimental

6.1. General

Allyl compounds of the type $XCH_2CH{=}CH_{cis}H_{trans}$, in general, have low field ^{1}H NMR spectra in which H_{cis} and H_{trans} appear as doublets. At high field or in expanded-scale low field spectra, those doublets are split further, to show geminal coupling, for example. Many of the spectra below are simplified, to have the appearance of low field spectra although a signal described as a doublet can actually look more complex if it is expanded.

^{1}H NMR spectra were obtained from solutions in C_6D_6, or in $CDCl_3$, with Bruker spectrometers operating at 200 or 600 MHz, unless otherwise indicated, and are referenced to the signal at 7.16 attributed to C_6HD_5 or to $CHCl_3$ at 7.26 ppm. ^{2}H NMR spectra were obtained at 92.1 MHz and are referenced to natural abundance deuterium in the benzene or chloroform solvent. ^{13}C NMR spectra, run at 50.9 or 150.9 MHz, in C_6D_6 or in $CDCl_3$, are referenced to the center line of the solvent triplet at 128.1 or 77.2 ppm, respectively. Mass spectra were run with a Micromass/Waters GCT time of flight instrument. 2,2-Dialkoxyoxadiazolines generally do not afford molecular ions in the mass spectrometer under any conditions and it was not possible to get high resolution data for compounds **7a**–**7d**. By NMR spectroscopy, they were >95% pure.

GC separations were performed with a 6′×4.0 mm (internal) column containing 10% OV 101. The helium flow rate was 40 mL min^{-1} and the temperature program was 60 °C for 3 min, then 5 °C per minute to 200 °C. Infrared spectra were taken with neat samples on a Bruker Tensor 27 FTIR instrument equipped with a Harrick ATR accessory and a ZnSe crystal.

6.1.1. 2-Acetoxy-2-methoxy-5,5-dimethyl-Δ^3-1,3,4-oxadiazoline (8a). This compound has been reported.[16a]

6.1.2. 2-Acetoxy-2-methoxy-5-(4-methoxyphenyl)-5-methyl-Δ^3-1,3,4-oxadiazoline (8b) (single isomer, purified by column chromatography). IR (cm^{-1}): 1747; ^1H NMR (600 MHz, $CDCl_3$) δ: 1.61 (s, 3H), 2.07 (s, 3H), 3.32 (s, 3H), 3.40 (s, 3H), 6.80 (d, $J=7.2$ Hz, 2H), 7.61 (d, $J=7.2$ Hz, 2H); ^{13}C NMR (50.9 MHz, C_6D_6) δ: 20.8, 25.0, 52.6, 54.8, 114.3, 124.5, 127.0, 128.9, 131.5, 160.3, 166.2.

6.1.3. Synthesis of 7a and 7b. To a solution of crude **8a** (7.32 g, ca. 4.7 g of pure **8a**) and 3.7 g of allyl alcohol (3.8 g of 1,1-dideuterioallyl alcohol) in methylene chloride (100 mL) was added *p*-toluenesulfonic acid (ca. 100 mg). The solution was stirred at room temperature for 3 days before it was washed twice with 50 mL of saturated $NaHCO_3$ solution and dried over $MgSO_4$. Evaporation of the solvent and column chromatography on SiO_2 with hexane (9 parts)/ethyl acetate (1 part) gave **7a** (**7b**) as colorless oils in 50–55% yield.

6.1.4. Synthesis of 7c and 7d. To a solution of $Pb(OAc)_4$ (12.4 g, 28 mmol) in methylene chloride (50 mL) was added, slowly at 0 °C, a solution of the methoxycarbonylhydrazone of 4-methoxyacetophenone (7.2 g, 28 mmol) in methylene chloride (30 mL).[15] The mixture was stirred at 0 °C for 7 h before it was washed with saturated $NaHCO_3$ solution and dried over $MgSO_4$. Evaporation of the solvent at 5–10 °C left a crude product that was a mixture of **8b** (ca 37%) and the acyclic isomer[13b,16] **8c**. To a solution of the mixture (6.0 g, 21 mmol) in 50 mL of methylene chloride was added 1.0 g of allyl alcohol, or 1,1-dideuterioallyl alcohol.[17] After 4 h of stirring at room temperature the solution was washed twice with 20 mL of saturated $NaHCO_3$ solution and dried with $MgSO_4$ before the solvent was evaporated at 5–10 °C. Column chromatography on 150 mL of SiO_2, with pentane (85 parts)/diethyl ether (15 parts) gave **7c** (**7d**) as pale yellow oils in about 49% yield. The diastereomers were not separated and the spectra that follow are those of the mixtures. It was possible to see the signals from the major diastereomer easily, but not all of the signals from the minor diastereomer were cleanly resolved. Isomer ratios were estimated from resolved signals.

Compound **7a**. ^1H NMR (200 MHz, C_6D_6) δ: 1.54 (s, 6H), 3.25 (s, 3H), 4.22–4.28 (m, 2H), 4.99 (d, $J=10.4$ Hz, 1H), 5.14 (d, $J=17.2$ Hz, 1H), 5.70– 5.89 (m, 8 lines, 1H); ^{13}C NMR (50.9 MHz, C_6D_6) δ: 23.9, 24.0, 51.7, 65.7, 116.6, 119.1, 134.1, 137.8; ^{13}C NMR (50.9 MHz, $CDCl_3$) δ: 24.0, 24.1, 52.0, 65.7, 117.2, 119.3, 133.4, 137.0. Similar oxadiazolines have absorptions at about 119 (C5) and at 137–138 (C2) ppm in their ^{13}C NMR ($CDCl_3$) spectra.[13c]

Compound **7b**. ^1H NMR (600 MHz, $CDCl_3$) δ: 1.55 (s, 3H), 1.56 (s, 3H), 3.25 (s, 3H), 5.18 (d, $J=10.4$ Hz, 1H), 5.30 (d, $J=17.2$ Hz, 1H), 5.91 (m, 1H); ^2H NMR (92.1 MHz, $CHCl_3$) δ: 4.21 (s), 4.28 (s); ^{13}C NMR (50.9 MHz, $CDCl_3$) δ: 24.1, 52.0, 117.5, 118.9 (C5), 119.3, 133.3, 137.0 (C2) (a signal from OCH_2, which would be expected at ca. 65 ppm, was absent); MS (ESI) (*m/z*): 211.1 $(M+Na)^+$, 187.1 $(M-H)^+$, 157.0 $(M-OMe)^+$.

Compound **7c** (*pale yellow oil*, *major diastereomer*, *ca. 75%*). ^1H NMR (200 MHz, C_6D_6) δ: 1.66 (s, 3H), 3.20 (s, 3H), 3.23 (s, 3H), 4.37 (t, $J=5.2$ Hz, 2H), 4.95 (d, $J=10.4$ Hz, 1H), 5.24 (d, $J=18.0$ Hz, 1H), 5.84 (m, 1H), 6.72 (d, $J=8.8$ Hz, 2H), 7.53 (d, $J=8.8$ Hz, 2H); ^{13}C NMR (150.9 MHz, $CDCl_3$) δ: 26.4, 52.2, 55.2, 65.9, 113.9, 117.3, 121.3, 126.5, 130.5, 133.6, 138.2, 159.8; minor diastereomer (ca. 25%); ^1H NMR (200 MHz, $CDCl_3$) δ: 3.39 (s, 3H), 4.19 (t, $J=6.1$ Hz, 2H), 4.90 (d, $J=10.5$ Hz, 1H), 5.17 (m, 1H), 5.76 (m, 1H); ^{13}C NMR (150.9 MHz, $CDCl_3$) δ: 26.2, 65.8, 117.0, 126.6, 130.3, 130.5, 133.2, 133.3 (4 signals not resolved).

Compound **7d** (*pale yellow oil*, *major diastereomer*, *ca. 72%*). ^1H NMR (600 MHz, $CDCl_3$) δ: 1.79 (s, 3H), 3.37 (s, 3H), 3.81 (s, 3H), 5.22 (d, $J=10.8$ Hz, 1H), 5.35 (d, $J=17.4$ Hz, 1H), 6.91 (d, $J=8.8$ Hz, 2H), 7.49 (d, $J=8.8$ Hz, 2H); ^2H NMR (92.1 MHz, $CHCl_3$) δ : 4.38; ^{13}C NMR (150.9 MHz, $CDCl_3$) δ: 26.4, 52.2, 55.2, 113.9, 117.3, 121.3, 126.5, 130.5, 133.6, 138.2, 159.8; minor diastereomer (ca. 28%): ^1H NMR (600 MHz, $CDCl_3$) δ: 1.69 (s, 3H), 3.60 (s, 3H), 5.13 (d, $J=10.8$ Hz,1H), 5.21 (d, $J=17.4$ Hz, 1H), 5.83 (m, 1H) (2 signals not resolved); ^2H NMR (92.1 MHz, $CHCl_3$) δ: 4.12; ^{13}C NMR (150.9 MHz, $CDCl_3$) δ: 26.2, 67.8, 113.9, 117.0, 126.6, 130.3, 133.2 (5 signals not resolved).

Compound **8d** (*yellow oil*). IR (cm^{-1}) 1765; ^1H NMR (200 MHz, C_6D_6) δ: 1.73 (s, 3H), 2.01 (s, 3H), 3.21 (s, 3H), 3.22 (s, 3H), 6.72 (d, $J=8.8$ Hz, 2H), 7.48 (d, $J=8.8$ Hz, 2H); ^{13}C NMR (150.9 MHz, C_6D_6) δ: 21.9, 24.2, 55.1, 55.4, 102.0, 114.2, 127.3, 130.8, 159.9, 162.0, 168.6.

6.1.5. Thermolysis of 7a in dry benzene. A solution of **7a** (239 mg, 1.5 mmol) in ordinary benzene (1 mL) at 110 °C for 24 h gave six products that were collected directly by GC. Yields were estimated from calibration graphs prepared by injection of benzene solutions of **9**, **10** and **11** and each yield was estimated from 2 or more runs.

6.1.6. Methyl 3-butenoate (9).[18] Yield 60%. ^1H NMR (200 MHz, C_6D_6) δ: 2.77 (d of t, 2H); 3.27 (s, 3H), 4.86–4.98 (m, 2H), 5.78–5.97 (m, 1H). MS (EI) *m/z*: 100 (M^+, 80%), 59 (96%), 41 (100%). The NMR spectrum matched that of an authentic sample of the ester, prepared by treating 3-butenonitrile with methanol.

6.1.7. Methyl-3-butenoate-d2. ^1H NMR (200 MHz, C_6D_6) δ: 2.78 (d, $J=7.0$ Hz, 2H), 3.27 (s, 3H) 5.79–5.93 (m, 1H); ^2H NMR (92.1 MHz, C_6H_6) δ: 4.92; HRMS (CI, NH_3) *m/z*: calcd for $C_5H_7D_2O_2$ $(M+H)^+$, 103.0728 found 103.0724.

6.1.8. Allyl methyl carbonate (10).[19] Colorless liquid. Yield (5.7%). ^1H NMR (600 MHz, C_6D_6) δ: 3.31 (s, 3H); 4.37 (d, $J=6.0$ Hz, 2H); 4.91 (d, $J_{cis}=10.8$ Hz, 1H), 5.08 (d, $J_{trans}=17.4$ Hz, 1H), 5.64 (m, 1H).

6.1.9. Allyl dimethyl orthoformate (11). Colorless liquid. Yield (<3%). ^1H NMR (200 MHz, C_6D_6) δ: 3.14 (s, 6H), 3.99 (d, 2H); 4.96 (s, orthoformyl H, partly superimposed on 5.00 (d, $J=9.5$ Hz, composite 2H), 5.23 (d, $J=17$ Hz, 1H), 5.77 (m, 1H). ^{13}C NMR (150.9 MHz, C_6D_6) δ: 51.0, 65.0, 113.9, 116.1, 134.9; MS *m/z*: calcd for $C_6H_{12}O_3$ 132.0786

found 132.0779. The structure was confirmed with the ^{1}H NMR spectrum of an authentic sample, prepared by reaction of trimethyl orthoformate (32 g, 0.30 mol) with allyl alcohol (8.7 g, 0.15 mol) in the presence of a catalytic amount of *p*-toluenesulfonic acid. The mixture was refluxed for 60 h, before it was washed with aqueous $NaHCO_3$ and extracted with methylene chloride. The allyl dimethyl orthoformate (4 g) was isolated by fractional distillation.

6.1.10. Allyl methyl 2-propenyl orthoformate (12). Colorless liquid. Yield (1–2%). ^{1}H NMR (600 MHz, C_6D_6) δ: 1.72 (s, 3H); 3.18 (s, 3H); 4.04 (br s, 3H, diastereotopic OCH_2 plus 1H of C=CH_2); 4.32 and 4.33 (d, J=3.3 Hz, 1H, other H of C=CH_2); 4.98 (d, J=10.6 Hz, 1H), 5.22 (d, J=17 Hz, 1H), 5.57 (s, 1H), 5.81 (m, 1H). Gradient HSQC and HMBC spectra were in agreement with the assignment. ^{13}C NMR (150.9 MHz, C_6H_6) δ: 20.0, 49.6, 64.0, 86.6, 110.5, 116.6, 133.8, 151.8; HRMS (CI, NH_3) *m/z*: calcd for $C_8H_{13}O_3$ $(M-H)^+$ 157.0865 found 157.0837.

6.1.11. Diallyl methyl orthoformate (13). Colorless liquid. Yield (2%). ^{1}H NMR (200 MHz, C_6D_6) δ: 3.16 (s, 3H); 3.99–4.03 (m, 4H), 5.00 (d, J=10.4 Hz, 2H), 5.10 (s, 1H), 5.24 (d, J=17 Hz, 2H) 5.73–5.89 (m, 2H); ^{13}C NMR (150.9 MHz, C_6D_6) δ: 51.0, 64.3, 112.3, 115.3, 134.1; HRMS (CI, NH_3) *m/z*: calcd for $C_8H_{15}O_3$ $(M+H)^+$ 159.1021 found 159.1021.

6.1.12. Methyl benzoate (14). Colorless liquid. Yield (1%). ^{1}H NMR (200 MHz, C_6D_6) δ: 3.47 (s, 3H), 7.06 (m, partly obscured by solvent signal), 8.09–8.14 (dd, 2H). Its identity was confirmed by running the ^{1}H NMR spectrum of authentic methyl benzoate in C_6D_6.

6.2. Standard procedures for thermolysis of 7a–7e

An oxadiazoline (**7a**,**b**) (1.4–1.5 mmol) in dry benzene (4.8 mL) was heated at 110 °C for 24 h in a sealed tube alone or with either TEMPO or *tert*-BuOH added. The products were separated directly by means of GC. Yields were estimated from calibration graphs and each yield was determined from two or more runs.

6.2.1. Thermolysis of 7a in dry benzene. Thermolysis of **7a** in benzene that was freshly distilled from CaH_2 gave **7** (60%). The other products (Scheme 6) gave only small displacements from the baseline of the GC trace.

6.2.2. Thermolysis of 7a in benzene containing *tert*-butyl alcohol. Thermolysis of **7a** (261 mg, 1.40 mmol) in benzene (5.0 mL) containing 424 mg (5.73 mmol) of *tert*-butyl alcohol gave **15** as a colorless oil, collected by means of GC. Yield 47%. ^{1}H NMR (600 MHz, C_6D_6) δ: 1.15 (s, 9H), 3.22 (s, 3H), 4.08 (m, 2H), 5.03 (d, J=10.2 Hz, 1H), 5.28 (d, J=17.4 Hz, 1H), 5.33 (s, 1H), 5.88 (m, 1H). ^{13}C NMR (150.9 MHz, C_6D_6) δ: 28.8, 49.8, 64.0, 73.8, 109.5, 115.7, 135.4. HRMS (EI) *m/z*: calcd for $C_8H_{15}O_2$ $(M-OMe)^+$ 143.1072, found 143.1072. Carbonate **10** (6.6%) was also obtained.

6.2.3. Thermolysis of 7a in benzene containing TEMPO. Thermolysis of **7a** (254 mg, 1.37 mmol) in dry benzene (5.0 mL) containing TEMPO (451 mg, 2.94 mmol) gave **16** (13%) and **17** (18%) that were separated and collected by GC. Compound **9** was also obtained (15%) as well as carbonate **10** (2.5%).

1-[(Methoxycarbonyl)oxy]-2,2,6,6-tetramethylpiperidine (**16**). This compound gave the ^{1}H NMR spectrum reported in the literature.[4b]

2,2,6,6-Tetramethyl-1-(2-propenyloxypiperidine) (**17**). The ^{1}H NMR spectrum of this compound matched that reported.[10]

6.2.4. Thermolysis of 7b in benzene. A solution of **7b** (243 mg, 1.29 mmol) in 4.4 mL of benzene was heated at 110 °C for 24 h. The workup was the same as those described above for **7a**.

6.2.5. Thermolysis of 7b in benzene containing TEMPO. A solution of **7b** (212 mg, 1.12 mmol) and TEMPO (399 mg, 2.62 mmol) in benzene (3.7 mL) was heated at 110 °C for 24 h. Workup was analogous to that described for **7a**.

6.2.6. Dideuterioallyl adducts of TEMPO. The mixture of α,α- and γ,γ-dideuterioallyl adducts was isolated by GC; ^{1}H NMR (200 MHz, $CDCl_3$) δ: 1.11 (s, 6H), 1.16 (s, 6H), 1.49 (m, 6H), 4.28 (d, J=5.3 Hz, 0.71H, therefore 1.29D), 5.12 (d, J=10.5 Hz) and 5.27 (d, J=17.2 Hz), composite area 0.90H, therefore 1.1D), 5.88 (m, 1H). The integrations give the isomer ratio (α,α: γ,γ)=1.17:1. MS (ESI) *m/z*: 200.1 $(M+H)^+$.

6.2.7. Thermolysis of 7c. Thermolysis of **7c** at 50 °C and workup as described for **7a** gave methyl 3-butenoate (35%) and compound **22**, 54%. In the presence of dry methyl-3-butenoate (conditions like those for **7a** above) the yield of **22** dropped. Addition of dry ethyl phenylacetate to a benzene solution of **7c** did not produce any benzyl-substituted analogue of **22**.

Methyl 2-allyloxy-2-methoxy-4-pentenoate (**22**). Colorless oil, IR (cm^{-1}) 1735; ^{1}H NMR (600 MHz, $CDCl_3$) δ: 2.67 (dt, J=7.2, 1.2 Hz, 2H, H-3), 3.32 (s, 3H, H-10), 3.77 (s, 3H, H-9), 3.96 (ddt, J=12.6, 6.0, 1.2 Hz, 1H, H-6), 4.06 (ddt, J=12.6, 6.0, 1.2 Hz, 1H, H-6), 5.12 (s, 1H, H-5, *cis*), 5.14 (dd, J=8.4, 1.2 Hz, 1H, H-5, *trans*), 5.18 (dd, J=10.8, 1.2 Hz, 1H, H-8, *cis*), 5.32 (dd, J=17.4, 1.5 Hz, 1H, H-8 *trans*), 5.65–5.71 (m, 1H, H-4), 5.91–5.97 (m, 1H, H-7); ^{13}C NMR (150.9 MHz, $CDCl_3$) δ: 39.1, 50.0, 52.5, 64.0, 102.3, 117.2, 119.3, 130.9, 134.0, 169.3; HRMS (EI) *m/z*: calcd for $C_9H_{13}O_3$ $(M-OMe)^+$ 169.0865, found 169.0855; calcd for $C_7H_{11}O_4$ $(M-CH_2CH=CH_2)^+$ 159.0657, found 159.0640; calcd for $C_8H_{13}O_2$ $(M-MeOCO)^+$ 141.0916, found 141.0902.

6.2.8. Thermolysis of 7d. Thermolysis of **7d** at 50 °C in dry benzene and workup as described for **7a** gave methyl 2-allyloxy-2-methoxy-pentenoate (50%, partially deuteriated, numbering system in Scheme 14).

Partially deuteriated **22** Colorless oil, IR (cm^{-1}) 1735; ^{1}H NMR (600 MHz, $CDCl_3$) δ: 2.66 (m, 2H, H-3), 3.31 (s, 3H,

H-10), 3.77 (s, 3H, H-9), 5.19 (d, $J=10.2$ Hz, 1H, H-8 cis), 5.33 (d, $J=16.8$ Hz, 1H, H-8 trans), 5.67 (bs, 1H, H-4), 5.92 (dd, $J=17.4$, 10.2 Hz, 1H, H-7); H-5 and H-6 signals were not observed, indicating that those sites were deuteriated; ^{13}C NMR (150.9 MHz, $CDCl_3$) δ: 38.9 (C-3), 50.0 (C-9), 52.5 (C-10), 63.6 (quint, $J=23.7$ Hz, C-6), 102.3 (C-2), 117.4 (C-8), 118.7 (quint, $J=23.7$ Hz, C-5), 130.7 (C-4), 133.8 (C-7), 169.3 (C-1); HRMS (EI) *m/z*: calcd for $C_{10}H_{13}D_4O_4$ $(M+H)^+$ 205.1378 found 205.1371.

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