

4,6-Dimethyl-*o*-quinone Methide and 4,6-Dimethylbenzoxete

Greg GuangHua Qiao, Keith Lenghaus, and David H. Solomon*

Polymer Science Group, Department of Chemical Engineering, The University of Melbourne, Parkville, Victoria 3052, Australia

Ales Reisinger, Ian Bytheway,¹ and Curt Wentrup*

Department of Chemistry, The University of Queensland, Brisbane, Queensland 4067, Australia

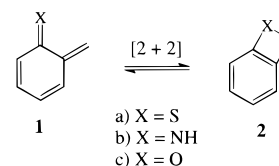
Received July 23, 1998

4,6-Dimethyl-*o*-quinone methide (**4**) was produced by FVP of alcohol **3** or of the trimer **6** and matrix isolated in Ar at 7.6 K. Photolysis of **4** with long wavelength light (>345 nm) at this temperature afforded 4,6-dimethylbenzoxete (**5**), which was observable up to room temperature in the solid state in the absence of water. **5** can be converted back to **4** by UV irradiation at 254/190 nm. Quantum chemical calculations on the thermal interconversion of **4** and **5** indicate activation barriers of the order of 40 kcal/mol for **4** → **5**, and 30 kcal/mol for **5** → **4**. The dimer, trimer, and tetramer (**8**, **6**, and **7**) of **4** are characterized.

Introduction

There has been a resurgence of interest in *o*-quinoid chemistry, due to its important roles in organic and bio-organic synthesis.² Of particular interest is isomerization to the four-membered ring compounds **2**. Benzothietes (**2a**)³ and benzazetines (**2b**)^{4,5} have been investigated in considerable detail; until recently, little was known about benzoxetes (**2c**). In 1993, Adam et al.⁶ reported the first synthesis of 2*H*-benzoxetes carrying methyl and acyl groups on position 2 of the four-membered ring, and methoxy or allyl substitutes on the aromatic ring. Most of these compounds are stable at –25 to –78 °C. More recently, Tomioka et al.⁷ observed the parent benzoxete (**2c**) and its interconversion with *o*-quinone methide **1c** in an Ar matrix at 10 K in the photolyses of benzofuran-2-one and *o*-(diazomethyl)phenol. We have also generated **2c** by flash vacuum pyrolysis (FVP) of benzofuran-2-one as well as *o*-(hydroxymethyl)phenol, followed by photochemical cyclization of the *o*-quinone methide **1**.⁸ Our warm-up experiments demonstrated that **2c** is stable till at least 155 K.⁸ We subsequently found that simple methyl substitution on the benzene ring stabilizes the benzoxete significantly. Here we report the generation

of *o*-quinone methide **4** and 4,6-dimethylbenzoxete (**5**), the latter being observable till room temperature in the solid state. Ab initio calculations of the spectra, energies, and the barrier for interconversion of **4** and **5**, are also reported.



Results and Discussion

1. Generation of Quinone Methide 4. Although other compounds, such as (*o*-hydroxyphenyl)carbene,⁷ have been used as the precursors of benzoxetes, the quinone methides proper are the most convenient, as they are easily generated from a number of precursors and can be isomerized to benzoxetes through photochemical four-electron electrocyclicization. Therefore, 2-(hydroxymethyl)-4,6-xylene (**3**) was subjected to an FVP experiment⁹ to generate the quinone methide **4**. Xylene **3** was sublimed at ca. 45 °C in high vacuum ($\sim 4 \times 10^{-6}$ mbar). The vapor of sublimed **3** was mixed with argon as a carrier gas and passed through a pyrolysis tube. The pyrolysate was immediately condensed on a KBr, BaF₂, or CsI target as an argon matrix at 7–12 K for IR spectroscopy. At a pyrolysis temperature of 500 °C, yellow 4,6-dimethyl-*o*-quinone methide (**4**) was observed in the matrix together with unchanged xylene **3** (Scheme 1). Above 650 °C, no starting material **3** survived, and only the yellow quinone methide **4** and the eliminated H₂O were trapped on the target. The observed IR spectrum of **4** generated by pyrolysis of xylene **3** at 600 °C and isolated in an Ar matrix (Figure S1 in the Supporting Information: identical with Figure 1b, where **4** is generated from precursor **6**, as described below), was compared with the theoretical one obtained by a B3LYP/6-31G* calculation (Figure 1a). The good agreement between the experimental and the theoretical spectra supports the observation of quinone methide **4** in this matrix. Fur-

(1) Current address: Department of Chemistry, University of Western Australia, Nedlands WA 6907 Australia.

(2) Recent review: Wan, P.; Barker, B.; Diao, L.; Fischer, M.; Shi, Y.; Yang, C. *Can. J. Chem.* **1996**, *74*, 465, and refs therein. Earlier reviews: Densimoni, G.; Tacconi, G. *Chem. Rev.* **1975**, *75*, 651. Turner, A. B. *Q. Rev.* **1964**, *28*, 347.

(3) Meier, H.; Gröschl, D. *Tetrahedron Lett.* **1995**, *36*, 6047. Schmidt, M. Meier, H.; Niedermann, H.-P.; Mengl, R. *Chem. Ber.* **1990**, *123*, 1143. Meier, H.; Eckes, H.-L.; Niedermann, H.-P.; Kolshorn, H. *Angew. Chem., Int. Ed. Engl.* **1987**, *26*, 1046. Kanakarajan, K.; Meier, H. *J. Org. Chem.* **1983**, *48*, 881. Meier, H. *J. Prakt. Chem.* **1997**, *338*, 383. Meier, H.; Mayer, A.; Groschl, D. *Sulfur Rep.* **1994**, *16*, 23. Wentrup, C.; Bender, H.; Gross, G. *J. Org. Chem.* **1987**, *52*, 3838.

(4) Pfister-Guillouzo, G.; Gracion, F.; Senio, A.; Lettulle, M.; Ripoll, J.-L. *Tetrahedron Lett.* **1992**, *33*, 5753. Smolinski, G. *J. Org. Chem.* **1961**, *26*, 4108. Burgess, E. M.; McCullagh, L. *J. Am. Chem. Soc.* **1966**, *88*, 1580. Murata, S.; Sugawara, T.; Iwamura, H. *J. Am. Chem. Soc.* **1985**, *107*, 6317.

(5) Lettulle, M.; Guenot, P.; Ripoll, J. L. *Tetrahedron Lett.* **1991**, *32*, 2013.

(6) Adam, W.; Hadjirapoglou, L.; Peter, K.; Sauter, M. *J. Am. Chem. Soc.* **1993**, *115*, 8603. Adam, W.; Sauter, M.; Zünkler, C. *Chem. Ber.* **1994**, *127*, 1115. Sauter, M.; Adam, W. *Acc. Chem. Res.* **1995**, *28*, 289.

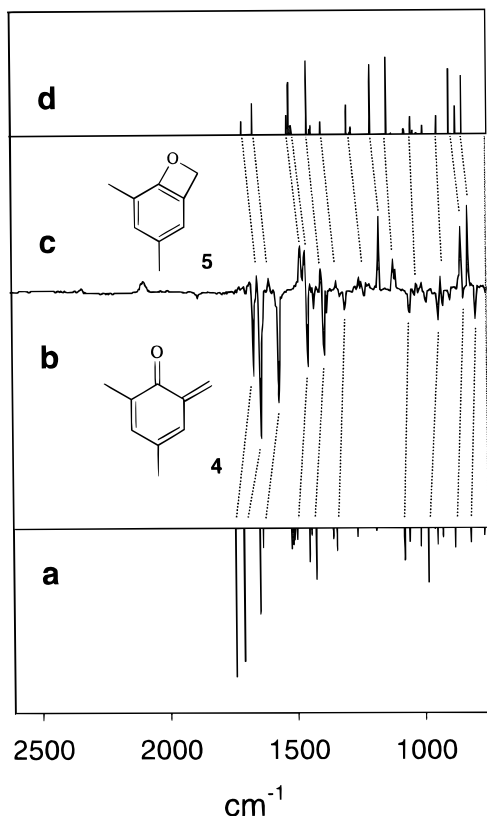
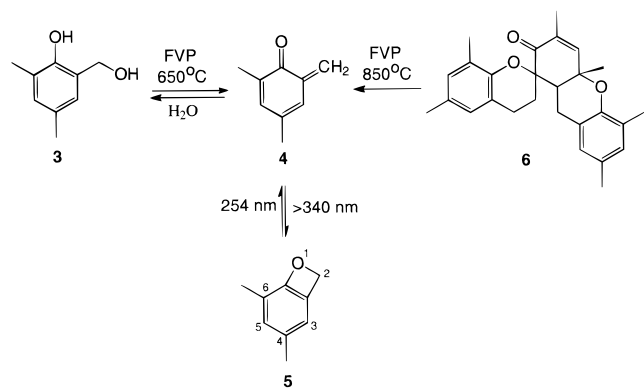


Figure 1. IR difference spectrum of 4,6-dimethylbenzoxete (**5**) (c, positive peaks) at 7.6 K in an Ar matrix, generated by photolysis of quinone methide **4** (b, negative peaks) (obtained by FVP of trimer **6**) with light of $\lambda > 345$ nm for 30 min; a: B3LYP/6-31G*-calculated IR spectrum of **4**; d: B3LYP/6-31G*-calculated IR spectrum of **5**.

Scheme 1



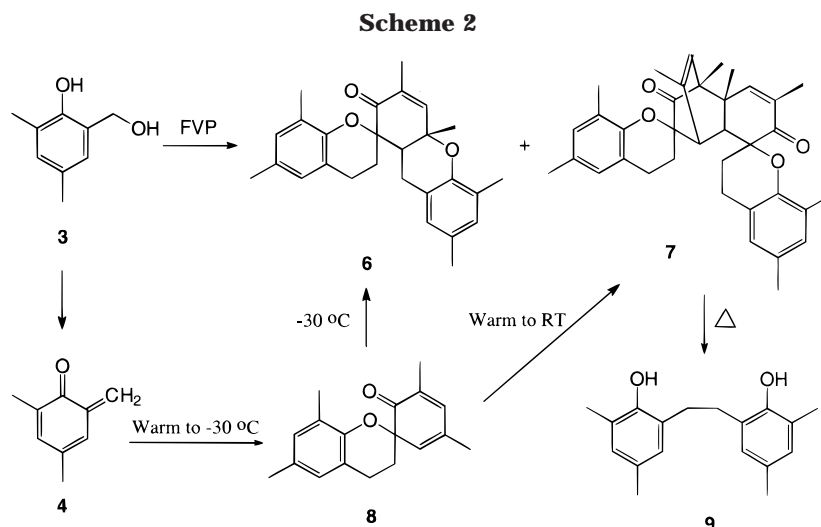
thermore, the main bands of **4** at 1668, 1642/1637, and 1569 cm^{-1} , due to C=O and C=CH₂ stretching, are similar to those in the parent compound **1c** in Ar matrix (1668, 1616, and 1568 cm^{-1}).^{7,8,10}

Next, FVP was performed on a preparative scale, whereby the thermolysate was isolated in a U-tube at 77 K. The use of a U-tube,¹¹ rather than a coldfinger, avoids regeneration of the starting material by reaction of quinone methide **4** with eliminated H₂O. At a pyrolysis temperature of 800 °C, all starting material had reacted, and a mixture of trimer **6** and tetramer **7** of the quinone methide **4** was isolated from the U-tube in a nearly 1:1 molar ratio and in 98% absolute yield (Scheme 2). These compounds were fully characterized spectroscopically (see Experimental Section).

The same trimer and tetramer were also observed by IR spectroscopy in a warm-up experiment of quinone methide **4** isolated neat at 7.6 K on a KBr target. In this experiment, the FVP was conducted at 700 °C without Ar as a carrier gas. A very slow sublimation rate of the precursor **3** was used, since this permits complete conversion of **3** as demonstrated by the IR spectrum. After deposition, the target was slowly warmed room temperature. IR spectroscopy revealed that the quinone methide **4** had disappeared and precursor **3** had regenerated on the target (reaction starting above -90 °C; see below). Because the water eliminated from **3** was cocondensed on the target, the regeneration of **3** was simply due to reaction of **4** with H₂O. Other major peaks appeared at 1732 and 1696 cm^{-1} and correspond to the main bands of trimer **6** (1695 cm^{-1}) and tetramer **7** (1695 and 1731 cm^{-1}). The material on the target was dissolved in chloroform and examined by GC-MS. Three peaks were observed; peak 1 appeared at a retention time of 6.5 min, contained 94.6% of the mixture according to integration (uncorrected), and had a mass of 152 amu and a mass spectrum identical with that of the precursor **3**. Peak 2 appeared at 10.9 min, corresponded to ca. 3% of the mixture, and had a mass of 402 amu. Based on a comparison with the mass spectrum obtained in the preparative work, peak 2 is due to trimer **6**.

The third peak appeared at 12.4 min, represented ca. 2.5% of the mixture, and had a mass of 270 amu. This is different from the tetramer **7** observed by IR spectroscopy at room temperature in the warm-up experiment. As the GC-MS sample was injected through a 200 °C injection port, it seems likely that tetramer **7** decomposed to another compound with a mass of 270 amu. This was confirmed by injection of pure **7** into the GC-MS, when the only resulting peak had a mass of 270 and the same retention time as peak 3 above. In the mass spectrum of this compound, the base peak is at m/z 135, which suggests that the m/z 270 compound is a symmetrical molecule. Thus, it is proposed that this compound is bis-(2-hydroxy-3,5-dimethylphenyl)ethane (**9**) (Scheme 2). Compound **9** was also synthesized by condensed phase thermolysis of either trimer **6** or tetramer **7** at 180 °C (see Experimental Section). Compound **9** is formally a product of reductive dimerization of **4**. We do not know the mechanism of this reaction and can only speculate. When the tetramer **7** is used as the precursor, two molecules of dimer **8** should form. Cleavage of the spiro-C-O bond in **8** leads to a diradical analogue of **9**, which can furnish alcohol **9** by hydrogen abstraction. When the trimer **6** is the precursor, a mixture of monomer **4** and dimer **8** should form, the latter reacting as before. The monomer **4** may dimerize to the same diradical in the condensed phase thermolysis. Surprisingly, the yield of **9** increased to 100% when the glassware was first washed with 1,1,1,3,3,3-hexamethyldisilazane. Photoacoustic IR measurements demonstrated that silazane compounds remain on the glass surface even after baking at 100 °C. A quantitative yield of compound **9** was obtained when trimer **6** was thermolyzed in the presence of water.

The mass spectrum of trimer **6** indicates that its molecular ion can easily fragment into dimer and monomer. This suggests that trimer **6** might be a better precursor of quinone methide **4**, as no byproducts would be formed, thus allowing an investigation of the inter-conversions and stabilities of quinone methide and benzoxete. In fact, this turned out to be the case.



Pyrolysis of the trimer **6** was carried out at 850 °C. The trimer was sublimed at ca. 105 °C with argon as a carrier gas. Under these conditions, pure quinone methide **4** was matrix isolated on a 7.6 K KBr target as evidenced by the IR spectrum (see Supporting Information). In a similar experiment, the pyrolysis of trimer **6** was carried out without argon. When the neat quinone methide **4** was warmed above -92 °C, new IR bands appeared, and the absorptions due to the quinone methide decreased. These newly formed bands became much stronger when the target was warmed further to -65 °C, and they are attributed to the formation of dimer **8** and trimer **6** by comparison with the IR spectrum of the trimer obtained in the preparative FVP work. Moreover, a low-temperature NMR experiment revealed the existence of dimer **8** (see below). After the target was warmed to room temperature, additional bands due to tetramer appeared. It seems obvious that dimerization would be the first step of reaction of quinone methide **4**. As this dimer was never isolated from any pyrolysis products, we concur with Ripoll⁵ that it is not stable at room temperature. Therefore, a low-temperature NMR experiment was carried out. Xylenol **3** was pyrolyzed at 650 °C, and quinone methide **4** was isolated on a coldfinger at 77 K. After pyrolysis, the system was isolated from the vacuum pumps, and CDCl_3 was injected and condensed on the coldfinger. On warm up, the chloroform melted and flowed with the pyrolysate into a round-bottomed flask cooled to 77 K in liquid N_2 . The solution was then transferred to a NMR tube and kept at 77 K until the NMR measurement. The NMR spectrum of the solution was first measured at -30 °C, revealing a mixture of dimer **8** and trimer **6**. When the probe was warmed to room temperature (20 °C), all peaks due to dimer **8** disappeared, and peaks due to tetramer **7** developed. This result demonstrates that tetramer **7** is formed from the reaction of two dimer molecules, and this reaction is far slower than the trimerization due to addition of a molecule of monomer to the dimer.

2. Photolysis of Quinone Methide 4. Pyrolysis of trimer **6** at 800 °C yielded pure quinone methide **4** in an Ar matrix at 7.6 K (Figure 1b). This matrix was irradiated at 340 nm using a high-pressure mercury lamp with a cutoff filter ($\lambda > 340\text{--}245$ nm). The reaction was monitored by IR spectroscopy. After 30 min photolysis, most of the yellow quinone methide **4** had disappeared, and the new compound (colorless) formed had major IR

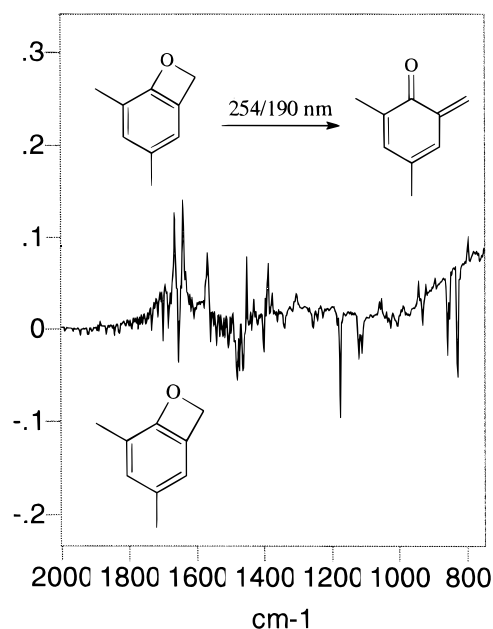


Figure 2. IR difference spectrum obtained after irradiation of **5** with UV light (254/190 nm) for 14 h in Ar matrix at 7.6 K. Positive peaks: regenerated quinone methide **4**; negative peaks: reacted benzoxete **5**.

bands at 1609, 1482, 1463, 1402, 1175, 1120, 930, 859, 850, and 830 cm^{-1} (Figure 1c). After further photolysis for 1 h, no quinone methide **4** remained. The new compound is assigned as benzoxete **5** for the following reasons: (1) As quinone methide **4** was matrix isolated in Ar, the photolysis product should be an isomer of **4**. A four-electron electrocyclicization of **4** to **5** (Scheme 1) is a logical reaction. (2) The ab initio calculated IR spectrum of **5** (Figure 1d) is in good agreement with the experimental spectrum (Figure 1c). (3) The IR spectrum of **5** is similar to that of the unsubstituted benzoxete^{7,8} (which has the main bands at 1600, 1453, 1180, and 790 cm^{-1}). (4) Further photolysis of **5** at 254 nm regenerates the quinone methide **4**. In this second photolysis, benzoxete **5** was irradiated with a low-pressure UV lamp (254/190 nm). After 14 h photolysis, about 20% of **5** had reverted to quinone methide **4** (Figure 2). (5) The same benzoxete **5** was also observed after the alcohol **3** was pyrolyzed at 650 °C, and the matrix-isolated product was photolyzed as above.

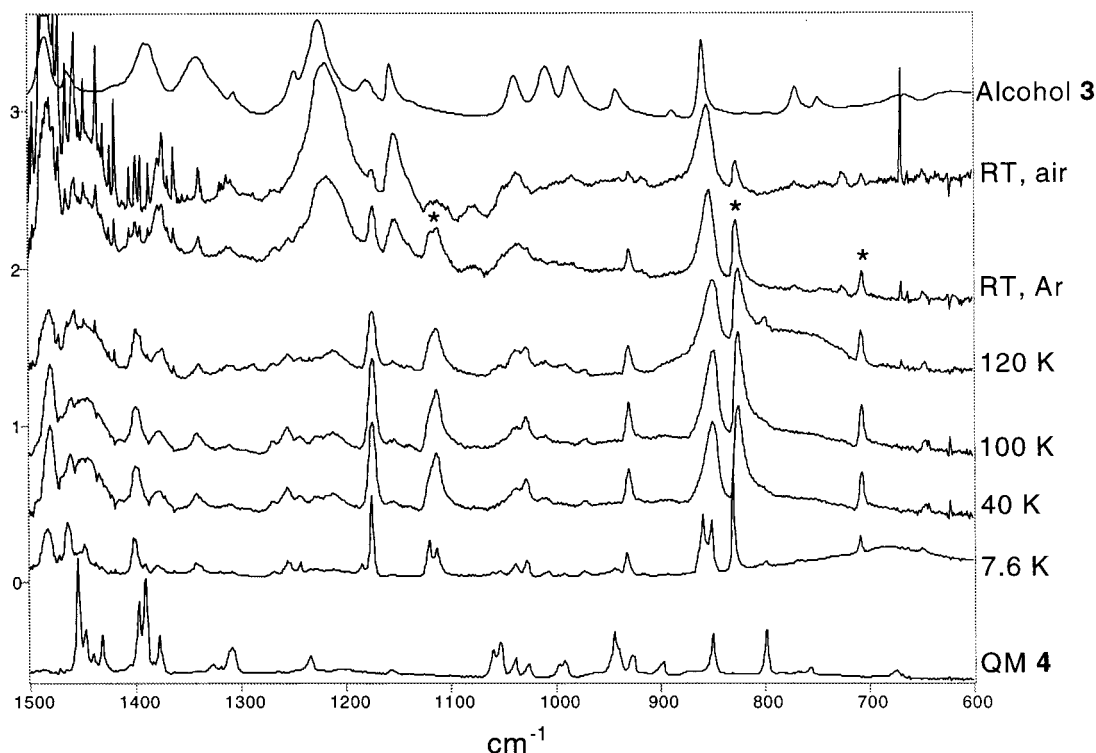


Figure 3. IR spectra taken during warm up experiment of benzoxete **5** in an Ar matrix, produced by photolysis of quinone methide **4** for 27 h, from 7.6 K to room temperature in Ar atmosphere, and at rt in air. IR spectra of quinone methide **4** and alcohol **3** are also shown for comparison. Peaks marked with * are the IR absorption bands due only to benzoxete **5**.

The stability of benzoxete **5** was tested in a warm up experiment. For this purpose, the quinone methide **4** was isolated on the 7.6 K target by pyrolysis of trimer **6** at 800 °C but using a lower Ar flow rate. The resulting higher substance/Ar ratio facilitates the subsequent evaporation of Ar. The sublimation of trimer **6** into the pyrolysis tube was controlled at a slow rate, and no unchanged **6** condensed on the target. Long wavelength irradiation (>340 nm) was performed until all of the quinone methide **4** had been converted into benzoxete **5**. Subsequently, benzoxete **5** was slowly warmed while monitoring the IR spectrum. The initial warming rate was very low, so the Ar evaporated very slowly without carrying the material away from the target. After complete evaporation of Ar, the IR spectrum of neat **5** showed that, as expected, all bands had broadened compared with the Ar matrix, but were still clearly observable (Figure 3). At 200 K, the system was isolated from the vacuum line, and the cryostat was turned off. To prevent any evaporation of the compounds on the target on further warming, the system vacuum was reduced by the addition of dry Ar. It needs to be mentioned here that the IR spectrum of alcohol **3** is very similar to that of **5**. Due to small amounts of water that might leak into the system, it is important to ascertain the difference between the two compounds. By comparison with the IR spectrum of **3** as shown in Figure 3, it is seen that bands at 705, 824, and 1114 cm^{-1} (marked with *) belong to **5** only. When the target was further warmed to -30 °C, benzoxete **5** remained unchanged. At room temperature, these bands were still clearly visible in the spectrum, although new bands probably due to **3** increased, indicating some reaction of **5** with adventitious water to form alcohol **3**. Air was then introduced into the system, resulting in an immediate reduction in intensities of the

bands due to **5**. After 3 to 4 min, only alcohol **3** was observed on the target.

Since benzoxete **5** was found to be stable in the solid form, an attempt was made to isolate it in solution for NMR spectroscopy. Unfortunately, preparative photolysis could not completely convert neat quinone methide **4** on a 77 K coldfinger into benzoxete **5**, and a low temperature (-30 °C) NMR measurement of the products isolated from the coldfinger after photolysis showed the major species to be dimer and trimer (**8** and **6**), together with a small amount of photolysis product. It was not possible to identify any peaks in this photolysis product as compound **5**. Most likely, benzoxete **5** is only stable as a pure solid, i.e., without any other reactive species present.

3. Quantum Chemical Calculations. It was initially surprising that solid benzoxete **5** was stable at room temperature, as such molecules are usually regarded as reactive intermediates.⁷ The stability of this molecule with respect to formation of **4** was therefore investigated using quantum chemical methods.

The geometries of quinone methide **4** and benzoxete **5**, and the transition state connecting them, were initially calculated at the HF/STO-3G level of theory. Subsequent calculations were then performed at the HF, B3LYP, and MP2 levels in conjunction with the standard 6-31G* basis set. At each level of theory, analysis of the normal modes of vibration confirmed that the optimized geometries of **4** and **5** were true local minima. The transition states were similarly analyzed, and at all levels of theory the imaginary frequency corresponding to formation of the O–C bond in **5** was located. The energies of **4** and **5** were also investigated by performing additional single point calculations using the expanded 6-311+G(3df,2p) basis in conjunction with the B3LYP/6-31G* and MP2/6-31G* geometries (optimized and transition state) and zero-

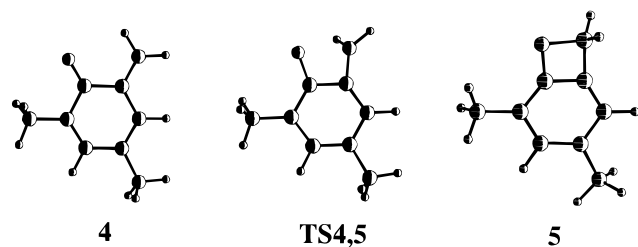


Figure 4. Ab initio calculated structures of quinone methide **4**, benzoxetene **5**, and the transition structure **TS4,5** for their interconversion (MP2/6-31G*).

Table 1. Calculated Relative Energies (kcal/mol; zero point energies added) of Quinone Methides **1c** and **4**, Benzoxetes **2c** and **5**, and the Transition States **TS1c,2c** and **TS4,5** Interconverting Them

level of theory	1c	TS1c,2c	2c	4	TS4,5	5
HF/6-31G*	0	55.9	15.9	0	58.6	18.3
B3LYP/6-31G*	0	39.3	11.0	0	41.4	13.6
B3LYP/6-31G*// B3LYP/6-311+G(3df,2p)	0	39.2	12.5	0	41.1	14.5
MP2/6-31G*	0	40.2	7.7	0	41.2	10.5
MP2/6-31G*// MP2/6-311+G(3df,2p)	0	38.4	6.0	0	40.0	9.0

point energies. The resulting relative energies of **4**, **5** and the transition state linking them (**TS4,5**), calculated for thermal reactions in gas phase, are given in Table 1. Imaginary frequencies for the transition state geometries are contained in Table S3, and full geometrical data is given in Table S4. All calculations were performed using the Gaussian 94 software package.¹²

As shown in Table 1, at the higher computational levels and with large basis sets, benzoxete **5** is found to be only 9–10 kcal/mol above the quinone methide **4**. While the aromaticity of **5** would stabilize this molecule, strain increases the energy. The optimized structures of **4**, **5**, and **TS4,5** are shown in Figure 4. The activation barrier is ca. 40 kcal/mol for the conversion of **4** to **5**, and about 31 kcal/mol for the reversion of **5** to **4**. This is sufficient to explain the persistence of **5** at room temperature in the absence of water and other reactive molecules. It is a thermodynamically stable molecule.

Tomioka and Matsushita^{7a} have reported calculations for the parent system **1c/2c** at the MP2/6-31G*//HF/6-31G* level of theory. To be able to compare directly with the results for **4/5**, we have carried out the corresponding calculations on the parent system **1c/2c**. The calculated energies and full geometries are listed in the supporting

(7) (a) Tomioka, H.; Matsushita, T. *Chem Lett.* **1997**, *5*, 399. Main IR bands of **1c** in Ar matrix: 1668, 1616, 1568, 1540, 852, 788 cm⁻¹. **2c**: 1600, 1453, 1180, 896, 874, 796, 740 cm⁻¹. (b) Tomioka, H. *Pure Appl. Chem.* **1997**, *4*, 837.

(8) Morawietz, J.; Wentrup C., Unpublished results.

(9) Wentrup, C.; Blanch, R.; Briehl, H.; Gross, G. *J. Am. Chem. Soc.* **1988**, *110*, 1874.

(10) The main IR bands of the parent quinone methide **1c** (neat, -196 °C) have been reported at 1656, 1565, and 1539 cm⁻¹: McIntosh, C. L.; Chapman, O. L. *J. Chem. Soc., Chem Commun.* **1971**, 771.

(11) Qiao, G. G.; Wong, M. W.; Wentrup, C. *J. Org. Chem.* **1996**, *61*, 8125.

(12) Frisch, M. J.; Trucks, G. W.; Schlegel, H. B.; Gill, P. M. W.; Johnson, B. G.; Robb, M. A.; Cheeseman, J. R.; Keith, T. A.; Peterson, G. A.; Montgomery, J. A.; Raghavachari, K.; Al-Laham, M. A.; Zakrzewski, V. G.; Ortiz, J. V.; Foresman, J. B.; Cioslowski, J.; Stefanov, B. B.; Nanayakkara, A.; Challacombe, M.; Peng, C. Y.; Ayala, P. Y.; Chen, W.; Wong, M. W.; Andres, J. L.; Replogle, E. S.; Gomperts, R.; Martin, R. L.; Fox, D. J.; Binkley, J. S.; DeFrees, D. J.; Baker, J.; Stewart, J. J. P.; Head-Gordon, M.; Gonzalez, C.; Pople, J. A. Gaussian 94; Gaussian Inc., Pittsburgh, PA, 1995.

documents. At all levels of calculation, the results are similar for the parent system and for **4/5**. For example, at the highest level (MP2/6-31G*//MP2/6-311+G(3df,2p)) the parent benzoxete **2c** is ca. 6 kcal/mol above **1c**, and the barrier is ca. 32.4 kcal/mol for the reversion of **2c** to **1c**. Thus, there is probably little intrinsic difference between the parent system (**1c/2c**) and the methyl-substituted one (**4/5**). As mentioned in the Introduction, **2c** is observable till at least 155 K.⁸ It appears that **2c** is just more reactive than **5** (i.e., a kinetic effect).

Experimental Section

Apparatus. Preparative FVP was carried out in a heated quartz tube, 25 cm in length and 2 cm in diameter. Samples were sublimed into the horizontal pyrolysis tube using a sublimation oven. The system was generally evacuated to ca. 10⁻⁴ mbar and remained attached to the vacuum line during the pyrolysis period. The pyrolysis products were trapped on a coldfinger or in a U-tube at 77 K. Further details of the FVP apparatus and the purpose of the U-tube have been published.^{9,11}

Matrix isolation was carried out using a 10 cm long, 0.8 cm diameter quartz tube in an oven directly attached to the vacuum shroud of a closed cycle liq He APD Cryogenics cryostat, CSW-204SL-6.5K, equipped with a Lakeshore Model 330-44 temperature controller. Argon was used as the matrix medium, which was passed over the sample while it was sublimed and cocondensed as a matrix at ca. 6.5–12 K on BaF₂, KBr, or CSI₂ targets for IR spectroscopy. A turbomolecular pump was used to maintain a vacuum of 10⁻⁶–10⁻⁷ mbar.

Photolysis was carried out with a low-pressure Hg lamp (75 W, 254 and 190 nm output; Gräntzel, Karlsruhe, Germany) or a high-pressure Xe–Hg Lamp (1000 W; Hanovia). In the preparative photolysis, a 2000 W white light theater Lamp (SEIECON, Luminaire Manufacturer, CP91, Auckland, New Zealand) was used. Melting points are uncorrected.

Materials. 4,6-Dimethyl-2-(hydroxymethyl)phenol (**3**) was synthesized according to a known method.¹³

Preparative FVP of 3. A 703.7 mg sample of **3** was sublimed at 45 °C (10⁻⁴ mbar) and pyrolyzed at 750 °C in the preparative apparatus. The pyrolysis product was trapped on a coldfinger at 77 K. After warming to room temperature, it was dissolved in chloroform, and a column chromatographic separation (silica gel, 250–400 mesh) afforded as the first fraction 357.2 mg (56%) of trimer **6**. A second fraction (206.6 mg) was recrystallized from ethyl acetate to yield 102.8 mg (25%) of tetramer **7**. Their spectroscopic data are as follows:

Trimer 6: mp 201–202 °C (lit.¹⁴ 199–201 °C); ¹H NMR (400 MHz, CDCl₃): δ 1.63 (s, 3H), 1.78 (d, *J* = 1.2 Hz, 3H), 1.99–2.27 (m, 3H), 2.12 (s, 3H), 2.15 (s, 3H), 2.15 (s, 3H), 2.17 (s, 3H), 2.33–2.73 (m, 3H), 2.89–3.01 (m, 1H), 6.43 (s, 1H), 6.59 (s, 1H), 6.65 (s, 1H), 6.74 (s, 2H); ¹³C NMR (400 MHz, CDCl₃): δ 15.45 (CH₃), 15.89 (CH₃), 15.94 (CH₃), 20.43 (CH₃), 20.53 (CH₃), 21.90 (CH₂), 25.62 (CH₂), 29.19 (CH₃), 30.23 (CH₂), 49.41 (CH), 77.20 (C_q), 80.59 (C_q), 119.53 (C_q), 124.78 (C_q), 125.53 (C_q), 125.84 (C_q), 125.95 (CH), 126.70 (CH), 128.92 (C_q), 129.35 (CH), 129.63 (CH), 130.01 (C_q), 133.15 (C_q), 144.86 (CH), 148.97 (C_q), 149.22 (C_q), 197.39 (C=O). The definitive NMR signal assignments were based on DEPT and two-dimensional ¹³C–¹H correlations with both short (HMQC) and long (HMBC) range couplings. IR (KBr): 669 w, 723 w, 852 m, 857 m, 910 m, 957 w, 1034 m, 1042 m, 1078 m, 1159 m, 1179 m, 1202 w, 1228 s, 1247 m, 1435 m, 1482 s, 1669 s, 2916 m, 2944 w, 3005 w cm⁻¹; MS *m/z* 402 (M⁺, 5%), 268 (45), 134 (100), 112 (30), 91 (60), 77 (20), 44 (44). Anal. Calcd for C₂₇H₃₀O₃: C, 80.56; H, 7.51; O, 11.92. Found: C, 80.10; H, 7.72.

(13) Ninagawa, A.; Kawazoe, M.; Matsuda, H. *Makromol. Chem.* **1979**, *180*, 2123.

(14) Merijan, A.; Shoulders, B. A.; Gardner, P. D. *J. Org. Chem.* **1963**, *28*, 2148.

Tetramer 7:¹⁵ mp 206–209 °C dec; ¹H NMR (400 MHz, CDCl₃): δ 1.23 (s, 3H), 1.41 (s, 3H), 1.81 (d, *J* = 1.3 Hz, 3H), 1.88 (d, *J* = 1.4 Hz 3H), 2.01 (s, 3H), 2.06 (s, 3H), 2.16 (s, 3H), 2.18 (s, 3H), 2.20–2.43 (m, 4H), 2.57–2.83 (m, 4H), 2.92 (d, *J* = 2.0 Hz 1H), 3.42 (t, *J* = 2.2 Hz 1H), 5.18 (s, 1H), 6.02 (s, 1H), 6.57 (s, 1H), 6.64–6.65 (m, 3H); ¹³C NMR (400 MHz, CDCl₃): δ 12.70 (CH₃), 15.83 (CH₃), 16.05 (CH₃), 16.59 (CH₃), 20.39 (CH₃), 20.42 (CH₃), 21.59 (CH₃), 22.08 (CH₂), 22.11 (CH₂), 23.56 (CH₃), 27.45 (CH₂), 33.98 (CH₂), 44.45 (CH), 45.65 (C_q), 47.79 (CH), 58.33 (C_q), 75.98 (C_q), 79.73 (C_q), 119.06 (C_q), 120.05 (C_q), 124.94 (C_q), 125.02 (C_q), 126.78 (CH), 126.85 (CH), 128.56 (CH), 128.66 (C_q), 129.02 (C_q), 129.56 (CH), 129.58 (CH), 134.35 (C_q), 142.45 (CH), 144.40 (C_q), 148.54 (C_q), 149.44 (C_q), 197.42 (C=O), 208.94 (C=O). The definitive NMR signal assignments were based on DEPT and two-dimensional ¹³C–¹H correlation's with both short (HMQC) and long (HMBC) range couplings. IR (KBr): 710 w, 854 m, 983 m, 1149 s, 1250 s, 1378 m, 1480 s, 1695 s, 1730 vs cm⁻¹; MS *m/z* 536 (M⁺, 5%), 402 (3.6), 268 (100), 253 (22), 251 (20), 225 (18), 135 (25), 106 (10). HRMS calcd for ¹²C₃₆H₄₀O₄ 536.29266; found 536.29289. Anal. Calcd for C₃₆H₄₀O₄: C, 80.56; H, 7.51; O, 11.92. Found: C, 80.65; H, 7.63.

4,6-Dimethyl-*o*-quinone Methide (4). (a) **FVP of 3.** Alcohol **3** was sublimed (10⁻⁶ mbar) at 45 °C with argon as the carrier gas and pyrolyzed at 650 °C. The compound isolated in the Ar matrix at 6.5 K was assigned as 4,6-dimethyl-*o*-quinone methide (**4**): IR (Ar KBr, 6.5 K) 488 w, 492 w, 501 w, 505 w, 603 w, 613 w, 624 w, 798 m, 849 m, 943 m, 1052 m, 1059 m, 1389 m, 1397 m, 1432 w, 1455 s, 1569 s, 1637 vs, 1642 s, 1668 s, 3521 w, 3533 w, 3704 m cm⁻¹. (b) **FVP of 6.** Trimer **6** was sublimed (10⁻⁶ mbar) at 110 °C with Ar as a carrier gas and pyrolyzed at 900 °C. Pure quinone methide **4** was isolated in argon matrix. IR (Ar KBr, 6.5 K) as above.

Bis(2-hydroxy-3,5-dimethylphenyl)ethane (9). (a) An ampule was washed with 1,1,1,3,3,3-hexamethyldisilazane and dried in an oven at 100 °C. A 14.2 mg (0.05 mmol) amount of trimer **6** was sealed in this tube under a nitrogen atmosphere before immersion in an oil bath at 180 °C. After 4 h, the tube was cooled to room temperature and the product analyzed by NMR. Bis(2-hydroxy-3,5-dimethylphenyl)ethane (**9**) was isolated as a white solid in quantitative yield and further purified by sublimation: mp 164–166 °C; ¹H NMR (300 MHz, CDCl₃): δ 2.19–2.25 (m, 12H), 2.77 (s, 4H), 6.84 (s, 4H); ¹³C NMR (75.4 MHz, CDCl₃): δ 16.22, 20.30 (CH₃), 32.12 (CH₂), 123.95, 127.17, 128.00, 129.39, 129.55, 150.34; IR (KBr) 459 w, 546 w, 741 w, 788 w, 854 m, 1033 w, 1159 m, 1210 vs, 1256 w, 1310 w, 1376 w, 1389 m, 1459 m, 1484 s, 2860 w, 2917 m, 3010 w, 3387 s/br cm⁻¹; GC-MS *m/z* 270 (M⁺, 33%), 135 (100), 91 (25), 79 (10), 41 (8). Anal. Calcd for C₁₈H₂₂O₂: C, 79.96; H, 8.20; O, 11.84. Found: C, 79.80; H, 8.22.

(b) Trimer **6** was also heated at 180 °C in the same way but without coating with hexamethyldisilazane. After 4 h, 16.7% of **9** was isolated.

(c) An ampule was washed with hexamethyldisilazane and dried in an oven at 100 °C. A 13.8 mg amount of tetramer **7** was sealed in this tube under a nitrogen atmosphere before immersion in an oil bath at 180 °C. After 3 h, the tube was cooled to room temperature and opened, and the content was extracted with CHCl₃. A 9.1 mg amount of **9** was isolated from the solution (65.5%).

(d) A 14.7 mg amount of tetramer **7** was heated at 180 °C in the same way but without coating with hexamethyldisilazane. After 3 h, 2.3 mg of **9** (15.5%) was isolated.

(e) Thermolyses of trimer **6** in the presence of water were carried out in sealed tubes at 180 °C for 2 and 4 h. The NMR spectrum of the product from the 2 h reaction indicated the presence of three compounds, alcohol **3**, trimer **6**, and compound **9**, in a ratio of ca. 1:14: 2.5. As the amount of the **3** was very small, it was confirmed by adding authentic **3** to the mixture, which resulted in a growth of the CH₂ peak. After the 4 h thermolysis, only compound **9** was obtained (quantita-

tive yield). Thus, all trimer **6** had reacted, and any alcohol **3** that had formed as an intermediate had thermolyzed again to the monomer (dimer, trimer), which produced **9** as the final product.

Dimer (8). Xylenol **3** (30 mg) was sublimed at 45 °C (10⁻⁴ mbar) and pyrolyzed at 800 °C in the preparative apparatus. After the pyrolysis products were trapped on a coldfinger at 77 K, the system was isolated from the vacuum line, and 2 mL of CDCl₃ (or acetone-*d*₆) was injected and cocondensed on the coldfinger. The coldfinger was allowed to warm until the CDCl₃ (or acetone-*d*₆) melted and flowed, together with the pyrolysate, into a round-bottom flask which was cooled at 77 K in liquid nitrogen. The solution was transferred at low temperature into a NMR tube, and the NMR measurements were conducted at a -30 °C probe temperature. The NMR spectra showed a mixture of dimer **8** and trimer **6** in a ca. 2:1 ratio. NMR data for dimer **8** are as follows: ¹H NMR (400 MHz, CDCl₃) δ 6.82 (s, 1H), 6.72 (s, 1H), 6.62 (s, H), 6.05 (s, 1H), 2.4–2.8 (m, 2H), 2.23 (s, 3H), 2.15 (s, 3H), 1.96 (t, *J* = 6.7 Hz, 2H), 1.92 (s, 3H), 1.88 (s, 3H); ¹³C NMR (100 MHz, acetone-*d*₆): δ 201.83, 150.16, 141.05, 134.13, 132.53, 130.96, 129.88, 128.71, 127.79, 126.47, 120.45, 80.21, 30.24, 21.52, 21.07, 20.33, 16.21, 15.16.

4,6-Dimethylbenzoxete (5). Ar matrix-isolated quinone methide **4** at 6.5 K, generated from either alcohol **3** or trimer **6**, was irradiated with a mercury lamp with a cutoff filter ($\lambda \geq 340$ –345 nm). After 2 h 15 min, **4** was completely converted to 4,6-dimethylbenzoxete (**5**): IR (Ar, KBr, 6.5 K) 628 w, 686 w, 689 w, 708 w, 830 vs, 850 s, 859 s, 930 w, 1113 m, 1120 m, 1175 vs, 1253 w, 1342 w, 1402 w, 1463 s, 1482 s, 1609 m, 1653 w, 2874 w, 2935 w, 2961 w cm⁻¹.

Warmup Experiment on 4,6-Dimethylbenzoxete (5). Trimer **3** was pyrolyzed at 800 °C, and the resultant quinone methide **4** was matrix isolated in Ar at 7.6 K. The sublimation rate of **3** was controlled at a slow rate, so that only the quinone methide was isolated on the target. The subsequent photolysis with the high-pressure mercury lamp (>340 nm) was performed for 27 h to convert **4** completely to benzoxete **5**. The target was slowly warmed, so that the Ar evaporated slowly. The warm-up was constantly monitored by IR spectroscopy. IR bands at 705, 824, and 1114 cm⁻¹ belong to **5** only and were used to monitor the presence of **5**. At 129 K, **5** remained unchanged. At -30 °C, the intensities of IR bands due to **5** decreased slightly, and bands due to alcohol **3** started to appear. **5** remained observable till room temperature as described in the text. Details are shown in Figure 3.

Supporting Information Available: Figures S1 and S2 showing observed matrix IR spectra of quinone methide **4** generated by pyrolysis of alcohol **3** at 650 °C and trimer **6** at 850 °C; Figure S3 showing IR spectra during warm up of **4** from 77 K to room temperature, indicating the disappearance of **4** and formation of dimer between -65 and -33 °C; Table S1 showing Cartesian coordinates at the B3LYP/6-31G* and MP2/6-31G* levels of theory for **1c**, **2c** and the transition structure **TS1c,2c** for their interconversion, and **4**, **5** and the transition structure **TS4,5** for their interconversion; Table S2 showing calculated electronic and zero point corrected energies at all levels for **1c**, **2c**, **TS1c,2c**, **4**, **5**, and **TS4,5**; Table S3 showing harmonic vibrational frequencies at HF, B3LYP, and MP2 levels with 6-31G* basis set for **TS1c,2c** and **TS4,5**; Tables S4A and Tables S4B showing the geometrical parameters at the B3LYP/6-31G* and MP2/6-31G* levels of theory for **1c**, **2c**, **TS1c,2c**, **4**, **5**, and **TS4,5** (17 pages). This material is contained in libraries on microfiche, immediately follows this article in the microfilm version of the journal, and can be ordered from the ACS; see any current masthead page for ordering information.

(15) A similar structure of the tetramer of **1c** has been reported: Faure, R.; Thomas-David, G.; Bartnik, R.; Cebulka, Z.; Graca, E.; Lesniak, S. *Bull. Soc. Chim. Fr.* **1991**, 128, 378.