Reactions of the Relatively Persistent Carboxylic Acid Enol−2,2-Ditipylethene-1,1-diol. The Reversibility of Ketene Hydration[1]

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Abstract: The reactions of solutions of 2,2-ditipylethene-1,1-diol (tipyl = 2,4,6-triisopropylphenyl) (**1**), which is the enol of ditipylacetic acid, were studied. Oxidation with $(p\text{-}BrC_6H_4)_3N^{\bullet+}SbCl_6^-$ gave a benzofuranone, i.e., a five-membered lactone (**5**) by cyclization via the oxygen on the ring, and ketonization with loss of aromaticity of the ring. Bromination also gave **5**, presumably via an initial oxidation of the oxygen, as well as a bromine-containing six-membered lactone, a benzopyranone (**9**), formed by cyclization on an *o*-*i*-Pr group and ring bromination. No product resulting from reaction of bromine with the double bond was formed. This is ascribed to shielding of the double bond by steric crowding. Attempted etherification of the enolic OH groups did not give the ketene trimethylsilyl or methyl acetals. With diazomethane a bicyclic trienone **13** was formed, presumably by cyclopropanation of the ditipylketene (**2**) which is in equilibrium with **1**, followed by a vinyl cyclopropanone rearrangement to **13**. The formation of **1** by addition of water to **2** was found to be reversible as shown by isolation of a ^{18}O-labeled-**2** from hydration of **2** in $H_2{}^{18}O$. Several diarylketenes react with $H_2{}^{18}O$ to give several isotopomeric diarylacetic acids, and the formation of $Ar_2CH^{18}O_2H$ indicates the generality of the reversibility of the ketene hydration for these species.

Introduction

We have recently reported the generation of solutions of ≥98% of the enol of an acid, i.e., 2,2-ditipylethene-1,1-diol **1** (tipyl = Tip = 2,4,6-triisopropylphenyl).[2] The enediol was prepared by hydration of ketene **2** in 42:5:3 DMF:THF:H_2O or in 9:1 THF:H_2O mixtures at 273K (eq 1), and it was characterized by NMR spectroscopy. While **1** is long-lived at 273 K,

$$\underset{\mathbf{2}}{Tip_2C{=}C{=}O} + H_2O \longrightarrow \underset{\mathbf{1}}{Tip_2C{=}C(OH)_2} \longrightarrow \underset{\mathbf{3}}{Tip_2CHCO_2H} \qquad (1)$$

on raising the temperature to room temperature ketonization to ditipylacetic acid, **3**, takes place in a few hours.

Observable 1,1-enediols are very rare species,[3] and the only reactions observed with several short-lived 1,1-enediols prepared by Wirz's[4,5a,b] and Kresge's[5] groups as well as two longer lived 2,2-diarylethene-1,1-diols (Ar = mesityl, C_6Me_5)[6] are ionizations and ketonization to the corresponding acids. Suggested, but not observed, intermediate 1,1-enediols in several reactions also gave the acids as the final products.[7] Bromine addition to enols is well-known,[8,9] but no evidence exists for such addition to 1,1-enediols. In sum, very little is known about the reactions of 1,1-enediols, excluding their ketonization.

The availability of long-lived solutions of enediol **1** enabled the study of its reactions. Enediols are ambident substrates. They can react at both the double bond and the OH sites. The two activated bulky aromatic groups of **1** can serve as additional reaction sites and can also shield the double bond and thus change the regioselectivity. Moreover, **1** may be regarded as ketene hydrate (eq 1), raising the possibility that the hydration is reversible, as is known for the saturated gem-diols formed by hydration of aldehydes and ketones. We therefore investigated now a few reactions of enediol **1**.

Results and Discussion

Oxidation. 1,2-Enediols[10a] are well-known reducing agents (reductones).[10a,b] Oxidation of aldehydes and ketones probably proceeds by oxidation of the enol tautomer.[10c] Oxidation of 1-*R*-2,2-dimesitylethenols and their acetates with the one-electron oxidant tris(*p*-bromophenyl)aminium hexachloroantimonate (TBPA) ($E_{1/2}$ 0.73 V) or electrochemically gives the corresponding benzofurans.[11] Air oxidation of ditipyl-substituted ethenols also gave benzofurans.[12] During attempted generation of **1** by several methods a radical, which was suggested to be the α-carboxy radical **4** was always formed.[2]

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(1) Presented in part in the 12th Conference on Physical Organic Chemistry, Padova, Italy, August 28−September 2, 1994; Abs. IC 2, p 35 and in the 2nd Symposium on Fundamental Organic Chemistry of Chemical Society of Japan, Kyushu University, October 15−17, 1994; Abs. 6, p 15.

(2) Frey, J.; Rappoport, Z. *J. Am. Chem. Soc.* **1996**, *118*, 5169−5181.

(3) For a review, see: Hegarty, A. F.; O'Neill, P. In *The Chemistry of Enols*; Rappoport, Z., Ed.; Wiley: Chichester, 1990; Chapter 10, p 639.

(4) (a)Urwyler, B.; Wirz, J. *Angew. Chem., Int. Ed. Engl.* **1990**, *29*, 790. (b) Almstead, J. K.; Urwyler, B.; Wirz, J. *J. Am. Chem. Soc.* **1994**, *116*, 954.

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(7) (a) Zimmerman, H. E.; Cutshall, T. W. *J. Am. Chem. Soc.* **1958**, *80*, 2893. (b) Zimmerman, H. E.; Cutshall, T. W. *J. Am. Chem. Soc.* **1959**, *81*, 4305.

(8) Meyer, K. H. *Chem. Ber*., **1912**, *45*, 2843; **1914**, *47*, 826.

(9) For a discussion of bromine addition for determining enol content of carbonyl compound, see: Toullec, J. In *The Chemistry of Enols*; Rappoport, Z., Ed.; Wiley: Chichester, 1990; Chapter 6, p 323.

(10) (a) Buehler, C. A. *Chem. Rev.* **1964**, *64*, 7. (b) Hesse, G. In *Methoden der Organishchen Chemie*; (Houben-Weyl), Georg Thieme Verlag: Stuttgart, 1978; Vol. VI/1d, p 217. (c) Verter, H. S. In *The Chemistry of the Carbonyl Group*; Zabicky, J., Ed.; Wiley: Chichester, 1970; Vol. 2, p 71.

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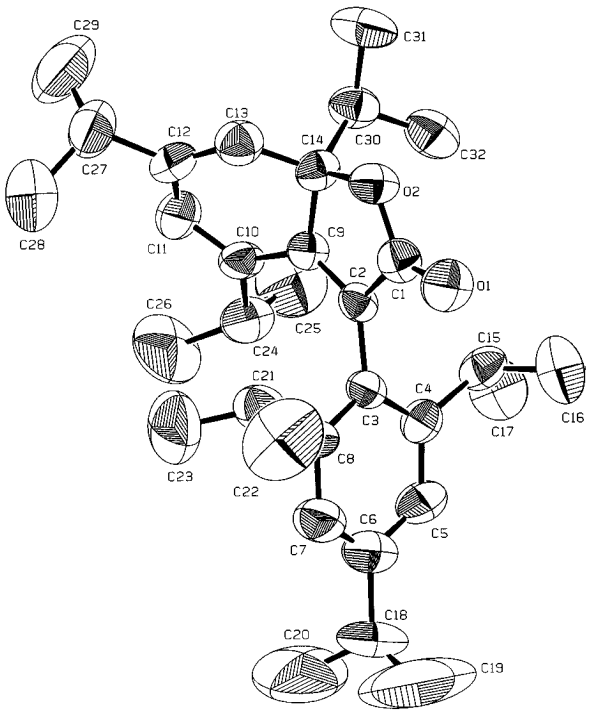
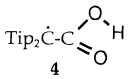


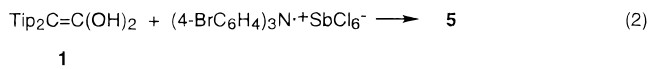
Figure 1. An ORTEP drawing and numbering scheme of lactone **5**.

Hence, formation of **4** or of 2-hydroxybenzofuran, followed by tautomerization to the ketone are possible alternatives under oxidation conditions.



4

(a) Oxidation with [(4-BrC$_6$H$_4$)$_3$N$^{\cdot+}$SbCl$_6^-$] (TBPA). When TBPA was added to the solution of **1** in 42:5:3 DMF:THF:water either at 0 °C or at −18 °C a rapid oxidation took place, judged by the rapid change of the blue-colored TBPA solution to a red-colored solution. The only product isolated was the five-membered lactone 4,6,7a-tris(1-methylethyl)-3-[2,4,6-tris-(1-methylethyl)phenyl]-2(7a*H*)benzofuranone **5**, where a ring carbon carrying an i-Pr group is attacked by the active oxygen species and the aromaticity of the ring is lost (eq 2). The structure of **5** fits its observed spectra and is corroborated by



1

X-ray diffraction. An ORTEP drawing is given in Figure 1 and selected bond lengths and angles are given in Table 1.[13] An interesting feature in the structure of **5** is the relatively long bond from the bridge carbon C(14) to the isopropyl group (1.543 Å), compared with the average (1.519 ± 0.012 Å) of the other five C-i-Pr bonds. This is due to steric crowding around the quaternary carbon C(14) and is found in the closely related structure shown in Figure 2.

The suggested mechanism is shown in Scheme 1. The initial oxidation can lead to the radical **4**.[2] Attack of the oxygen on the aromatic ring and further oxidation will give cation **7**. We present an alternative where the attacking species is the cation **6a** ↔ **6b**. Following Schmittel, who investigated the mechanism of the oxidative cyclization of enols and found that the radical oxidation is faster than its cyclization,[11] we believe that cation **6** is formed via oxidation of the initially formed radical. The electrophilic attack by the positive oxygen on the alkyl-bearing carbon leads to a Wheland type carbocationic intermediate **7**. Analogous reactions in the past led to product formation via two modes of loss of a positive moiety, as summarized in Scheme 2. With mesityl-substituted enols a 1,2-shift of the methyl group on the attacked carbon followed by loss of the

Table 1. Selected Structural Parameters for the Five-Membered Lactone **5**

bond length	Å	bond angle	deg
C(1)−O(1)	1.207 (6)	O(1)−C(1)−O(2)	120.5 (6)
C(1)−O(2)	1.368 (7)	O(1)−C(1)−C(2)	129.4 (6)
C(1)−C(2)	1.467 (7)	O(2)−C(1)−C(2)	110.0 (6)
C(2)−C(3)	1.495 (7)	O(2)−C(14)−C(9)	104.1 (4)
C(2)−C(9)	1.345 (7)	O(2)−C(14)−C(13)	111.0 (5)
C(9)−C(10)	1.479 (7)	O(2)−C(14)−C(30)	107.4 (5)
C(9)−C(14)	1.498 (7)	C(1)−O(2)−C(14)	108.3 (5)
C(10)−C(11)	1.337 (8)	C(1)−C(2)−C(3)	122.8 (5)
C(11)−C(12)	1.463 (9)	C(1)−C(2)−C(9)	107.2 (5)
C(12)−C(13)	1.331 (8)	C(2)−C(9)−C(10)	132.6 (5)
C(13)−C(14)	1.495 (8)	C(2)−C(9)−C(14)	110.1 (5)
C(14)−O(2)	1.462 (6)	C(3)−C(2)−C(9)	129.5 (5)
C(14)−C(30)	1.543 (7)	C(9)−C(10)−C(11)	113.9 (6)
5 C(ring)−C(i-Pr)	1.50(1)−1.534(8)	C(9)−C(14)−C(13)	109.2 (5)
		C(9)−C(14)−C(30)	114.8 (5)
		C(10)−C(9)−C(14)	116.8 (5)
		C(10)−C(11)−C(12)	123.9 (6)
		C(11)−C(12)−C(13)	119.5 (6)
		C(12)−C(13)−C(14)	119.2 (6)
		C(13)−C(14)−C(30)	110.2 (5)

Dihedral angle	deg
Tip[a]−CHD[b]	65.18
CHD[b]−LAC[c]	37.67
Tip[a]−LAC[c]	91.06

[a] Tip = C(3)−C(8). [b] CHD = C(9)−C(14). [c] LAC = C(1)−C(2)−C(9)−C(14)−O(2).

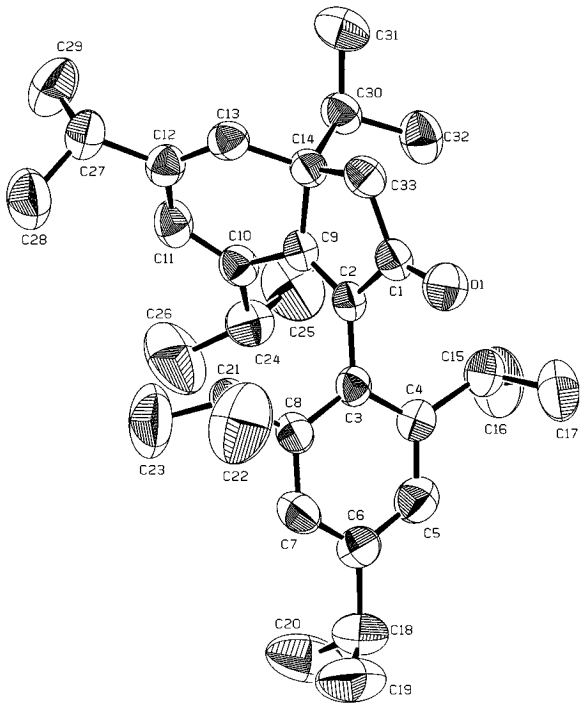


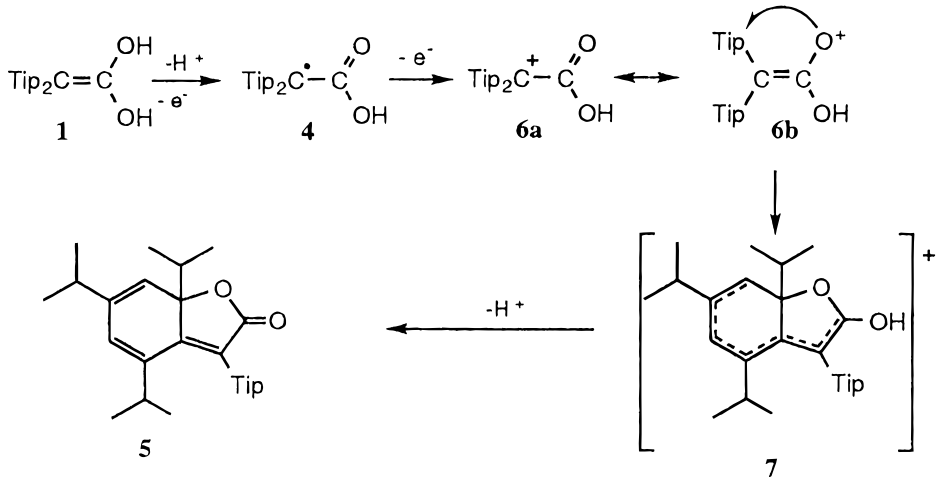
Figure 2. An ORTEP drawing and numbering scheme of the bicyclic trienone **12**.

(11) (a) Schmittel, M.; Baumann, U. *Angew. Chem., Int. Ed. Engl.* **1990**, *29*, 541. (b) Schmittel, M.; Röck, M. *Chem. Ber.* **1992**, *125*, 1611. (c) Schmittel, M.; Gescheidt, G.; Röck, M. *Angew. Chem., Int. Ed. Engl.* **1994**, *33*, 1961. (d) Röck, M.; Schmittel, M. *J. Chem. Soc., Chem. Commun.* **1993**, 1739. (e) Schmittel, M.; Heinze, J.; Trenkle, H. *J. Org. Chem.* **1995**, *60*, 2726.

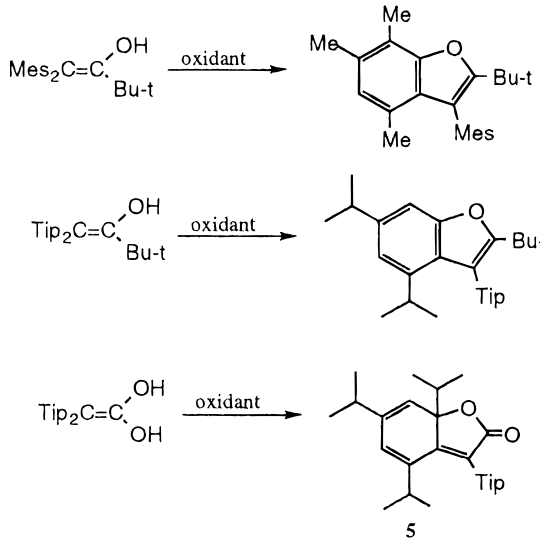
(12) Frey, J.; Rappoport, Z. Unpublished results. Frey, J. Ph.D. Thesis, The Hebrew University, Jerusalem, 1996.

(13) For a stereoview and additional crystallographic data see the supporting information.

Scheme 1

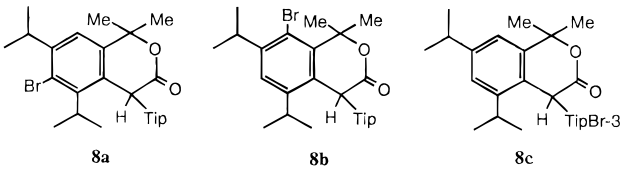


Scheme 2



neighboring hydrogen retained the aromaticity of the ring.[11a,b] With 2,2-ditipyl-1-H or 1-R ethenols an i-Pr^+ is lost by an overall oxodeisopropylation, retaining again the aromaticity.[12] A third course is followed by **1** where the aromaticity of the ring is lost, but the formed hydroxyallylic dienylic carbocation **7** is highly delocalized by the double bonds and the OH group, and the proton is lost from the latter to give **5** (Scheme 2). In spite of the loss of the aromaticity, **5** is stable. When it was refluxed in EtOH/NaOH, neither hydrolysis of the lactone ring nor loss of the isopropyl group took place.

(b) Reaction with Bromine. **(i) Reaction of 1.** Reaction of a 98% solution of enediol **1** in the ternary DMF:THF:water mixture with 2:1 excess of bromine in CCl_4 at −18 °C was impossible to follow by the bromine decoloration since the solution remained bright orange. However, the ^{1}H NMR spectrum showed an immediate disappearance of the enediol doublet at 0.3 ppm and formation of at least two products: the five-membered lactone **5**, formed in the oxidation by TBPA and a new bicyclic six-membered bromine-containing lactone **8**, which are formed in a 0.58:1 ratio. Both compounds were isolated by chromatography. The skeleton of **8** was assigned as of 4-[2,4,6-tris(1-methylethyl)phenyl]-1,4-dihydro-1,1-dimethyl-5,7-bis(1-methylethyl)-3*H*-2-benzopyran-3-one on the basis of its high resolution and EI mass spectra, the high wavenumber IR absorption of the C=O group at 1746 cm^{-1}, the presence of two singlet diastereotopic Me groups at δ 1.99 and 2.04, five C−H isopropyl heptets, a singlet CH−CO at δ 5.59, and three Ar−H singlets at δ 6.51, 7.00, and 7.02 ppm in the ^{1}H NMR spectrum. However, we could not unequivocally assign the position of the bromine and it may be either at position 6 or 8 of the condensed ring (**8a** or **8b**, respectively) or at position 3 of the free tipyl ring (**8c**). The position of the bromine is closely associated with the mechanism of formation of **8** (see below). Unfortunately, single crystals suitable for X-ray diffraction could not be obtained so far, thus precluding the unequivocal structure determination. When the same reaction was conducted at room temperature, only **8** was formed.



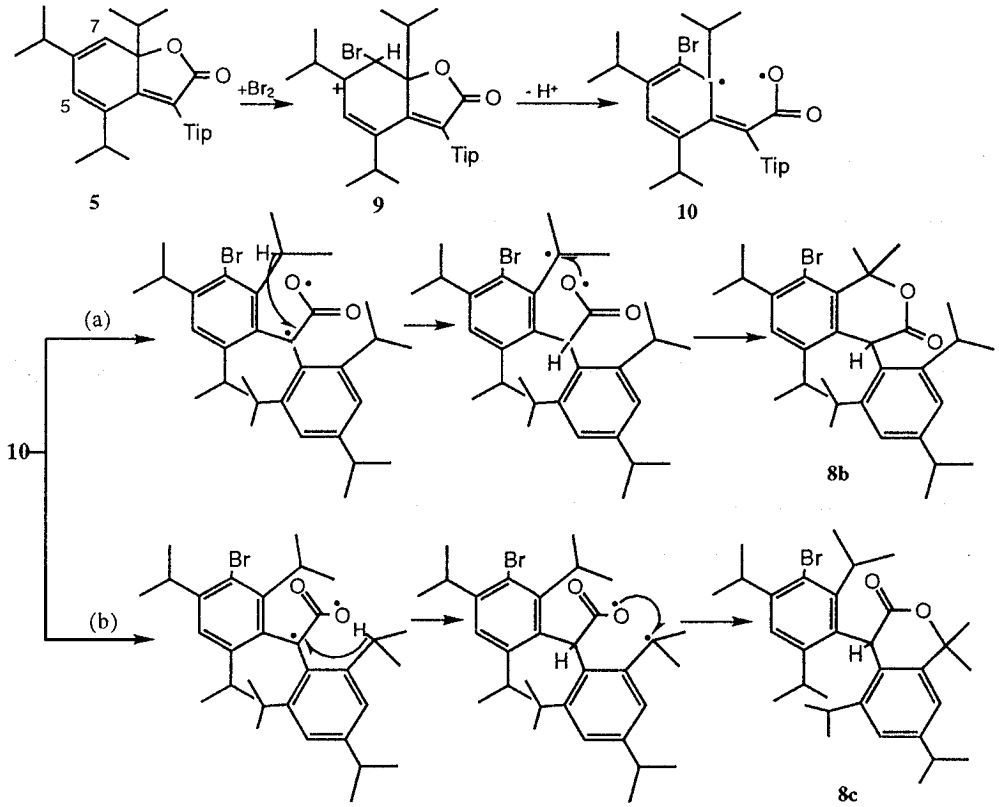
Formation of **5** and **8** is reminiscent of the formation of benzofurans by oxidation of the 2,2-ditipyl-1-*R*-ethenols (R = H, Me, t-Bu).[12] A similar oxidative cyclization gave two isomeric dibrominated benzofurans in the addition of bromine to 2,2-dimesityl-1-*tert*-butylethenol.[14] We therefore suggest that the cyclization initiates by oxidation of the enediol moiety by bromine. Indeed, **5** was formed together with **4** in an attempted oxidation of **1** with iodine at −18 °C and both are formed in the air oxidation of **1** at 4 °C. In order to find out if **5** and **8** are formed in parallel or by a consecutive sequence, a solution of pure **5** in DMF:THF:water was reacted with bromine in CCl_4 at room temperature for 16 h. The only product observed was lactone **8** indicating that it is derived from **5**. Hence we suggest that **1** or its enolate ion $\mathbf{1}^-$ is initially oxidized by bromine to **4**, which generates the kinetically controlled product **5** (Scheme 1)**,** and the latter then gives **8**. This scheme is consistent with the mechanism suggested by Bailey[15] and Schmittel[11] for oxidation of 1-R-2,2-dimesitylethenols (R = alkyl, aryl). The main difference between Ar = Mes and Ar = Tip will be discussed elsewhere.

The difficulty in assigning the position of the bromine in **8** is that the three ^{1}H NMR signals at δ 6.51, 7.00, and 7.02 ppm could be equally assigned to one of the two positions in the condensed bezopyran ring or to a *m*-position in the noncondensed bromo-substituted tipyl ring. That the two low field

(14) Shainyan, B. A.; Eventova, I.; Rappoport, Z. *J. Chem. Soc., Perkin Trans. 1* **1993**, 1281.

(15) Bailey, P. S.; Potts, F. E. III; Ward, J. W. *J. Am. Chem. Soc.* **1970**, *92*, 230. Bailey, P. S.; Ward, J. W.; Potts, F. E. III, Chang, Y.-G.; Hornish, R. E. *J. Am. Chem. Soc.* **1974**, *96*, 7228.

Scheme 3



signals are doublets with $J = 1.7$ Hz is consistent with a *m*-coupling expected for either of these structures. The HRMS fragment at *m*/*z* 260 seems consistent with the loss of the TipBr fragment by a simple α-cleavage from structure **8c**, but the same fragment can be formed from **8a** or **8b** by cleavage of two bonds. We attempted an alternative approach based on dynamic NMR for locating the bromine. The assumption is that since we see three Ar-H, seven i-Pr-Me, and five i-Pr-H signals if the structure were **8a** or **8b** the Ar-H and the *o*-i-Pr-methyls and methines of the noncondensed ring, respectively, are diastereotopic due to slow rotation of the ring. Hence, if raising the temperature will lead to a coalescence process, the bromine is on the condensed ring. When a sample of **8** in CD_2Cl_2 was heated up to 413 K neither coalescence nor broadening of the Ar-H, Me, or C*H*Me_2 signals was observed. Assuming that the shielded proton is on the bromine-containing ring, (δ Ar-H (TipBr) > δ Ar-H(Tip-H)), we calculate from the $\Delta\nu$ difference of the other two signals a lower limit of >22.5 kcal mol^{-1} for the rotational barrier. This high barrier is reminiscent of the >24 kcal mol^{-1} lower limit for the rotation barrier measured by Miller[16] for the rotation around the Tip-C bond in 2-tipylacenaphthylenol. Consequently, if the rotation barrier is high, we cannot acertain the structure of **8** by DNMR.

Two alternative routes according to the position of the bromine could account for the transformation of **5** to **8** (Scheme 3). Both start by attack of the bromine on either carbon 6 or 8 (and the latter possibility is shown in the scheme) of the cyclohexadiene ring of **5** followed by loss of a proton from **9**. A homolytic cleavage of the C−O bond facilitated by the crowding around the carbon and the adjacent electron-withdrawing bromine atom generates diradical **9**, which can rearrange by cyclization with an isopropyl group of either the brominated (route a, giving **8b**) or the nonbrominated (route b, giving **8c**) tipyl ring. The cyclization can proceed by a hydrogen transfer to the carbon radical, followed by rapid combination of the formed carbon radical with the oxygen radical. A mechanism involving bromination of the free tipyl ring, followed by cyclization is also possible, but we note that the more deactivated ketene **2** and acid **3** are inert to bromine under similar conditions (see below).

The lack of bromine addition to the double bond, in spite of the high rates of reaction of even monoenols with bromine,[9] is certainly due to the severe steric hindrance at the double bond, which results in its shielding to the approaching bromine electrophile. The reagent is then directed to the more available oxygen reaction site. In contrast with previous suggestions, even the enol of vinylmesitylene is brominated on the ring, but the steric reason does not predominate in this case.[17]

(ii) Reaction of 2 and 3 with Bromine. The formation of **5** or **8** is not due to the presence of unreacted ditipylketene **2** or the product ditipylacetic acid **3**, since in the reactions of **2** and **3** with 2 molar equiv of bromine under conditions similar to those of the reaction of **1** at both 0 °C and −18 °C the starting materials were recovered unchanged.

(c) Reaction with Iodine. When a solution of **1** in THF-d_8 was reacted with 2 molar equiv of iodine, two products were formed in an ca. 1:1 ratio. They were separated and identified by ^{1}H NMR as lactone **5**, and the species whose spectrum is given in Figure 5 of the preceding paper which was ascribed to the radical **4**, presumably associated with one molecule of **3**.[2]

(d) Air Oxidation. When a solution of **1** in THF-d_8 which was kept at 4 °C for 30 days was analyzed, a ca. 1:1 mixture of **5** and ditipylacetic acid **3** was formed.

The oxidation reactions under various conditions are summarized in Scheme 4.

Attempted Etherification. A strong evidence for the structure of **1** will be a conversion of its two OH groups to

(16) Miller, A. R. *J. Org. Chem.* **1976**, *41*, 3599.

(17) Kresge, A. J.; Schepp, N. P. *J. Chem. Soc., Chem. Commun.* **1989**, 1548.

Scheme 4

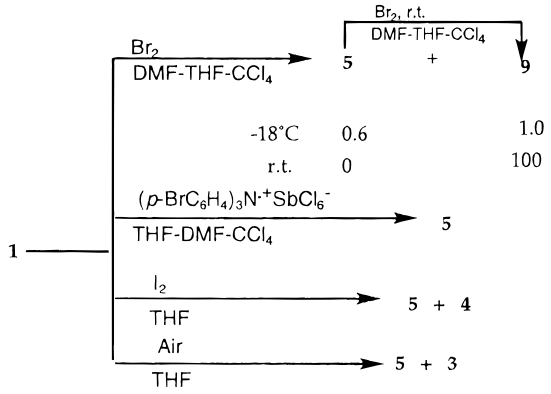


Table 2. Selected Structural Parameters of **12**

bond length	Å	bond angle	deg
C(1)−O(1)	1.215 (3)	O(1)−C(1)−C(2)	125.9 (3)
C(1)−C(2)	1.480 (4)	O(1)−C(1)−C(33)	125.5 (3)
C(1)−C(33)	1.512 (4)	C(1)−C(2)−C(3)	122.5 (2)
C(2)−C(3)	1.485 (4)	C(1)−C(2)−C(9)	108.5 (2)
C(2)−C(9)	1.354 (3)	C(1)−C(33)−C(14)	105.6 (2)
C(9)−C(10)	1.473 (4)	C(2)−C(1)−C(33)	108.6 (2)
C(9)−C(14)	1.522 (4)	C(2)−C(9)−C(10)	129.1 (2)
C(10)−C(11)	1.351 (4)	C(2)−C(9)−C(14)	113.5 (2)
C(11)−C(12)	1.472 (4)	C(3)−C(2)−C(9)	128.7 (2)
C(12)−C(13)	1.320 (4)	C(9)−C(10)−C(11)	114.6 (3)
C(13)−C(14)	1.508 (4)	C(9)−C(14)−C(13)	107.5 (2)
C(14)−C(30)	1.567 (4)	C(9)−C(14)−C(30)	110.7 (2)
C(14)−C(33)	1.538 (4)	C(9)−C(14)−C(33)	103.2 (2)
5 C(ring)−C(i-Pr)	1.505(4)−1.518(4)	C(10)−C(11)−C(12)	123.1 (3)
		C(10)−C(9)−C(14)	117.2 (2)
		C(11)−C(12)−C(13)	119.0 (3)
		C(12)−C(13)−C(14)	122.1 (3)
		C(13)−C(14)−C(30)	108.6 (2)
		C(13)−C(14)−C(33)	114.6 (2)
		C(13)−C(14)−C(33)	114.6 (2)
		C(30)−C(14)−C(33)	112.1 (2)

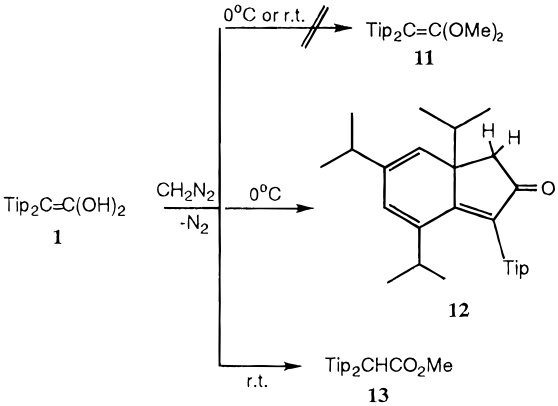
Dihedral angle	deg
Tip[a]−CHD[b]	53.38
CHD[b]−KET[c]	142.69
Tip[a]−KET[c]	102.23

[a] Tip = C(3)−C(8). [b] CHD = C(9)−C(14). [c] KET = C(1)−C(2)−C(9)−C(14)−C(33).

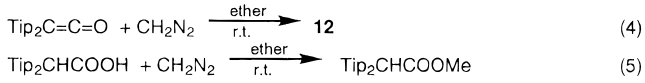
either two OMe or two $OSiMe_3$ groups. None of the expected ketene acetals had been formed as described below.

Reaction with Diazomethane.[18] When a solution of ≥90% of **1** in THF was reacted with diazomethane the expected dimethyl acetal **11** was not formed. Instead a nearly quantitative yield of the conjugated bicyclic trienone 3,3a-dihydro-3a,5,7-tris(1-methylethyl)-1-[2,4,6-tris(1-methylethyl)phenyl]-2*H*-inden-2-one **12** was isolated from the reaction after 12 h at 0 °C. The structure of **12** was corroborated by X-ray diffraction. Its ORTEP drawing is given in Figure 2, and selected structural parameters are given in Table 2.[13] As in the structure of **5**, to which **12** closely resembles the C(14)−C(30) bond is appreciably longer (1.567 Å) than the average of the other five C−C(i-Pr) bond lengths (1.517 ± 0.004 Å) for the same reason, i.e., crowding around C(14). Some interaction between C(32) and the C(33) hydrogen may be responsible for the longer bond than in **5**. The ring/ring dihedral angles in **5** and **12** are of the same magnitude.

The methyl ester Tip_2CHCO_2Me **13** was formed only in traces, but when the reaction was conducted for 4 days at 4 °C the **13** to **12** ratio was 1:0.92, and when the reaction was conducted at room temperature **13** was formed in >99% yield (eq 3). The presence of only one oxygen in **12** suggests that ketene **2** is a likely precursor to it. Indeed the reaction of **2** with diazomethane gave **12** (eq 4). In contrast, reaction of acid **3** with diazomethane gave only ester **14** (eq 5). We therefore believe that a reversibly formed ketene **2** from **1** (see below) reacts at its double bond to give the arylcyclopropanone **14**[19] which reacts further with one of the tipyl rings to give **12**.



(3)



(4)

(5)

Two conclusions can be drawn from the product ratios. First, the lower the temperature, the more kinetically favored is the dehydration of **1** to **2** over its trapping. Second, the total absence of acetal **11** suggests that the second hydroxylic proton of **1** is much less acidic than the first one, so that **13** is formed by etherification of one hydrogen and tautomerization of the hemiacetal formed before further etherification. We also note that **1** is more acidic than 2,2-ditipylethenol **16** which failed to yield the enol ether when reacted with diazomethane under similar conditions. Indeed, Kresge[5b] and others had shown that there is a large difference in the pK_a's of the two hydroxy groups of the 1,1-enediols, e.g., for $PhC(CN)=C(OH)_2$ pK_a^1(**3**) = 0.99; pK_a^2 = 8.70).[5b] Note however that at 4 °C almost no tautomerization of **1** to **3** takes place so that initial tautomerization to **3**, and its further esterification to **13** does not take place. Apparently, the tautomerization of the hemiacetal $Tip_2C=C(OH)OMe$ is faster than etherification of the other hydrogen.

Mechanistically, the **2** to **12** transformation can be rationalized by two alternative routes: (a): a vinylcyclopropane type rearrangement, involving one of the aromatic double bonds of **14** (Scheme 5a) [The only precedent we found of such a rearrangement involving an aromatic double bond is the pyrolysis of phenylcyclopropane in which indene was suggested as a minor product.[20]] and (b) the formation of an oxyallyl intermediate **15** which is intramolecularly trapped by an aromatic double bond (Scheme 5b). Since recent *ab initio* calculations[21] suggest that oxyallyl has a strong biradical character, a rearrangement through a biradical intermediate, formally similar to a stepwise vinylcyclopropane rearrangement is presented in Scheme 5b. The ring-opening of cyclopropanones produces

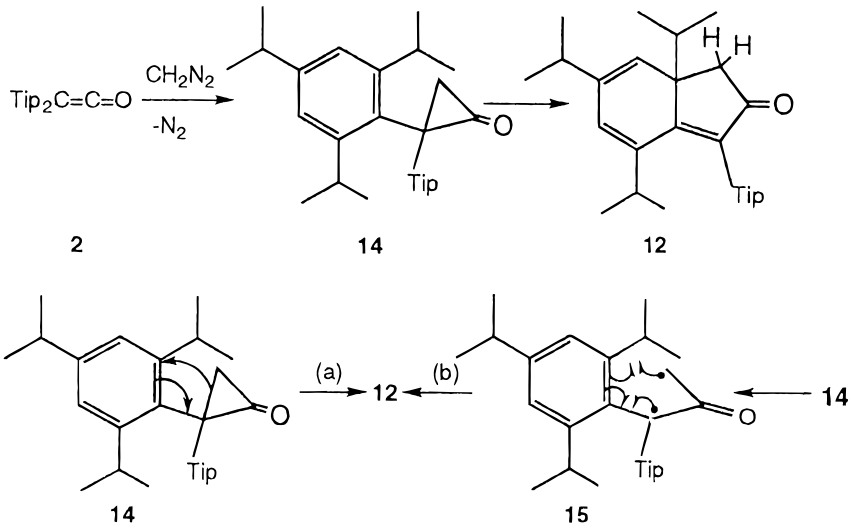
(18) For a preliminary communication see Frey, J.; Rappoport, Z. *J. Am. Chem. Soc*. **1995**, *117*, 1161.

(19) For formation of cyclopropanone from ketene and diazomethane, see: Turro, N. J.; Hammond, W. B. *Tetrahedron* **1968**, *24*, 6017.

(20) Wood, J. T.; Arney, J. S.; Cortes, D.; Berson, J. A. *J. Am. Chem. Soc.* **1978**, *100*, 3855.

(21) Kim, D.; Hrovst, D. A.; Borden, W. T.; Jorgensen, W. L. *J. Am. Chem. Soc.* **1994**, *116*, 3494.

Scheme 5



oxyallyl systems,[22] and bulky substituents on the cyclopropanone skeleton facilitate this reaction.[23] The loss of aromaticity in either route is apparently compensated by the relief of the cyclopropanone ring strain.

A possible alternative reaction initiated by reaction of the diazomethane at the C═O bond will give a vinylideneoxirane (an allene oxide). However, allene oxides rearrange to cyclopropanones,[20,24] so that **14** will be formed by this route, too.

Reaction with Trimethylchlorosilane. When a solution of >90% of **1** in THF-d_8 was reacted with an equimolar amount of Me_3SiCl, ditipylacetic acid **3** was formed immediately, according to the ^1H NMR spectrum. We ascribe the rapid isomerization to catalysis by the HCl formed from the reaction of the silane with the water present in the solution. The known[2] bis(trimethylsilyl) ketene acetal **17** was not observed.

$Tip_2C{=}CHOH$ **16** $Tip_2C{=}C(OSiMe_3)_2$ **17**

Reversibility of Ditipylketene Hydration.[18] Hydration of simple carbonyl compounds is reversible[25] but the possibility of reversibility of the ketene hydration was not previously discussed, presumably due to the rapid following tautomerization to the carboxylic acid. Also, it was commented about the 1,1-enediols formed by ketene hydration that they "...have also been called 'ketene hydrates'. Their chemistry, however, is quite different from that of other carbonyls, e.g., aldehyde and ketone hydrates, and more like that of enol isomers of aldehydes and ketones".[5c] However, the formation of **12** with diazomethane in the reaction of a ≥98% solution of enediol **1** which contained <2% ketene **2,** and the independent formation of **12** from ketene **2** were interpreted above as due to reaction of the diazomethane with **2** which is present in the solution of **1**. The high yield of **12** excludes reaction only with the residual ketene which did not hydrate to **1**. Hence, **2** should be formed from **1** in solution. Since **1** is formed from **2** and water (eq 1), the ketene hydration would have to be reversible. This was corroborated by several ways.

During the hydration of **2**, we noted that although it is nearly completely hydrated to enediol **1**, it never disappeared completely, and a certain amount of **2** persisted. For example, when 2.7 mmol $H_2{}^{18}O$ (95% ^{18}O) were added to 0.045 mmol of **2** in THF-d_8 at 0 °C, the ^1H NMR spectrum showed after 8 h the presence of a 3.5% **2**, 93% **1**, and 3.5% **3** mixture. When the temperature was raised to 25 °C**,** the irreversible tautomerization of **1** to acid **3** was accelerated, but it was also accompanied by an *increase* in intensity of the signals of ketene **2** at the expense of those of enediol **1**. On recooling, more **2** was converted to **1** showing that the **2** ⇌ **1** interconversion is reversible. After 4 h at 25 °C the same mixture consisted of 8% **2**, 28% **1**, and 64% **3**. When this mixture was rapidly chromatographed on a short silica column using petroleum ether eluent, 0.5 mg (1.12×10^{-6} mol) of the pure **2** were isolated. Negative ion mass spectrometry showed that the recovered ketene was partially ^{18}O-labeled since fragments at *m*/*z* 448 ($Tip_2C{=}C{=}{}^{18}O$) and 446 ($Tip_2C{=}C{=}{}^{16}O$) were formed in a 2:1 ratio. Positive ion mass spectrometry showed cluster formation in the *m*/*z* range of the molecular peak, but two M-Tip fragments at *m*/*z* 245 ($TipC{=}C{=}{}^{18}O$) and 243 ($TipC{=}C{=}{}^{16}O$), were again formed in a 2:1 ratio. FTIR of the recovered ketene in CCl_4 showed two signals, at 2095 cm^{-1} ($Tip_2C{=}C{=}{}^{16}O$) and at 2068 cm^{-1} (ascribed to $Tip_2C{=}C{=}{}^{18}O$) in a 2:1 intensity ratio (see Figure 1 in ref 18). Since the ϵ value of $C{=}{}^{16}O$- and $C{=}{}^{18}O$- species are not necessarily identical[26] their intensity ratio can serve only as an approximation of the [labeled]/[nonlabeled] species ratio. To our knowledge this is only the second observation of an ^{18}O-labeled ketene. The $\Delta\nu$ value between the ^{16}O- and the ^{18}O-species for the parent ketene (ν = 2085.6, 2058; $\Delta\nu$ = 28 cm^{-1}),[27] or for benzophenone (ν = 1664, 1635, $\Delta\nu$ = 29 cm^{-1}),[28] or fluorenone (ν = 1716, 1685; $\Delta\nu$ = 31 cm^{-1})[29] resemble those of **2.** We conclude that ketene hydration involves formation of an intermediate symmetrical with respect to the oxygens (excluding isotopic differences)**,** which is presumably the labeled enediol **1*** and that the hydration is

(22) Wasserman, H. H.; Berdahl, D. R.; Lu, T-J. in *The Chemistry of the Cyclopropyl Group*; Rappoport, Z., Ed.; Wiley: Chichester, 1987; Chapter 23, p 1455 and references cited therein.

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(24) Crandall, J. K.; Machleder, W. J. *J. Am. Chem. Soc.* **1968**, *90*, 7347; Crandall, J. K.; Machleder, W. H.; Sojka, S. J. *J. Org. Chem.* **1973**, *38*, 1149.

(25) (a) For a review, see: Ogata, Y.; Kawasaki, Y. In *The Chemistry of the Carbonyl Group*; Zabicky, J., Ed.; Wiley-Interscience: 1970; Vol. 2, Chapter 1, pp 3−11. (b) For extensive recent calculations on the hydration of C═O compounds see Wolfe, S.; Kim, C.-K.; Yang, K.; Weinberg, N.; Shi, Z. *J. Am. Chem. Soc.* **1995**, *117*, 4240.

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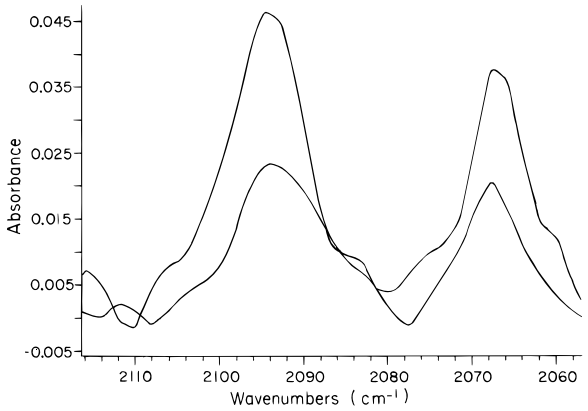
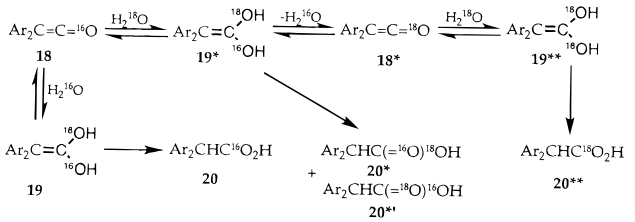
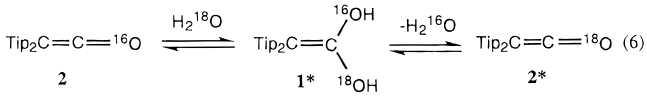


Figure 3. FTIR spectra of the ketene stretching region in the reaction of **2** with $H_2{}^{18}O$ in THF at 1 °C. Top: after 8 h (2:3 **2***:**2**); bottom: after 26 h (1:1 **2**:**2***).

Scheme 6



reversible and leads to extensive exchange in the reisolated ketene **2**, i.e., to formation of **2*** (eq 6).



The extent of exchange was followed briefly by observing the formation of labeled ketene by FTIR. Reaction of a 120-fold excess of 97% $H_2{}^{18}O$ over **2** in THF at 1 °C showed after 8 and 26 h, 9% and 5% of the ketene which was 40% and 50% **2***, respectively (Figure 3).

Reversibility of Other Diarylketenes Hydration. Both the hydration and the hydrolysis of ketenes become slower with the increased bulk of the ketene substituents.[2,30] Hence, attempted isolation of labeled ketene from the reaction mixtures formed in the hydration of less bulky and more reactive ketenes with $H_2{}^{18}O$ may not be easy, and a more convenient evidence for the reversibility of the hydration is desirable. Such evidence will be the observation of a partial formation of a di-^{18}O labeled carboxylic acid in the hydration of the unlabeled ketene as demonstrated in Scheme 6. The hydration of an O^{16}-diarylketene with $H_2{}^{16}O$ (either formed in the reaction [Scheme 6] or derived from atmospheric or solvent-derived water) will give the di-^{16}O-labeled 1,1-enediol **19** which will tautomerize to the di-^{16}O-labeled acid **20**. Hydration of **18** with $H_2{}^{18}O$ will give the mono-^{16}O, mono-^{18}O-enediol **19*** which by hydrolysis will give the two isomeric $^{16}O^{18}O$-acids **20*** and **20*′** (which may interconvert rapidly by ionization) and by reversal of the hydration will give both **18** and the labeled ketene **18***. **18*** could be hydrated with the formed $H_2{}^{16}O$ to **19*** (ending as **20*** and **20*′**), and hydration with $H_2{}^{18}O$ will give the di-^{18}O-labeled enediol **19**** which will give the di-^{18}O-labeled acid **20****. Consequently, hydration with $H_2{}^{18}O$ should give the four acids **20, 20*, 20*′,** and **20****. The observation of the dilabeled acid **20**** should serve as strong evidence that the ketene hydration is reversible since it can arise only from the labeled ketene **18***. This will be an unequivocal evidence if oxygen exchange of the diarylacetic acid with $H_2{}^{18}O$ by a mechanism which does not involve a ketene intermediate (e.g., by nucleophilic attack of water on the C═O of the acid) is much slower than the hydration. Indeed, oxygen exchange of carboxylic acids under conditions related to the hydration is known to be very slow.[31]

Table 3. Percentage of Acids Formed on Hydration of Ketenes with 95% $H_2{}^{18}O$ in THF

acid/ketene	**2**[a]	**21**[a]	**22**[a]	**23**[b,c]
$Ar_2CHC^{16}O_2H$	5 (9.3)[d]	14 (22.4)[d]	11 (16.0)[d]	39 (77.8)[d]
$Ar_2CHC^{18}O^{16}O_2H$	59 (100)[d]	65 (100)[d]	71 (100)[d]	50 (100)[d]
$Ar_2CHC^{18}O_2H$	36 (60.0)[d]	21 (33.5)[d]	18 (25.0)[d]	11 (21.8)[d]

[a] From the MN^+-Ar signals. [b] From the MH^+ signals. [c] Reaction in 97% -$^{18}O-H_2{}^{18}O$. [d] Relative values to those for the ^{18}O-mono-labeled acids (see text).

We corroborated these assumptions by analyzing the acid isolated from the hydration of ditipylketene with $H_2{}^{18}O$, from the experiment which had already shown the reversibility of the hydration. The acid was analyzed by CI mass spectrometry which should distinguish among **20, 20*** + **20*′**, and **20****. The most relevant signals appeared as a triad of signals at *m*/*z* 469, 467, and 465 (MH + 4, MH + 2, and MH) and at *m*/*z* 265, 263 and 261(TipCHC$^{18}O_2$H, TipCHC$^{18}O^{16}$OH, TipCHC$^{16}O_2$H). For each set of signals the intensities ratio $^{18}O_2$-species/$^{18}O^{16}O$-species was 64:100. This finding strongly supports the formation of labeled ketene **18*** by reversal of the hydration.

We extended this tool in order to find out whether the reversibility of hydration is more general and not restricted only to **2**. Ketenes **21**−**23** were hydrated with 60-fold excess of $H_2{}^{18}O$ in THF, and the composition of the labeled carboxylic acid products was determined from the relative abundances of the appropriate signals (Table 3). A control experiment by using CI-MS analysis had shown that **3** and the acids **24**−**26** which are the hydration products of **21**−**23** in $H_2{}^{16}O$ do not exchange oxygen under the reaction conditions. Hence the $^{18}O_2$-acids are obtained from the reaction of $H_2{}^{18}O$ with the initially formed ^{18}O-labeled ketenes, and hydration of **21**−**23** is also reversible.

$Ar_2C=C=^{16}O$	$Ar_2CHC^{16}O^{16}OH$
21: Ar = C_6Me_5	**24**: Ar = C_6Me_5
22: Ar = Mes (2,4,6-$Me_3C_6H_2$; mesityl)	**25**: Ar = Mes
23: Ar = Ph	**26**: Ar = Ph

The ratio of the observed M + 1 to the M signals of the three isotopic signals differed somewhat from the expected ratio based on the 1.1% ^{13}C isotopes. We therefore assume that M − 1 peaks might also contribute to these intensities, and regard the results of Table 3 as only qualitative. Moreover, since the di-^{16}O acid arises both from the reaction of unlabeled ketenes with $H_2{}^{16}O$ and from traces of the acid in the original ketenes, we ascribe no significance to its relative percentage. Consequently, we also give in Table 3 the relative ratios of the mono-^{18}O-labeled to the di-^{18}O labeled, taking that of the monolabeled acid as 100%.

Two generalizations arise from Table 3. First, the extent of exchange increases qualitatively with increased stability of the intermediate enediol, which in turn increases with the increased bulk of the ketene substituents (*vide supra*). This selectivity-reactivity type behavior is connected with the decreasing life-

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(31) Samuel, D.; Silver, B. L. *Adv. Phys. Org. Chem.* **1965**, *3*, 123.

time of the enediol **19/19*/19**** due to tautomerization to the acid. It seems that in the competition between the tautomerization and the expulsion of the ketene from isotopomeric **19** the rate of the former reaction responds more strongly to a change of the (bulk of) the substituents. If this behavior will be extended to less bulkier aliphatic ketenes, reversibility in their hydration may not be observed. The second generalization is relevant to the extensively experimentally and computationally[30] investigated question whether the neutral hydrolysis of ketenes proceeds via water addition to the C═C or to the C═O bond. The observed reaction rates were interpreted by a mechanism involving an interaction between a lone pair in H_2O and the ketene LUMO.[32] Satchell et al.[33] suggested that dimeric water add concertedly across the C═C double bond, whereas theoretical studies of ketene hydration in the gas phase indicated that addition across the C═O bond is favored.[34,35] It was argued that addition to the C═C bond is not prohibitively higher in energy and cannot be completely excluded for all ketenes. The preferred mechanism is dependent on steric, conformational, and electronic effects imposed by the C_β substituent.[34] A recent *ab initio* calculation indeed suggests that the energies of the transition states for addition to the C═C and the C═O bonds are similar.[36] Another recent calculation deals with decarboxylation vs. dehydration (i.e., ketene formation) from ethene-1,1-diol, i.e., the C═O "adduct".[37] Our experimental observation of the 1,1-enediolic intermediates in ketene hydration processes and the apparent $^{18}O/^{16}O$ exchange in such species, as reflected by the hydration reversibility firmly corroborates the preference of C═O addition over the C═C pathway for **2** and related systems**.** A few years ago Kresge and co-workers[34] concluded that "...there is no theoretical or experimental evidence... to suggest that this mechanism also applies to... unsubstituted ketene and such sterically hindered ketenes as di-*tert*-butylketene and diphenyl ketene in aqueous solution... in these cases, enol intermediates have not been observed experimentally...". Our results give strong new evidence for C═O addition for the bulky ketenes. The detection of $^{16}O/^{18}O$ exchange is particularly interesting for the more reactive diphenylketene, where 1,1-enediol intermediate could not be observed and the reversibility is the only evidence for its intermediacy.

Conclusions. Except for ketonization to the carboxylic acid, other reactions of the 1,1-enediol **1** at the C═C double bond or at the two OH groups did not give the expected products. This is ascribed to easy oxidation of the OH group, shielding of the double bond by the bulky aryl groups, large pK_a difference of the two OH groups, rapid ketonization of the ketene hemiacetal, and the elimination of water from the enediol to form the ketene. How general is this behavior is unknown since data for comparison are not available.

Experimental Section

General Methods. Melting points, UV spectra, FT infrared spectra, NMR spectra, EI and CI and high resolution (HR) mass spectra, and X-ray diffraction data were measured as described in the preceding paper. CI (MS) analysis of the ^{18}O labeled compounds were conducted at the Mass Spectrometry Center at the Technion, Haifa on a Finnigan MAT 711 apparatus.

Solvents and Materials. Tetrahydrofuran (THF) was distilled from sodium benzophenone ketyl and ether was distilled from $LiAlH_4$. All purchased reagents were the best commercial samples and were used without purification. DMF-d_7 (Ferak, Berlin, Germany) was dried over 4 Å molecular sieves. Small portions of THF-d_8 were kept in separate sealed ampules. ^{18}O labeled water (95% ^{18}O) was purchased from Enritech, Rehovot, Israel. The solvents used for chromatography were not purified. Ketene **2** was available from previous work[2,18] and ketenes **21**,[6b] **22**,[38] and **23**[39] were prepared according to the literature.

Ketene Hydration Studies. NMR samples for the hydration of the ketenes were prepared as follows: 10 mg (0.022 mmol) of the ketene was dissolved at room temperature in 0.05 mL of THF-d_8 in an NMR tube. A 42:3 mixture of the appropriate solvent/deionized H_2O (0.45 mL) was then added at room temperature, and the resulting solution was stirred vigorously for 15 s before being introduced into a precooled NMR probe.

Oxidation of 1 with Tris(*p*-bromophenyl)aminium Hexachloroantimonate [$(4\text{-}BrC_6H_4)_3N^{\bullet+})\cdot SbCl_6^-$]. To a solution of **1**, prepared from ditipylketene (100 mg, 0.22 mmol) in THF (0.5 mL), DMF (5 mL) and water (0.3 mL) which was kept at −18 °C for 6 h, solid tris(*p*-bromophenyl)aminium hexachloroantimonate (350 mg, 0.43 mmol) was added. The oxidant's blue color faded, and the solution turned deep red immediately. The reaction mixture which was protected from light was kept for 12 h at room temperature, the reaction was terminated by addition of saturated aqueous sodium bicarbonate solution (5 mL), and CH_2Cl_2 (20 mL) was then added. After separation of the organic layer the aqueous phase was extracted thrice with CH_2Cl_2 (20 mL), the organic layers were washed with brine (2 × 20 mL), water (2 × 20 mL) and brine again (2 × 20 mL), and dried ($MgSO_4$), and the solvents were evaporated. Chromatography of the residual oil on silica gel using a 2−20% ether−petroleum ether gradient as eluent gave the bicyclic five-membered 4,6,7a-tris(1-methylethyl)-3-[2,4,6-tris(1-methylethyl)phenyl]-2(7a*H*)benzofuranone **5** (65 mg, 63%). Identical results were obtained when the oxidation was performed at −18 °C. ^1H NMR (400 MHz, $CDCl_3$) δ: 0.89 (3H, d, J = 6.7 Hz, i-Pr-Me), 0.94 (3H, d, J = 7.6 Hz, i-Pr-Me), 0.96 (3H, d, J = 7.4 Hz, i-Pr-Me), 0.98 (3H, d, J = 7.2 Hz, i-Pr-Me), 1.02 (3H, d, J = 6.8 Hz, i-Pr-Me), 1.03 (3H, d, J = 6.8 Hz, i-Pr-Me), 1.06 (3H, d, J = 6.8 Hz, i-Pr-Me), 1.14 (3H, d, J = 6.8 Hz, i-Pr-Me), 1.21 (3H, d, J = 6.9 Hz, i-Pr-Me), 1.24 (6H, d, J = 6.9 Hz, i-Pr-Me), 1.25 (3H, d, J = 6.8 Hz, i-Pr-Me), 2.12 (1H, m, J = 6.9 Hz, i-Pr-CH), 2.29 (1H, m, J = 6.8 Hz, i-Pr-CH), 2.35 (1H, m, J = 6.8 Hz, i-Pr-CH), 2.51 (1H, m, J = 6.9 Hz, i-Pr-CH), 2.87 (1H, m, J = 6.9 Hz, i-Pr-CH), 2.94 (1H, m, J = 6.8 Hz, i-Pr-CH), 5.71 (1H, dd, J = 1.56 Hz, C−C═CH), 6.11 (1H, unresolved dd, C−C═CH), 6.92 (1H, d, J = 1.7 Hz, Tip-H), 7.00 (1H, d, J = 1.7 Hz, Tip-H). ^{13}C NMR (50.32 MHz, $CDCl_3$) δ: 16.79, 17.54, 19.71, 20.85, 21.69, 23.05, 23.77, 23.81, 23.93, 23.99, 24.97, 25.20 (12 i-Pr-Me), 28.70, 30.04, 31.84, 33.28, 34.21, 36.38 (6 i-Pr-CH), 92.39 (*C*−O-C═O), 120.89, 120.93, 123.97, 124.00, 124.67, 125.69, 126.39, 142.80, 143.40, 147.53, 149.29 (11 aryl- and vinyl-C), 167.89 (*C*═C−C═O), 173.79 (C═O). FTIR: ν_{max} cm^{-1} (Neat): 1743 (C═O), 1644, 1621, 1607 (w, C═C). MS (EI, 70 eV) *m*/*z*, relative abundance, assignment): 462 (36%, M), 420(68%, M − MeCH═CH_2), 419 (B, M − i-Pr), 391 (50%, M − i-Pr − CO), 378 (12%, M −2MeCH═CH_2), 241(10%, $TipCCO^+$), 217 (55%, $TipCH_2$). HRMS (*m*/*z*): 462.353. $C_{32}H_{46}O_2$ requires 462.350. Crystal data: $C_{32}H_{46}O_2$, space group *Pbca*, a = 19.636(3) Å, b = 33.83(1) Å, c = 9.073(2)) Å, V = 6028(2) Å^3, Z = 8, ρ_{calc} = 1.02 g cm^{-3}, μ(MoKα) = 0.57 cm^{-1}, no. of unique reflections = 4191, no. of reflections with $I \geq 3\sigma_I$ = 1982, R = 0.081, R_w = 0.078.

Reaction of 1 with Br_2. (a) Ditipylketene (106 mg, 0.24 mmol) was dissolved in a mixture of THF, DMF, and water (0.5 mL:4 mL: 0.3 mL) and kept at −18 °C for 6 h. Bromine (0.42 mL of a 1.12 M solution in CCl_4, 0.47 mmol) was added and the mixture was kept *at room temperature* for 6 h. The yellowish color of the solution indicated that not all of the bromine had reacted, and its excess was reduced with 10% aqueous $NaHSO_3$. The solution was diluted with CH_2Cl_2 (20 mL), washed with water (5 × 25 mL), and dried ($MgSO_4$). The solvent was removed *in vacuo* leaving a residual oil. Silica gel

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chromatography using 2:8 ether:petroleum ether as eluent afforded a yellowish solid, mp 92−4 °C (79 mg, 54%) which is either one of the monobrominated derivatives (**8a, 8b**, or **8c**) of 4-[2,4,6-tris(1-methylethyl)phenyl]-1,4-dihydro-1,1-dimethyl-5,7-bis(1-methylethyl)-3*H*-2-benzopyran-3-one. ^{1}H NMR (400 MHz, $CDCl_3$) δ: 0.85 (3H, d, J = 6.8 Hz, i-Pr-Me), 0.94 (3H, d, J = 6.8 Hz, i-Pr-Me), 0.97 (3H, d, J = 6.8 Hz, i-Pr-Me), 1.01 (3H, d, J = 6.8 Hz, i-Pr-Me), 1.13 (6H, dd, J = 6.8 Hz, i-Pr-Me), 1.18 (3H, d, J = 6.8 Hz, i-Pr-Me), 1.25 (9H, overlapping 6H and 3H d, J = 6.9 Hz, i-Pr-Me), 1.99 (3H, s, Me), 2.04 (3H, s, Me), 2.10 (1H, m, J = 6.8 Hz, i-Pr-CH), 2.37 (1H, m, J = 6.8 Hz, i-Pr-CH), 2.91 (1H, m, J = 6.9 Hz, i-Pr-CH), 2.94 (1H, m, J = 6.8 Hz, i-Pr-CH), 3.19 (1H, m, J = 6.8 Hz,i-Pr-CH), 5.59 (1H, s, CH-CO), 6.51 (1H, s, Tip-H), 7.00 (1H, d, J = 1.7 Hz, Tip-H), 7.02 (1H, d, J = 1.7 Hz, Tip-H). ^{13}C NMR (50.32 MHz, $CDCl_3$) δ: 17.36, 18.21, 20.78, 21.18, 21.47, 22.54, 23.94, 24.19, 24.99, 26.27, 27.83, 30.35, 31.51, 32.63, 34.15 (aliphatic C), 52.94 (α-CH), 87.68 (Me_2CO), 120.87, 121.04, 123.93, 124.84, 124.96, 138.17, 141.09, 147.34, 147.53, 148.06, 149.22, 158.14 (Ar-C), 173.33 (C═O). FTIR: ν_{max} cm^{-1} (Nujol): 1746 (s, C═O), 1609 (m, C═C). MS (EI, 70 eV, *m/z*, relative abundance, assignment): 542, 540 (22%, 22%, M, ^{81}Br and ^{79}Br), 500, 498 (8%, 7%, M − MeCH═CH_2), 462 (5%, MH − Br), 421 (10%, MH_2 − Br − MeCH═CH_2), 420 (15%, MH − Br − MeCH═CH_2), 419 (41, M − Br − MeCH═CH_2), 418 (33%, M − Br -i-Pr), 377 (11%, M − Br − 2MeCH═CH_2), 375 (10%, M − Br − 2i-Pr), 260 (25%, TipCHCO_2). HRMS (*m/z*): 542.2594, 540.2626. $C_{32}H_{45}{}^{81}BrO_2$ and $C_{32}H_{45}{}^{79}BrO_2$ require 542.2583 and 540.2603.

(b) Ditipylketene (90 mg, 0.2 mmol) was dissolved in a mixture of THF (0.5 mL), DMF (3 mL), and water (0.2 mL) and kept at −18 °C for 6 h. Bromine (0.4 mL of a 1.12 M solution in CCl_4, 0.45 mmol) was added, and the mixture was kept *at* −18 °C. After 14 h the red-yellow color had not faded, the excess bromine was reduced with 10% aqueous sodium bisulfite solution, and the reaction was worked up as described. The ^{1}H NMR spectrum of the crude product mixture showed a 1:0.6 ratio of **8** to **5**.

Attempted Bromination of 2 and 3. Solutions of either ditipylketene **2** or ditipylacetic acid **3** in THF−DMF−water solvent mixtures (5:42:3) were reacted with twofold excess of bromine both at room temperature and at −18°C. The reactions were worked up as described above by dilution with CH_2Cl_2, reduction of the unreacted bromine with $NaHSO_3$ solution, washing with water, drying ($MgSO_4$), and evaporation of the solvent. On analysis by ^{1}H NMR only the starting materials were detected.

Reaction of 1 with I_2. A solution of **1** in THF (3 mL) was prepared from **2** (50 mg, 0.11 mmol) as described above. Iodine crystals (57 mg, 0.22 mmol) were added, and the solution was kept at room temperature for 6 h. Aqueous sodium bisulfite solution (5%) was added until total decoloration, and the reaction was worked up as described above. TLC of the deep red crude product mixture showed two spots which were separated by chromatography on a slurry packed silica gel column using a petroleum ether−ether gradient as eluent. Lactone **5** and radical **4** were isolated in an almost equimolar ratio.

Radical **4**: ^{1}H NMR (400 MHz, $CDCl_3$) δ: 0.93 (12H, *o*-i-Pr-Me), 1.02 (12H, br, *o*-i-Pr-Me), 1.19 (12H, d, J = 6.8 Hz, *p*-i-Pr-Me), 2.83 (2H, m, J = 6.8 Hz, *p*-i-Pr-CH), 3.05 (4H, br, *o*-i-Pr-CH), 5.90 (1H, Tip_2CH), 6.93 (4H, Tip-H). ^{13}C NMR (100 MHz, $CDCl_3$) δ: 23.94, 24.09 (broad), 29.63, 33.85, 121.94, 132.92 (very broad and weak) 146.76 (broad), 147.32, FTIR: ν_{max} cm^{-1} (Nujol): 1675 (s, C═O) ESR: (THF) g = 2.0047.

The spectra of **4** was discussed in the preceding paper.[2]

Air Oxidation of 1. A solution of **1** in THF (3 mL) which was prepared from **2** (50 mg, 0.11 mmol) as described above was kept at 4°C for 30 days. The ^{1}H NMR spectrum of the crude product mixture showed a 1:1 mixture of ditipylacetic acid **3** to the lactone **5**.

Reaction of 5 with Bromine. A solution of **5** (14.5 mg, 0.03 mmol) in a THF:DMF:water (0.25 mL:1 mL:0.25 mL) mixture was reacted with bromine (0.03 mL of a 1.12 M solution in CCl_4) at room temperature for 16 h. After workup as above the product mixture was analyzed by ^{1}H NMR. The six-membered lactone **8** was detected as the sole product.

Attempted Hydrolysis of 5. A solution of **5** (10 mg, 0.02 mmol) in ethanolic KOH (1 M, 20 mL) was refluxed for 18 h. The solvent was removed, and the residual solid was analyzed by ^{1}H NMR. Only **5** was detected.

Reaction of 1 with Trimethylchlorosilane. A solution of **1** was prepared from **2** (20 mg, 4.5×10^{-5} mol) and water (0.06 mL) in THF-d_8 (0.5 mL) in an NMR tube at 273 K. Me_3SiCl (15 mg, 0.135 mmol) was added, and an NMR spectrum of the mixture was recorded immediately. Ditipylacetic acid **3** was the only detected product.

3,3a-Dihydro-3a,5,7-tris(1-methylethyl)-1-[2,4,6-tris(1-methylethyl)phenyl]-2*H*-inden-2-one (12). To a solution of ditipylketene **2** (50 mg, 0.11 mmol) in ether (10 mL) an ethereal solution of diazomethane (50 mL, ca. 10 mg/mL) was added at room temperature. After 2 h the unreacted diazomethane was destroyed with acetic acid. The organic phase was washed thrice with 5% aqueous $NaHCO_3$ (25 mL) and twice with water (25 mL) and dried ($MgSO_4$), and the solvent was evaporated. Chromatography of the residual solid on silica using a 3:1 high boiling petroleum ether:ether mixture as eluent gave slightly yellow crystals of the bicyclic trienone **12** (30 mg, 58%), mp 159−160 °C. ^{1}H NMR (400 MHz, $CDCl_3$) δ: 0.80 (3H, d, J = 6.7 Hz, i-Pr-Me), 0.90 (3H, d, J = 7.6 Hz, i-Pr-Me), 0.91 (3H, d, J = 6.8 Hz, i-Pr-Me), 0.92 (3H, d, J = 7.0 Hz, i-Pr-Me), 1.04 (3H, d, J = 6.9 Hz, i-Pr-Me), 1.05 (3H, d, J = 6.8 Hz, i-Pr-Me), 1.06 (3H, d, J = 6.8 Hz, i-Pr-Me), 1.06 (3H, d, J = 7.8 Hz, i-Pr-Me), 1.19 (3H, d, J = 6.9 Hz, i-Pr-Me), 1.22 (3H, d, J = 6.8 Hz, i-Pr-Me), 1.27 (6H, d, J = 6.1 Hz, i-Pr-Me), 2.14 (1H, m, J = 6.8 Hz, i-Pr-CH), 2.18 (1H, m, J = 6.8 Hz, i-Pr-CH), 2.36 (1H, m, J = 6.9 Hz, i-Pr-CH), 2.47 (1H, d, J = 18.3 Hz, half of an AB CH_2), 2.49 (1H, m, J = 6.8 Hz, i-Pr-CH), 2.72 (1H, d, J = 18.3 Hz, half of an AB CH_2), 2.88 (3H, m, three overlapping i-Pr-CH), 5.81 (1H, s, C−C═CH), 5.90 (1H, s, C−C═CH), 6.92 (1H, d, J = 1.7 Hz, Tip-H), 7.00 (1H, d, J = 1.7 Hz, Tip-H). ^{13}C NMR (50.32 MHz, $CDCl_3$) δ: 18.19, 19.22, 20.52, 21.05, 22.13, 22.89, 23.68, 23.97, 24.05, 24.48, 25.28, 25.34 (12 i-Pr-Me), 28.57, 30.07, 31.80, 33.31, 34.21, 35.73 (6 i-Pr-CH), 41.42 (sp^3 ring fusion C), 51.15 (CH_2), 120.63, 120.69, 124.10, 127.24, 131.68, 138.12, 140.98, 143.15, 146.91, 147.03, 148.46 (11 Ar-C and vinyl-C), 178.08 (*C*═C−C═O), 208.18 (C═O) FTIR: ν_{max} cm^{-1} (Nujol): 1701 (s, C═O), 1640 (m, C═C), 1599 (m). MS (CI, *i*-C_4H_{10}) *m/z* (relative abundance, assignment): 460 (10%, M), 418 (B, M − MeCH═CH_2), 357 (22%, M − i-Pr − MeCH═CH_2 − H_2O), 333 (17%, M − i-Pr − 2MeCH═CH_2), 315 (27%, M − i-Pr − 2MeCH═CH_2 − H_2O), 273 (23%, M − i-Pr − 3MeCH═CH_2 − H_2O), 231 (25%, M − i-Pr −4MeCH═CH_2 − H_2O), 215 (40%, TipC). Microanalysis: calculated for $C_{33}H_{48}O$: C, 86.03; H, 10.50. Found: C, 86.35; H, 10.66. Crystal data: $C_{33}H_{48}O$, space group $P1$, a = 13.942(2) Å, b = 13.946(2) Å, c = 8.320(1) Å, α = 95.17(2), β = 106.83(2), γ = 77.86(2), V = 1513.1(6) Å^3, Z = 2, ρ_{calc} = 1.01 g cm^{-3}, μ(MoKα) = 0.55 cm^{-1}, no. of unique reflections = 4213, no. of reflections with $I \geq 3\sigma_I$ = 2901, R = 0.056, R_w = 0.075.

Reaction of 1 with Diazomethane. (a) A solution of 2,2-ditipylethene-1,1-diol (**1**) in THF was prepared by reacting ditipylketene (50 mg, 0.11 mmol) with water (150 μL) in dry THF (5 mL) at −18 °C for 6 h. Ethereal diazomethane (100 mL, ca. 10 mg/mL) was added *at room temperature*, and the resulting mixture was stirred for 12 h at room temperature. The unreacted diazomethane was destroyed with acetic acid (3 mL), and 5% aqueous sodium bicarbonate solution was added until the pH was 10. The organic phase was separated, washed with water (50 mL), dried ($MgSO_4$), and evaporated. The bicyclic trienone **12** (45 mg, 86%) was isolated as the sole product. The ^{1}H NMR spectrum of the crude product mixture suggested the presence of some methyl ditipylacetate (**13**) which was isolated in the following experiment.

(b) An identical experiment was conducted *at 4 °C* for 4 days. The ^{1}H NMR spectrum of the crude product mixture shows the presence of **12** and **13** in a 0.92:1 ratio. Ester **13** (18 mg, 34%) was isolated by silica gel chromatography using an 8:2 petroleum ether:ether mixture as eluent and recrystallized from methanol, mp 111−112 °C. ^{1}H NMR (400 MHz, $CDCl_3$) δ: 0.91 (12H, d, J = 6.8 Hz, *o*-i-Pr-Me), 1.00 (12H, d, J = 6.8 Hz, *o*-i-Pr-Me), 1.19 (12H, d, J = 6.9 Hz, *p*-i-Pr-Me), 2.82 (2H, m, J = 6.9 Hz, *p*-i-Pr-CH), 2.98 (4H, m, J = 6.8 Hz, *o*-i-Pr-CH), 3.73 (3H, s, OMe), 5.78 (1H, s, Tip_2CH), 6.92 (4H, s, Tip-H). ^{13}C NMR (100.62 MHz, $CDCl_3$) δ: 23.95 (*o*-i-Pr-Me), 24.09 (*o*-i-Pr-Me), 24.11(*p*-i-Pr-Me), 29.78 (*p*-i-Pr-CH), 33.88 (*o*-i-Pr-CH), 52.09 (Tip_2C), 122.18 (*m*-Tip-C), 132.39 (*ipso*-Tip-C), 147.19 (*o*-Tip-C), 147.22 (*p*-Tip-C), 175.93 (C═O). FTIR: ν_{max} cm^{-1} (Nujol): 1735 (s, COOR),

1609 (m, C═C). MS (+DCI, *i*-C_4H_{10}) *m*/*z* (relative abundance, assignment): 478 (7%, M), 435 (3%, M − i-Pr), 371 (4%), 275 (B, TipCHCOOH). (-DCI, *i*-C_4H_{10}): 477 (B, M − H), 445 (4%), 303 (5%). Microanalysis: calculated for $C_{33}H_{50}O_2$: C, 82.79; H, 10.53. Found: C, 83.01; H, 10.76.

Reaction of 2,2-Ditipylethenol (16) with Diazomethane. A solution of **16** (20 mg, 0.045 mmol) in dry ether (2 mL) to which a freshly prepared solution of diazomethane in ether (50 mL of ca. 10 mg/mL) was added at 0 °C was kept overnight at room temperature. AcOH (2 mL) was then added, and the solution was worked up as described above. NMR spectrum of the crude mixture showed the presence of only the starting material.

^{18}O Labeling Experiments. Ditipylketene (20 mg, 4.5×10^{-5} mol) was dissolved in THF-d_8 in an NMR tube. $H_2{}^{18}O$ (54 mL of 95% ^{18}O, 2.7 mmol) were added at room temperature and the sample was immediately introduced into the precooled to 0 °C NMR probe. The sample was kept for 8 h at 0 °C and for an additional 4 h at 25 °C. The solution was then rapidly chromatographed on a slurry packed silica gel column using high boiling petroleum ether as eluent. The first eluted compound was pure ditipylketene (0.5 mg, 0.0012 mmol) which was analyzed by MS and FTIR.

The di-^{18}O-labeling of carboxylic acids was conducted according to the following general method: 3×10^{-5} mol of diarylketene (ditipyl, 13.4 mg; bis(pentamethylphenyl), 10 mg; dimesityl, 9 mg; diphenyl, 5.9 mg) was dissolved in dry THF (3 mL). $H_2{}^{18}O$ (60 μL of 95% ^{18}O, 4.1 mmol) was added under argon at 0 °C, and the resulting mixture was kept at −18°C for 30 min and for 12 additional h at room temperature. The solvent was evaporated, and the residual solid was analyzed by MS.

Control experiments of the $^{16}O/^{18}O$ exchange of diarylacetic acids were conducted analogously by dissolving the appropriate amount af carboxylic acid in THF containing the same concentration of $H_2{}^{18}O$. The solutions stood for 60 h at room temperature, the solvent was then evaporated, and the residual solid was analyzed by MS.

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Supporting Information Available: Crystallographic summary for **5** and **12** including tables of crystal data and structure refinement, bond lengths and angles, least squares planes, atomic coordinates and equivalent displacement parameters, hydrogen atom coordinates and isotropic displacement parameters and stereoviews for **5** and **12** (25 pages). Ordering information is given on any current masthead page.

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