# Unusual Kinetic Stability of Enols to Ketonization: 1,2-Dimesityl-3-methylbut-1-en-1-ol and Related β-Alkyl-α,β-dimesitylethenols[1]

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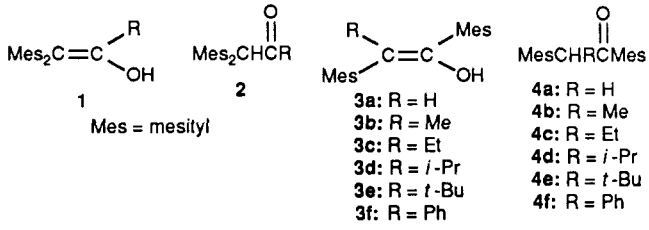
The β-alkyl-α,β-dimesitylethenols **3** and the isomeric β-alkyl-α,β-dimesitylethanones **4** (β-alkyl = Me, Et, *i*-Pr) were prepared and their spectral properties are reported. X-ray diffraction of the β-isopropyl enol **3d** showed that the two mesityl rings are nearly perpendicular to the double-bond plane. Attempts to determine the **3**/**4** equilibrium constants in hexane were unsuccessful. Under no conditions were identical **3**/**4** mixtures obtained starting separately from the enol and ketone precursors. Under catalytic conditions the enols isomerized very slowly and the ketones did not isomerize at all, suggesting that the ketone is favored at equilibrium and that the slow and incomplete isomerization is due to the high kinetic stability of the enols. This is ascribed to the hindered approach of the acid catalysts to $C_\beta$ of the double bond of the enol or the enolate ion due to its shielding by the aryl groups and is corroborated by analysis of the occupied and empty space around the protonation site in **3d**.

Previously we prepared α-substituted-β,β-dimesitylethenols **1** (R = H, alkyl, aryl, $SiMe_3$) and their isomeric carbonyl derivatives **2**,[2,3] except for ketone **2**, R = $SiMe_3$. The keto ⇌ enol equilibrium constant (ketone ⇌ enol ($K_{enol}$)) in hexane at 353.6 K decreases strongly with the increased bulk of R from 20 for R = H to 0.006 for R = *t*-Bu.[2] This is ascribed to reduced enol stability by the decreased conjugation of the two mesityl groups with the double bond, as corroborated by X-ray crystallography and MM calculations,[1a,4] coupled with increased relative stability of the ketone. Since β-alkyl groups also increase the enol stability[5] by interaction with the double bond, with no compensating effect on the keto derivative, it was interesting to study the keto–enol equilibria of the isomeric α,β-dimesityl-β-alkyl(or β-H)ethenols **3a–e**/α,β-dimesityl-β-R-ethanones **4a–e**.

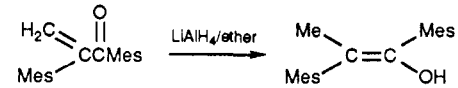



Few data on the **3**/**4** equilibria are available. Whereas **4a** is known, attempts to generate enol **3a** were unsuccessful,[6] indicating that $K_{enol} \leq 50$. Both **3f** and **4f** are known[7] and $K_{enol}$(hexane, 323 K) of 2.2[8] is slightly higher than $K_{enol}$ = 1.0 for **1**/**2** (R = Ph).[9] The **3b**/**4b** pair[10] and enol **3c**[11] were prepared, but $K_{enol}$ was not determined. It is noteworthy that **3b** is converted completely to **4b** in refluxing HCl/MeOH, whereas **4b** is converted completely to **3b** in refluxing EtONa/EtOH.[10b]

Wheland[12] explained these findings by suggesting that the carbonyl species is favored at equilibrium: only the acid is a true catalyst that does not affect the equilibrium constant. In contrast, the excess base affects the position of the quilibrium by generating the enolate of **4b**, which forms **3b** on acidification by protonation on oxygen. Hart[13] ascribed the exclusive formation of **4b** and **3b** under acidic or basic conditions, respectively, to the kinetic stabilities of both species. The planes of the enolate and of the mesityl rings are perpendicular, and the *o*-methyl groups sterically hinder the protonation on carbon but not on the oxygen leading to **3b**. On the other hand, the carbenium ion formed on protonation of the double bond of **3b** in acid prefers deprotonation from the oxygen, thus giving **4b**. It is therefore of interest to obtain X-ray data for enols **3** in order to evaluate the steric effects in these systems.[14]

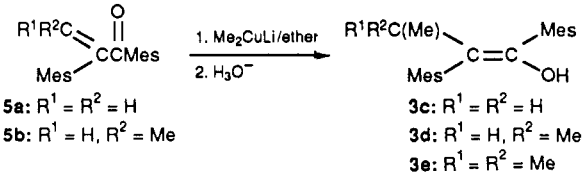
## Results

**Synthesis. Enols.** Enols **3b**[10a] and **3c**[10b] were prepared previously by Fuson et al.[10a] by a 1,4-reduction of enone **5a**, which was derived from ketone **4a**. We reduced **5a** with $LiAlH_4$[15] (eq 1) rather than with $H_2/PtO_2$. Fuson obtained



(1)

**3c**·MeOH, mp 69–70.5 °C,[10b] according to eq 2, whereas we obtained methanol-free **3c** (75 °C).



(2)

**5a**: $R^1 = R^2 = H$
**5b**: $R^1$ = H, $R^2$ = Me
**3c**: $R^1 = R^2 = H$
**3d**: $R^1$ = H, $R^2$ = Me
**3e**: $R^1 = R^2$ = Me

(1) Stable Simple Enols. 25. (a) For 23, see: Kaftory, M.; Nugiel, D. A.; Biali, S. E.; Rappoport, Z. *J. Am. Chem. Soc.* **1989**, *111*, 8181. (b) For 24, see: Nadler, E. B.; Rappoport, Z., *Tetrahedron Lett.* **1990**, *31*, 555.
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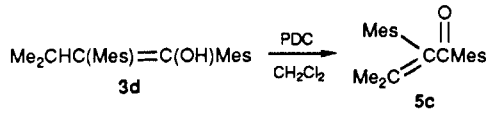
Enol **3d** was prepared analogously to **3c**. Enone **5b** is formed by oxidation of **3c** with pyridinium dichromate (PDC) in $CH_2Cl_2$. Addition of lithium dimethylcuprate in ether to **5b** followed by acidification affords **3d** (eq 2).

Attempted preparation of enol **3e** either by reaction of **5c** (formed according to eq 3) with lithium dimethylcuprate or by other methods failed.



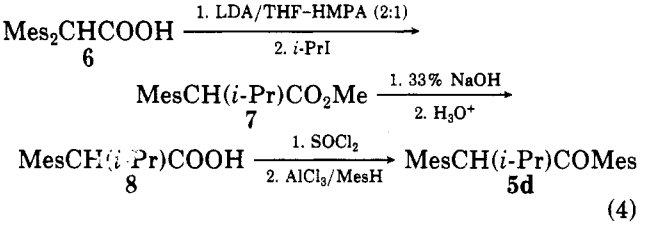
(3)

Enols **3b** and **3c** decompose in solution, especially in $CH_2Cl_2$, $CHCl_3$, or $CCl_4$, even at 0 °C. Solid **3b** decomposes after 2 weeks at 0 °C, whereas **3c** is stable at 0 °C but decomposes slightly at 25 °C. **3d** is more stable both in the solid state and in solution than are **3b** and **3c**. Fuson reported that **3b** decomposes to MesCOMe and MesCOOH and isolated an intermediate peroxide.[10b] Air oxidation of **3c** gave MesCOEt and MesCOOH.[11] These reports were now corroborated. After 168 h in $CH_2Cl_2$ at 0 °C **3b** gave **5a**, MesCOMe, and MesCOOH, which were separated by preparative TLC and identified by comparing their mass, NMR, and IR spectra with those of authentic samples or with literature values. In a similar experiment **3c** afforded unreacted **3c**, MesCOOH, and MesCOEt. The oxidation products of **3b** and **3c** are also obtained in refluxing MeOH/HCl when no special precautions against oxidation are taken or in the equilibration experiments (see below).

Similarly to Fuson,[6] we were unable to obtain the parent 1,2-dimesitylethenol (**3a**). **4a** was recovered from its reactions with NaH or LDA, followed by addition of $NH_4Cl$, or with MeONa followed by dilute HCl. Reflux of the silyl enol ether MesCH=C(Mes)OSiMe$_3$ in $CD_3OD$ showed (by NMR) only the presence of **4a**-$d_2$ and the ether. Only **4a** was observed after several minutes of treatment of a solution of the ether in THF-$d_8$ with $Bu_4NF$.[16]

**Ketones.** Fuson reported that **4b** was obtained as a solid by isomerization of **3b** in methanolic HCl.[10b] We found by NMR that even when the reflux time exceeds the 13 h used by Fuson, the **4b**/**3b** ratio was ≤6.6:1. Chromatography gave **4b** as a viscous oil, which failed to crystallize even after 3 years at 0 °C.

Fuson failed to obtain ketone **4c** by refluxing **3c** in HCl/MeOH[11] when **3c** was added to MeOH saturated with HCl in which **3c** was insoluble. However, when **3c** is first dissolved in MeOH and then the mixture is saturated with HCl and refluxed, **4c** is obtained. Ketone **4d** could not be synthesized efficiently by ketonization of **3d**, and it was prepared by the Friedel–Crafts reaction of the acyl chloride of the acid **8** with mesitylene (eq 4).



(4)

**Spectral Properties of 3 and 4. A. IR Spectra. (i) Enols 3.** The accurate O–H stretching absorptions (Table I) show the following features. (i) An 0.5% solution of **3** in $CCl_4$ shows two absorptions: (a) at 3514 ± 4 cm$^{-1}$ (strong), (b) at 3598 ± 2 cm$^{-1}$. On increased crowding, i.e., changing from **3b** to **3d**, absorption (a) shifts to lower wavenumbers and absorption (b) shifts to higher wavenumbers. (ii) At 5% of **3** in $CCl_4$, the intensity ratio (a)/(b) increases over that of the lower concentration without peak broadening.

The "free" OH absorption at 3620 cm$^{-1}$ is shifted to lower wavenumbers when weak hydrogen bonds are formed. In enols **1** (R = H, *t*-Bu, Mes, 9-anthryl) and **3f** in $CCl_4$ the main absorption is at 3529 cm$^{-1}$ or lower.[9,17,18] Hence, absorptions (b) and (a) are ascribed respectively to a free OH in an anti-clinal C=C—OH conformation and to intramolecularly associated OH with the $\pi$-system of the cis $\beta'$-mesityl ring.[17b]

The increased intensity of absorption (a) of **3** at higher concentrations can be ascribed to formation of intermolecular $\pi$-OH bonds or OH···OH hydrogen-bonded dimers.[19a] This is surprising due to the severe steric hindrance to a mutual approach of two enol molecules. Indeed, a concentration effect on $\nu_{OH}$ was not observed for **1** (R = *p*-$C_6H_4$OPh), and all enols **1** (R = Ar) studied show only one $\nu_{OH}$.[9] The shift of absorption (a) to lower wavenumbers on increasing the bulk of R may result from a stronger $\pi$($\beta$-Mes)–HO interaction, provided that the $\beta$-Mes—C=C dihedral angle increases with the size of R, as was found for the $\alpha$-R—C=C angle in enols **1**.[1a,4]

**(ii) Ketones 4.** At a concentration of 1% in $CH_2Cl_2$ $\nu_{C=O}$ for **4a**, **4b**, **4c**, and **4d** appears at 1695, 1693, 1691, and 1688 cm$^{-1}$, respectively. The small differences reflect the similarity in electronic effects of Me, Et, and *i*-Pr.[19b] The lower wavenumbers than for the isomeric ketones **2**[2] are due to the Ar–CO conjugation in **4**.

**B. UV Spectra. (i) Enols 3b–d.** The UV spectra are given in Table I. In spite of the formal two Ar—C=C conjugative interactions in **3**, in general the absorption of **3** shows both hypsochromic and hypochromic shifts compared with the planar *trans*-stilbene ($\lambda_{max}$(heptane) 201.5 nm (4.38), 228.5 (4.21), 294 (4.45)[20] and for **3c** and **3d** even in comparison with styrene ($\lambda_{max}$(hexane) 250 nm (4.17)).[21]

**3b** displays a strong hypochromic effect compared with (*E*)-1,2-dimesitylethylene ($\lambda_{max}$(heptane) 214 nm (4.55), 263 (4.20)[22]) in spite of the expected strong oxochromic effect of the OH. Consequently, the Mes—C=C torsional angle in **3b** in solution seems to be larger than 54°, the value estimated for (*E*)-MesCH=CHMes in heptane.[22] The very similar spectra of **3c** and **3d** show hypso- and hypochromic effects and less fine structure compared with **3b**. This probably indicates a sharp increase in the Mes—C=C torsional angle(s) resulting from increased bulk of the $\beta$-alkyl group, judging by the change of the Ph—C=C torsional angle from 0° in (*E*)-PhCH=CHPh to an estimated angle of ca. 35° for (*E*)-PhC(Me)=CHPh.[23]

**(ii) Ketones 4a–c.** The UV spectra (Table I) show lower $\lambda_{max}$ and higher $\epsilon$ than those of $PhCOCH_2Ph$ ($\lambda_{max}$(c-$C_6H_{12}$) 323 nm, log $\epsilon$ 2.10),[24] but higher $\lambda_{max}$ than for $Ph_2CHCOPh$, **4f**, or $Ph_2CHCOMes$,[25] suggesting a lower steric hindrance to conjugation in the former ketones.

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**Table I. Spectral Data for Enols 3, Ketones 4, and Enones 5**

| compd | $\lambda_{max}$ (hexane), nm (log $\epsilon$) | $\nu_{max}$ (Nujol), $cm^{-1}$ | $\delta(CCl_4)$,[b] ppm | m/z (relative abundance,[c] assignment) |
|---|---|---|---|---|
| **3b** | 209 (4.38), 239 sh (3.69), 269 sh (3.30), 280 sh (3.04) | 3600 (OH, w),[a] 3518 (OH, s),[a] 1690 (C=C, s), 1670 (C=C, s), 1610 (s) | [b]1.57 (3 H, s, MeC=), 2.30 2.36, 2.40 (18 H, 3 s, Mes-*Me*), 4.27 (1 H, s, OH), 6.91, 6.96 (4 H, 2 s, Mes-*H*) | 295 (73, M + 1), 294 (94, M), 279 (39, M - Me), 276 (13, M - $H_2O$), 265 (87, M - CHO), 261 (42, M - Me - $H_2O$), 251 (14, $Mes_2CH$), 246 (12, M - 2Me - $H_2O$), 235 (11, $Mes_2CH$ - $CH_4$), 231 (8, M - 3Me - $H_2O$), 221 (9, $Mes_2CH$ - 2Me), 174 (12, M - MesH), 159 (25, (M - MesH - Me), 147 (100, MesCO), 131 (47, MesCO - $CH_2$), 128 (25), 119 (86, Mes), 115 (41, MesCO - $2CH_2$), 105 (44, PhCO), 91 (75, $C_7H_7$), 78 (19, PhH) |
| **3c** | 207 (4.50), 214 sh (4.40), 236 sh (3.81) | 3597 (OH, w),[a] 3517 (OH, s),[a] 1680 (C=C), 1670–1660 (C=C, s), 1610 (s) | [b]0.76 (3 H, t, $J$ = 7 Hz, $CH_2Me$), 2.04 (2 H, q, $J$ = 7 Hz, $CH_2Me$), 2.30, 2.38, 2.42 (18 H, 3 s, Mes-*Me*), 4.31 (1 H, s, OH), 6.91, 6.96 (4 H, 2 s, Mes-H) | [d]309 (16, M + 1), 308 (68, M), 293 (13, M - Me), 265 (19, M - $C_3H_7$ or M - $CH_2CHO$), 173 (9, M - Mes - Me - H), 159 (11, M - Mes - 2Me), 147 (100, MesCO), 133 (8, $MesCH_2$), 119 (22, Mes), 105 (9, PhCO), 91 (11, $C_7H_7$), 77 (s, Ph) |
| **3d** | 208 (4.52), 215 sh (4,45), 236 sh (3.76) | 3597 (OH, w),[a] 3510 (OH, s),[a] 1655–1645 (C=C, m), 1610 (C=C, s) | [b]0.85 (6 H, d, $J$ = 6 Hz, *i*-Pr), 2.30, 2.41, 2.45 (3 s) + 2.56–2.72 (m) [10 H, Mes-Me + $CHMe_2$], 4.27 (1 H, s, OH), 6.91 (2 H, s, Mes-H), 6.97 (2 H, s, Mes-H) | 322 (37, M), 307 (39, M - Me), 187 (11, MeC(*i*-Pr)=$CH^+$), 174 (30, *i*-PrCMes), 159 (100, MesCO), 133 (8, $MesCH_2$), 119 (26, Mes), 105 (10, PhCO), 91 (13, $C_7H_7$), 77 (6, Ph) |
| **4a** | 213 (4.25), 274 sh (2.73), 301 (sh) (2.48), 310 sh (2.58), 318 sh (2.54) | 1695 (C=O, m),[a] 1600 (C=C, w) | 2.17, 2.21, 2.26, 2.28 (18 H, 4 s, Mes-Me), 4.08 (2 H, s, $CH_2$), 6.82 (2 H, s, Mes-H), 6.87 (2 H, s, Mes-H) | 280 (2, M), 265 (0.2, M - Me), 147 (100, MesCO), 133 (47, $MesCH_2$), 119 (52, Mes), 105 (18, PhCO), 9 (49, $C_7H_7$), 77 (45, Ph) |
| **4b** | 207 (4.49), 275 sh (2.83), 300 sh (2.76), 307 (2.81), 315 sh (2.81) | 1693 (C=O, m),[a] 1610 (C=C, w) | 1.60 (3 H, d, $J$ = 7 Hz, MeCO), 1.91, 2.20, 2.22 (18 H, 3 s superimposed on br peak at 1.65–2.45, Mes-Me), 4.57 (1 H, q, $J$ = 7 Hz, CH), 6.70, 6.75 (4 H, 2 s, Mes-H) | [d]294 (2, M), 147 (100, MesCO), 132 (4, MesCO - Me), 119 (21, MesH), 105 (3, PhCO), 91 (14, $C_7H_7$), 77 (6, Ph) |
| **4c** | 207 (4.43), 275 sh (2.69), 298 sh (2.69), 317 sh (2.65) | 1691 (C=O, m),[a] 1610 (C=C, w) | 0.89 (3 H, t, $J$ = 7 Hz, $CH_2Me$), 1.87, 1.91 (br), 2.20, 2.21, 2.39 (5 s) + 2.09–2.35 (m), (20 H, Mes-Me + $CH_2Me$), 4.38 (1 H, t, $J$ = 7 Hz), 6.69 (br s) + 6.77 (s) (4 H, Mes-H) | 308 (18, M), 161 (48, MesCHEt), 147 (100, MesCO), 133 (49, $MesCH_2$), 119 (53, Mes), 115 (39), 105 (29, PhCO), 91 (30, $C_7H_7$), 77 (38, Ph) |
| **4d** | 196 (4.76), 225 sh (4.15), 230 sh (4.06) | 1688 (C=O, m), 1610 (C=C, w) | 0.65, 0.67 (3 H, d, $J$ = 6.9 Hz, $CHMe_2$), 1.20, 1.22 (3 H, d, $J$ = 6.4 Hz, $CHMe_2$), 1.53 (3 H, s, Mes-Me), 1.82 (3 H, s, Mes-Me), 2.18, 2.19 (7.2 H, 2 s, *Mes*-Me)[f], 2.38 (4.3 H, s, Mes-Me),[f] 2.95–3.07 (1 H, m, $CHMe_2$), 4.15, 4.19 (1 H, d, $J$ = 10.9 Hz, CHCO), 6.66 (3 H, br s, Mes-H), 6.73 (1 H, s, Mes-H) | 322 (3, M), 175 (16, CH(*i*-Pr)Mes), 147 (100, MesCO), 133 (34, $MesCH_2$), 119 (73, Mes), 105 (10, PhCO), 91 (32, $C_7H_7$), 77 (12, Ph), [e]323 (100, $MH^+$), 203 (3, M - Mes), 175 (45), 147 (29) |
| **5a** | 207 (4.46), 213 sh (4.42), 257 (3.20), 345 (1.73), 360 (1.67), 378 sh (1.53) | 1640–1665 (C=O, s), 1605 (C=C, m) | 2.22, 2.26, 2.31 (18 H, 3 s, Mes-Me), 6.10 (1 H, d, $J$ = 1.4 Hz, =C*H*H), 6.18 (1 H, d, $J$ = 1.4 Hz, =CH*H*), 6.87 (2 H, s, Mes-H), 6.93 (2 H, s, Mes-H) | [d]292 (19, M), 147 (100, MesCO), 145 (4, M - MesCO), 129 (4), 119 (13, Mes), 115 (4), 91 (6, $C_7H_7$) |
| **5b** | 208 (4.48), 216 (4.45), 253 (3.34), 340 (1.70), 352 (1.69), 368 sh (1.53) | 1620–1670 (C=O, s), 1610 (C=C, m) | 1.61 (3 H, d, $J$ = 7 Hz, Me), 2.15, 2.26, 2.31 (18 H, 3 s, Mes-Me), 6.71–6.81 (1 H, q, $J$ = 7 Hz, HC=), 6.86 (2 H, s, Mes-H), 6.94 (2 H, s, Mes-H) | [d]306 (56, M), 155 (22, M - MesCO), 147 (100, MesCO), 144 (11, M - MesCO - Me), 129 (20, M - MesCO - 2Me), 119 (32, Mes), 91 (18, $C_7H_7$), 77 (9, Ph) |
| **5c** | 202 (4.66), 239 sh (4.41), 319 sh (2.26), 328 (2.30), 337 sh (2.29) | 1600–1620 (C=C, +C=O, s), (?), 1590 (C=C, m) | 1.56 (3 H, s, =CMe),[h] 1.87 (3 H, s, MeC=), 2.02 (6 H, s, Mes-Me), 2.24, 2.25 (6 H, 2 s, Mes-Me), 6.73, 6.81 (4 H, 2 s, Mes-H) | [d]320 (23, M), 305 (15, M - Me), 173 (27, M - MesCO), 147 (100, MesCO), 143 (82, M - MesCO - 2 Me), 119 (13, Mes) |

[a] Solution of 5 mg in 0.5 mL of $CCl_4$. [b] Enols **3** in $CDCl_3$. For multiplets the $\delta$ of the center is given. [c] 70 eV at 70 °C. [d] 70 eV at room temperature. [e] In $CH_2Cl_2$ solution. [f] Integration of the mesityl-Me and mesityl-H signals is not accurate due to broadening of the signals due to a dynamic process. [g] CI spectrum. [h] Integration is inaccurate due to overlap with a solvent signal.

**C. $^1$H NMR Spectra. (i) Enols 3.** In the $^1$H NMR spectra of **3b–d** ($CDCl_3$, 292 K) the mesityl methyls appear as sharp singlets in a 1:1:1 ratio (*p*-Me:*o*-Me($\beta$-ring):*o*-Me($\alpha$-ring)) at 2.30–2.45 ppm. In $(CD_3)_2CO$ at 292 K the two *p*-Me groups give different signals. The OH gives a sharp singlet at $\delta$ 4.3 (in $CDCl_3$) and the Mes-H appear as two sharp singlets at 6.90–6.97.

When an acetone solution of the enols is cooled to 186–188 K, no splitting or broadening of the *o-Me*, the Mes-*H*, or the $CH_2CH_3$ or $CHMe_2$ signals was observed, although it was observed with di- and trimesitylethenols.[4,26] This is understood if in solution the mesityl rings and the C=C bond planes are nearly orthogonal as found for solid **3d**. A flip process involving an enantiomer interconversion by ring rotation via a plane perpendicular to the C=C plane[26a] will then be a very low energy process and unobservable by $^1$H NMR.

**(ii) Ketones 4.** The NMR spectra of **4b** and **4c** in $CDCl_3$ at room temperature indicate a coalescence process,

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**Table II. Selected Bond Lengths (in Å) and Angles (in deg) for the Crystallographic Independent Molecules (A and B) of 3d**

| bond | A | B | angle | A | B |
|---|---|---|---|---|---|
| C(1)–C(2) | 1.28 (1) | 1.31 (1) | O–C(1)–C(3) | 110.2 (8) | 109.5 (7) |
| C(1)–O | 1.40 (1) | 1.39 (1) | C(2)–C(1)–C(3) | 126.6 (9) | 128.5 (7) |
| C(1)–C(3) | 1.50 (1) | 1.50 (1) | C(1)–C(2)–C(21) | 122.3 (8) | 121.8 (7) |
| C(2)–C(12) | 1.55 (1) | 1.53 (1) | C(12)–C(2)–C(21) | 117.7 (8) | 118.3 (7) |
| C(2)–C(21) | 1.52 (1) | 1.52 (1) | C(1)–C(2)–C(12) | 120.0 (8) | 119.8 (7) |
| C(21)–C(22) | 1.55 (2) | 1.55 (2) | O–C(1)–C(2) | 123.1 (8) | 122.0 (7) |
| C(21)–C(23) | 1.52 (1) | 1.52 (1) | C(Ar)–C(Ar)–C(Me) ($\alpha$-Mes) | 119 (1)–121.3 (8) | 119 (1)–122.8 (9) |
| C(4)–C(9) | 1.51 (2) | 1.52 (1) | | | |
| C(8)–C(11) | 1.52 (2) | 1.52 (2) | C(Ar)–C(Ar)–C(Me) ($\beta$-Mes) | 117.6 (9)–122.6 (9) | 118 (1)–123.2 (8) |
| C(6)–C(10) | 1.54 (2) | 1.53 (2) | | | |
| C(13)–C(18) | 1.57 (2) | 1.52 (1) | C–C–C ($\alpha$-ring) | 119.2 (8)–121 (1) | 117.9 (8)–122.5 (9) |
| C(17)–C(20) | 1.54 (2) | 1.52 (2) | | | |
| C(15)–C(19) | 1.54 (2) | 1.54 (2) | C–C–C ($\beta$-ring) | 117.2 (8)–122 (1) | 117.4 (8)–125 (1) |
| C(3)–C(4) | 1.39 (1) | 1.37 (1) | | | |
| C(3)–C(8) | 1.41 (1) | 1.41 (1) | C(2)–C(21)–C(22) | 114 (1) | 113.8 (8) |
| C–C($\alpha$-Mes) | 1.34 (2)–1.40 (2) | 1.36 (2)–1.39 (1)[a] | C(2)–C(21)–C(23) | 115 (1) | 113.7 (8) |
| | | | C(22)–C(21)–C(23) | 108 (1) | 109.8 (9) |
| C(12)–C(17) | 1.38 (1) | 1.41 (1) | C(1)–C(3)–C(4) | 122.7 (8) | 121.7 (7) |
| C(12)–C(13) | 1.41 (1) | 1.41 (1) | C(1)–C(3)–C(8) | 117.8 (7) | 117.4 (8) |
| C–C($\beta$-Mes) | 1.37 (1)–1.40 (1) | 1.35 (2)–1.39 (1) | C(2)–C(12)–C(17) | 122.0 (7) | 122.9 (7) |
| | | | C(2)–C(12)–C(13) | 120.8 (7) | 119.6 (7) |

[a] The shorter bonds are C(6)–C(7) in the $\alpha$-ring and C(14)–C(15) in the $\beta$-ring.

**Table III. Nonbonded Distances (in Å) between Carbons of Methyl Groups in 4d**

| carbon–carbon pairs | distance in structure A | B |
|---|---|---|
| C(9)···C(20) | 3.86 | 3.84 |
| C(9)···C(22) | 4.06 | 4.16 |
| C(20)···C(22) | 3.41 | 3.40 |
| C(11)···C(18) | 3.84 | 3.90 |
| C(11)···C(23) | 4.10 | 4.07 |
| C(18)···C(23) | 3.39 | 3.34 |

[a] All distances ±0.02 Å.

especially of the Mes-*Me* groups. Two rotational barriers were measured for **4b**. This will be discussed elsewhere.

**Crystallographic Data.** Crystals of **3b** were either unsuitable or decomposed during data collection. The only information obtainable from a crystal of **3c** was that the two mesityl groups are trans to each other, but a complete solution was not feasible. The structure of **3d** ($R$ = 0.093) was determined. Bond lengths and angles are given in Table II, and important nonbonded distances are given in Table III. The ORTEP drawing with the numbering scheme is in Figure 1, and a stereoscopic view of **3d** is in supplemetary figure S1. A complete list of the bond lengths and angles, positional and thermal parameters, and structure factors is given in supplementary tables S1–S5.

Enol **3d** has a $Z$ configuration and appears as two crystallographically independent molecules A and B. The two rings are nearly perpendicular to the C=C plane. The torsional angles O–C(1)–$\alpha$-Mes and C(21)–C(2)–$\beta$-Mes are 92.36° and 90.59° in A and 95.47° and 91.19° in B, respectively. Consequently the angles between the two rings are 6.49° (in A) and 5.59° (in B), i.e., the rings are nearly parallel to one another. The torsional angles between the two parts of the double bond are 3.07° (A) and 4.00° (B). the conformation of the C=C—O—H moiety is syn-planar, with angles of 17° (A) and -9° (B).

Bond angles around the C=C bond (Table II) reflect steric interactions of bulky juxtapositioned substituents. The O–C(1)–C(3) angle of 110.2° (A) and 109.5° (B) is almost tetrahedral, and the C(2)–C(1)–C(3) angle is opened to 126.6° (A) and 128.5° (B). Deviations of other bond angles from 120° are small. Bond angle changes resemble those in the isomeric **1** (R = *i*-Pr).[1a] In the *i*-Pr group the C(22)–C(21)–C(23) angle is close to tetrahedral, whereas

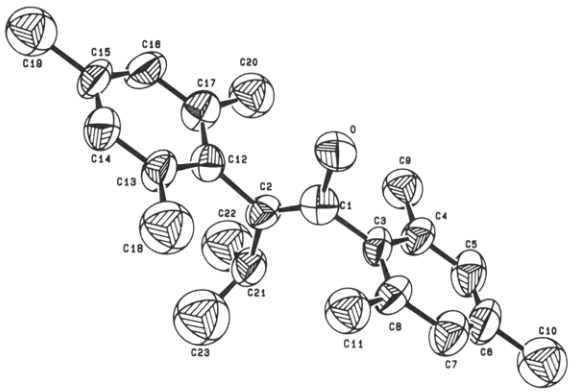


**Figure 1.** ORTEP drawing with the numbering scheme for **3d**.

bond angles involving C(2) open to 113.7–115°. The interring as well as the Ar–Me angles are mostly close to 120°.

The C(1)–C(2) bond length of 1.28 Å (A) and 1.31 Å (B) is shorter than that observed[27] but close to the calculated value for vinyl alcohol.[28] It is appreciably shorter than the value for **1** (R = *i*-Pr).[1a] The C–O bond of 1.40 Å (A) and 1.39 Å (B) is longer than that in **1** (R = *i*-Pr) (1.37 Å). The C(1)–$\alpha$-Mes bond of 1.50 Å resembles the C–Ar bond lengths for compounds **1**, whereas the C(2)–$\beta$-Mes bond of 1.55 Å (A) and 1.53 Å (B) is appreciably longer. The intraring bonds are 1.34–1.41 Å, with bonds of the ipso carbon to the double bond mostly the longest. The bonds to the mesityl–methyl group are longer than normal C-($sp^2$)–C($sp^3$) bonds (and a value of 1.57 Å seems too long).

Figure 1 shows that nonbonded distances between Me groups on the two rings or with the C*H*$Me_2$ are short, reflecting severe nonbonded interactions considering the methyl group van der Waals radius (2.0 Å) and the half-width of a benzene ring (1.85 Å).[29] Table III shows short distances between pairs of methyl groups.

**Keto ⇌ Enol Equilibrations.** Mechanically, the most enlightening result is our failure in obtaining identical **3**/**4** ratios starting separately from **3** or **4** under a variety of

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(29) Cotton, F. A.; Wilkinson, G. *Basic Inorganic Chemistry*; Wiley: New York, 1976; p 88.

**Table IV. Equilibration Studies for the 3/4 System**

| compd | solvent[a] | catalyst | T, K | reactn time, h | results[b,c] E/K | E/O | K/O | E/D | K/D |
|---|---|---|---|---|---|---|---|---|---|
| **3b** | H | TFA (0.4%) | 340 | 15 | 12 | 10 | | | |
| **4b** | H | TFA (0.2%) | 367.5 | 21.5 | NR[f] | | | | |
| **3c** | H | TFA (0.2%) | 353.6 | 44 | *d* | 1 | | | |
| | | | | 44 | | | | | |
| **4c** | H | TFA (0.2%) | 353.6 | 44 | | | *e* | | |
| **3d** | C | TFA (0.4%) | 396 | 144 | 1.8 | | | 0.2 | |
| **3c** | H | $H_3PO_4$ (0.04%) | 367.5 | 5 | NK[g] | | | *e* | |
| **4d** | C | TFA (0.4%) | 396 | 51 | 20 | 0.8 | | 2.5 | |
| **3c** | H | $MeSO_3H$ (0.2%)[h] | 367.5 | 92 | ca. 1 | | 0.6 | | |
| **4c** | H | $MeSO_3H$ (0.2%)[h] | 367.5 | 44.5 | 0.8 | 3.5 | 4.4 | | |
| **3b** | H | $MeSO_3H$ (0.06%)[i] | 366.5 | 1512 | 2.7 | 2.6 | | | |
| **4b** | H | $MeSO_3H$ (0.06%)[i] | 366.5 | 1512 | 0.03 | | 17 | | |
| **3c** | H | $MeSO_3H$ (0.06%)[j] | 366.5 | 1512 | 2.7 | 2.6 | | | |
| **4c** | H | $MeSO_3H$ (0.06%)[j] | 366.5 | 1512 | 0.018 | | | | |
| **3d** | H | $MeSO_3H$ (0.06%)[j] | 366.5 | 1512 | 9.2 | | | 2.1 | |
| **3c** | H | $CF_3SO_3H$ (0.08%)[i] | 353.6 | 25 | NK[g] | 3.1 | | | |
| **4c** | H | $CF_3SO_3H$ (0.08%)[i] | 353.6 | 25 | NR[f] | | | | |
| **3b**[i] | M | HCl (2.7 N) | 353.6 | 108 | 0.7 | | | 0.5 | |
| **4b**[i] | M | HCl (2.7 N) | 353.6 | 108 | NE[h] | | | | |
| **3c**[i] | M | HCl (2.7 N) | 353.6 | 108 | 4.4 | | | 1.7 | |
| **4c** | M | HCl (0.08 N) | 353.6 | 24 | NE[g] | | | | 6.8 |
| **3b** | H | $Et_3N$ (0.4%) | 340 | 16 | NK[g] | 18 | | | |
| **4c** | H | $Et_3N$ (0.2%) | 367.5 | 24 | NE[g] | | | | 1.1 |
| **3c** | H | P.S.[j] (0.0007 M) | 367.5 | 27.5 | NK[g] | 11.4 | | 3.9 | |
| **4c** | H | P.S.[j] (0.0007 M) | 367.5 | 27.5 | NE[g] | | | | 1.3 |
| **3c** | H | MeONa (0.006 M) | 361 | 51 | NK[g] | 1.9 | | 6.4 | |
| **4c** | H | MeONa (0.006 M) | 367.5 | 51 | 0.04 | | | | 3.9 |
| **3c**[i] | H | LDA (0.0015 M) | 353.6 | 108 | NR[f] | | | | |
| **4c**[i] | H | LDA (0.0015 M) | 353.6 | 108 | NR[f] | | | | |

[a] H = hexane, M = MeOH, C = cyclooctane. [b] Workup: The reaction mixture was cooled, the solvent was evaporated, and the remainder was dissolved in $CDCl_3$ and analyzed. [c] E/K = enol/ketone ratio; E/O = enol/double-bond oxidative cleavage product ratio; K/O ketone-/double-bond oxidative cleavage product; E/D = ratio of enol to unidentified decomposition products; K/D = ratio of ketone to unidentified decomposition product. [d] Only traces of ketone were observed. [e] Slight decomposition. [f] No reaction. [g] NE = no enol; NK = no ketone. [h] $MeSO_3H$ is insoluble in hexane. [i] Sample sealed under vacuo. [j] Proton Sponge.

**Table V. NMR Spectral Data ($\delta$) for 3d and $3d^-$ in DMSO-$d_6$**

| species | NMR | *i*-Pr-Me | Mes-Me | Ar-H ($ArC^+C{=}C$) | OH | C-H |
|---|---|---|---|---|---|---|
| **3d** | $^1H$ | 0.71, 0.74 | 2.22, 2.25, 2.31, 2.39 | 6.83, 6.90 | 7.34 | |
| **$3d^-$** | $^1H$ | 0.67, 0.65 | 2.20, 2.35, 2.37 | 6.71, 6.79 | | |
| **3d** | $^{13}C$ | 20.24, 20.45, 20.56, 21.51, 21.89 | | 114.35, 127.90, 128.02, 134.08, 134.51, 134.98, 136.27, 136.48, 137.25, 144.62 | | 31.15 |
| **$3d^-$** | $^{13}C$ | 20.48, 20.63, 22.03, 23.33 | | 100.58, 127.44, 127.72, 131.85, 132.13, 134.08, 138.78, 140.02, 145.00, 157.93 | | 32.05 |

conditions. Typical results are given in Table IV, and all the attempted equilibration experiments are summarized in supplementary table S6.

**Acid Catalysts.** With all the acid catalysts used, 3/4 mixtures were obtained starting from enols **3**, but no enol was obtained from precursors **4**, with one exception. Several catalysts, e.g., $CF_3COOH$, HCl, were successfully used previously for related equilibrations.[2,9,10b,25a] The ratios [acids] to [**3**] or [**4**] were 0.1–910. The solvent was mostly hexane, but cyclooctane was used for isomerization of **3d** and for an attempted isomerization of **4d** at 396 K and methanol was used with acids sparingly soluble in hexane. Reaction temperatures were 353.8–396 K, and reaction times 8 h–9 weeks.

In several isomerizations the use of vacuum-sealed ampules reduced but not eliminated completely the oxidative cleavage of the enol to MesCOR and $MesCO_2H$.[10b,11] Oxidation was especially facile for **3b** and decreased with the increased bulk of R in **3**. At high acid concentration, or at 391 K, other decomposition products became significant.

The lowest 3/4 ratio (0.7) was found for equilibration of **3b** with 910 molar equiv of HCl in MeOH for 108 h at 354 K. Only when each of **3b–d**, **4b**, or **4c** kept with $MeSO_3H$ in hexane for 9 weeks at 366.5 K was a low percent of enols obtained starting from ketones (Table IV). At 396 K in cyclooctane, **3d** gave 36% of **4d** after 6 days, but **4d** did not give any **3d**.

When identical solutions of **3d** and of **1** (R = *t*-Bu) in hexane/0.2% TFA were kept at 353.3 K in pressure ampules for 6.5 h **1** (R = *t*-Bu) gave ≥95% of **2** (R = *t*-Bu), whereas **3d** was recovered unchanged. A mixture of **1** (R = *t*-Bu) and **3d** gave an identical result.

**Basic Catalysts.** Reactions were also conducted in hexane, with the basic catalysts $Et_3N$, NaOMe, 1,8-bis-(dimethylamino)naphthalene, and lithium diisopropylamide (LDA), at 353.8 K or 367 K with catalyst/substrate ratios of 0.1–1.2 for 24–108 h. Starting from **3**, **4** was not observed, and starting from **4**, **3** was not observed (with one exception) and appreciable decomposition took place. Only for [NaOMe]/[**4c**] = 0.1 in hexane at 367.7 K was a small amount of **3c** obtained, together with decomposition products. Other enols did not isomerize with NaOMe.

Partial **4d** to **3d** isomerization is achieved by forming the enolate with dimsylsodium in DMSO, followed by protonation.

**NMR Spectra of the Enolate of 3d.** The enolate of **3d**, i.e., $3d^-$, was obtained by adding NaH to a solution of

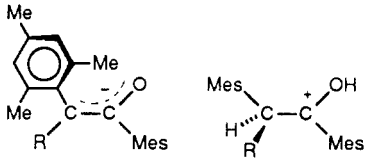
**3d** in DMSO-$d_6$. The $^1$H NMR spectra of **3d** and **3d**$^-$ differ only little, whereas larger differences, especially in the aromatic carbons, are shown by the $^{13}$C NMR spectra (Table V). The enolate from **4d** displays a different $^1$H NMR spectra and is probably a geometrical isomer of **3d**$^-$, but it was not investigated further.

## Discussion

The upshot of the equilibration experiments is that due to a very slow enol ⇌ ketone interconversion under a variety of conditions, the positions of the **3/4** equilibria are unknown. The disinclination toward catalyzed isomerization may reflect either a high kinetic barrier or an unfavorable equilibrium, at least for one of the species or both. We will therefore try to rationalize the high kinetic barrier and estimate the equilibrium constant.

We start with Fuson's report that **3b** completely isomerizes to **4b** in HCl/MeOH and **4b** completely isomerizes to **3b** in NaOEt/EtOH.[10] If Wheland's interpretation[12] that only the acid is a true catalyst is correct, the ketone should be the more stable species, and $K_{enol}$ value will be small.

The kinetic stability argument for the slow isomerization of **3b/4b** was discussed by Hart[13] in terms of structures **9** for the enolate ion formed under basic conditions and




**9** **10**

the cation **10** formed under acidic conditions. In **9** the perpendicular mesityl group hinders carbon protonation but not oxygen protonation. The conversion of **10** to **4** is ascribed to a faster loss of the OH proton than of the β-H proton.

The new facts revealed in the present and related works are the following. (i) Under acid catalysis isomerization of **3b** is not complete, but in contrast to a previous report[11] **3c** converts to **4c**. (ii) The acid-catalyzed isomerization becomes qualitatively slower on increasing the bulk of aliphatic R's: **3d** (R = *i*-Pr) does not isomerize under conditions where **3b** and **3c** (R = Me, Et) isomerize. (iii) When R = Ph, **3f** or **4f** isomerize in hexane. (iv) Crystallographic data for **3d** are available. (v) The enolate **3d**$^-$ was prepared. (vi) Isomerization via **4d–3d** takes place.

**Relative Stability of 3/4 Pairs.** In the absence of equilibrium data, we have to estimate the stability of the two species. If one species is ≥50 times more stable, it will not display isomerization under our conditions.

Aryl-substituted enols are thermodynamically stable due to a combination of mainly resonance and steric effects.[14] An important stabilizing interaction is the ArC=C conjugation, which requires planarity of this moiety. An α-aryl substituent reduces $K_{enol}$ since the conjugation energy of ArC=O exceeds that of ArC=C. The closer the C=C or C=O plane and the α-Ar plane come to orthogonality, the lower the relative destabilizing effect of the α-aryl group. A β-aryl group that can approach planarity can lead to observable quantities of enols of β-aryl aldehydes[30a] but to lower percentages of enols of β-aryl ketones.[30b]

β-Alkyl groups stabilize enols by RC=C hyperconjugation, which has no counterpart in the ketone. For example, in the ArC(Me)=CHOH/ArCHMeCHO equilibrium mixtures in DMSO the enols consist of 6.3–50%.[31] A β-Me group stabilization is apparent from the p$K_{enol}$ values of $Me_2CHCHO$ (3.86)[32] and MeCHO (6.23)[5a] and from gas-phase data.[33] In contrast, α-alkyl substituents reduce the enol stability compared with hydrogen, e.g., p$K_{enol}$ = 8.33 for $Me_2CO$.[34]

The situation at the β-position for **3/4** may be compared with that of the ArC(Me)=CHOH/ArCHMeCHO pair. In DMSO, when Ar = anisyl (An) $K_{enol}$ = 0.067.[31] The Ar-C=C conjugation is appreciable, presumably due to a small torsional angle. The change from AnC(Me)=CHOH to **3d** should decrease $K_{enol}$ due to three causes. First, the solvent change DMSO → hexane should reduce $K_{enol}$ appreciably since for the acenaphthylenol/acenaphthenone it decreases $K_{enol}$ by >650-fold.[35] Second, **3d** is a ketone enol whereas AnC(Me)=CHOH is an aldehyde enol. This should reduce $K_{enol}$ by at least 2 orders of magnitude as found for, e.g., $Me_2CO$ versus MeCHO[5a,34] or for $Mes_2C$=C(R)OH (R = H, Me) in hexane.[2] Third, the orthogonality of the β-mesityl and the C=C planes of **3d** should reduce the ArC=C conjugation to nearly zero and the enol stability by at least 2 orders of magnitude, using Hine's value of 4–5 kcal mol$^{-1}$ for the planar ArC=C interaction.[36]

The "steric effect" combined with the α-aryl substituent effect, which thermodynamically stabilizes several mesityl-substituted enols compared with the isomeric ketones, should operate in the opposite direction. For example, the percentage of the enol at equilibrium increases from ca. 28% for **1** (R = *i*-Pr)[2] to 98.8% for **1** (R = Mes).[25]

Crystallographic data are available for **3d** but not for **3b** and **3c**. The similarity in the $^1$H NMR and UV spectra of **3b–d** and the appreciable Ar—C=C torsional angle shown by space-filling models of **3b** and **3c** suggest that these enols may also not be observable at equilibrium. However, $K_{enol}$ for (*Z*)-9-AntC(Me)=C(OH)Ant-9/9-AntCH(Me)COAnt-9, the anthryl analogues of **3c/3d**, is 3.55 in MeOH at 333 K in the presence of $NaBH_4$,[37] although the two Ar—C=C torsional angles in the enol are 87.7°, as in **3d**.[38] Since extensive enolate ion formation can occur, the $K_{enol}$ value may not be relevant to our case.

Apparently, the parent enol **3a** lacks the RC=C stabilization of several kcal mol$^{-1}$ present when R = alkyl. The gain in β-ArC=C conjugation is insufficient to make the enol stable.

The estimated higher stability of ketones **4a–d** agrees with Wheland's interpretation of the isomerization data.[12] However, for the pair **3f/4f** with R = Ph, 69% enol is present at equilibrium in hexane at 323 K. The torsional angles in **3f** are 74.4° (Mes), 79° (Mes), and 38.3° (Ph),[39] not so much different than those in **3d**. Since phenyl stabilizes a double bond better than *i*-Pr,[36] the conclusion that **3d** is less stable than **4d** remains valid.

**Reason for the Kinetic Stability of Enols 3.** If the enols are less stable, they should isomerize to the ketones with acid catalysis. The alleged complete[10b] isomerization

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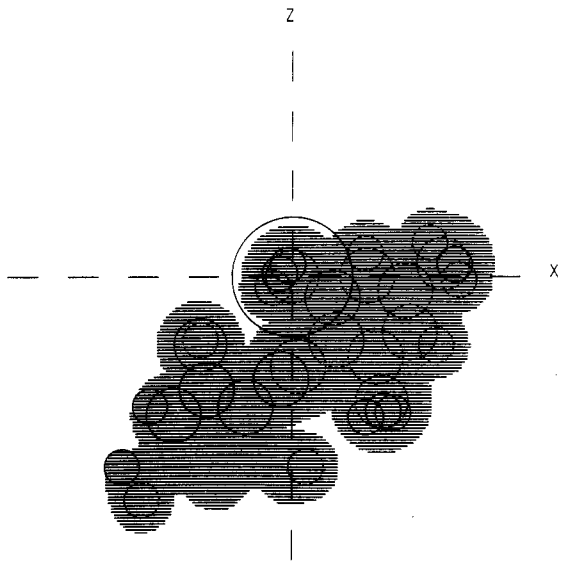


**Figure 2.** Meyer's plots of **3d**: cut through the upper methyl group of the $\beta$-mesityl ring.

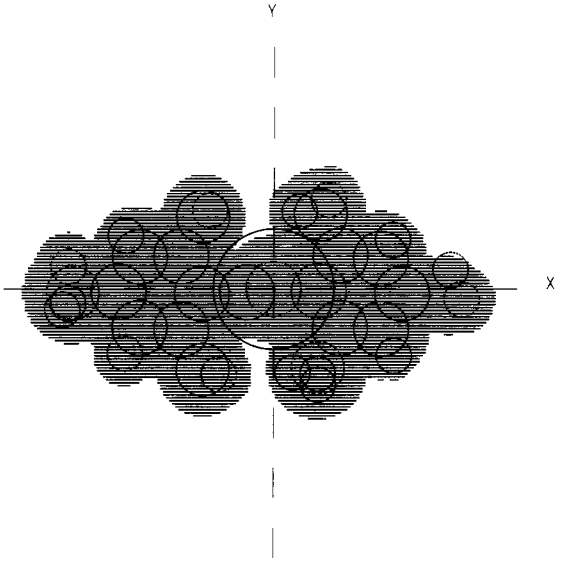


**Figure 3.** Meyer's plot of **3d**. $XY$ plane is the average plane of the molecule. Cut through $C_\beta$.

of **3b** only under forcing conditions was ascribed by Hart to formation of carbocation **10**, which loses the OH proton.[13] However, our finding of incomplete or lack of isomerization of **3** to **4** suggests therefore a kinetic stability of **3** due to steric inhibition to protonation of its double bond (especially in **3d**), which generates **10**.

The crystallographic structure of **3d** clearly demonstrates that the *o*-methyl groups of the $\beta$-mesityl ring, and to a lesser extent those of the $\alpha$-mesityl group lying above and below the C=C plane, mask $C_\beta$ from a perpendicular approach of reagents including protons. This is also deduced from the nonbonded distances between the mesityl methyls and isopropyl methyls (Table III). Meyer's figures, which graphically display the filled and the empty space around a molecule, can be used to elegantly demonstrate this shielding of the double bond. In this approach, the figures depict various cuts through the "van der Waals body" of the molecule.[40] This body is a system of interlocking spheres, constructed computationally by assigning van der Waals radii to the constituting atoms. For help in orientation, the atom through which the cut is taken is placed at the origin and inscribed by a large circle. Atoms lying within 0.4 Å of the plane of the cut are marked by small circles (actually, of radius equal to half their van der Waals radius). Oxygen, whenever encountered by the plane of cut, is represented by sparse hatching. The scale is conveyed by dashing of the coordinate axes, where each dash represents 1 Å.

Figure 2 and supplementary figure S2 give cuts through the upper methyl group of the $\beta$-ring and the lower methyl group of the $\alpha$-ring, respectively. The proton approaches perpendicularly to the double bond from above or below in a direction that is shown by the white channels leading to $C_\beta$. Since each unit is 0.1 nm, approximately the radius of a bare hydrogen, the approach of even the nonexistent bare proton from both directions is highly hindered. Since the catalyst in hexane should be either the bulkier $CF_3C$-OOH molecule or an $CF_3COO^-H^+$ ion pair solvated by other TFA molecules, the hindrance is indeed severe. Most revealing is Figure 3 in which the average plane of the molecule is the $XY$ plane and the cut is through $C_\beta$. The narrow tunnels leading to the $\pi$-system of both $C_\alpha$ and $C_\beta$ clearly indicate the difficulty in protonating **3d**. The hindrance should be less severe for **3b** and **3c**, where presumably the torsional angles of the rings are smaller.

The absence of appreciable base-catalyzed isomerization of the enols also results from steric hindrance.[13] The enolate ion **9** is easily formed by OH deprotonation, but deprotonation of ketones **4b** and **4c** is more hindered and necessitates reflux to enable the **4** → **3** isomerization. Once **9** is formed, the steric situation resembles that of **10**, since the NMR spectrum suggests that the geometries of $\mathbf{3d}^-$ and **3d** are not appreciably different. Consequently, protonation of $C_\beta$ of $\mathbf{3d}^-$ is as hindered as the protonation of **3d** and it occurs mainly (probably exclusively) on the more exposed and electronegative oxygen under kinetic control in an antithermodynamic direction. Indeed, **4d** nearly completely isomerizes to **3d**, when it is first converted to its enolate ion, which is then protonated on oxygen.

We conclude that the steric inhibition to approach of a proton of $C_\beta$ of the double bond of a $\beta$-alkyl-$\alpha$,$\beta$-dimesitylethenol or of its enolate ion make the enol extremely kinetically stable in spite of a thermodynamic driving force for isomerization. Since ketonization of thermodynamically less stable enols is facile, this is an extreme example of how steric effects effectively inhibit a potentially otherwise very facile reaction.

**Torsional Angles of 3d.** The near perpendicularity of the two mesityl groups and the C=C bond in solid **3d** is of general interest. A search of the Cambridge Structural Database (1987 release)[41] retrieved 70 crystallographically independent molecules with the *trans*-stilbene moiety. For structures with $R$ factor <0.10 the aryl torsional angles are always lower than those for **3d**. The nearest values are for (*E*)-PhC(Me)=C(Me)Ph (73.2°, −73.2°)[42] and $\alpha$,$\alpha'$,4,4'-tetrachlorostilbene (72.8°, 72.8°).[43] The only comparable values are the angles (87.7°, 87.7°) for **11** and for 1,2-bis-(9-anthryl)-1-methoxypropene (87.4°, 81.0°).[38]

**Association of Enols 3b–d,f with Hydrogen-Bond-Accepting Solvents.** The association constants of enols

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**3b–d,f** with one DMSO-$d_6$ molecule were recently calculated from the changes of the $\delta$(OH) value in $CCl_4$–DMSO-$d_6$ mixtures and found to decrease with the increased bulk of R.[44] Association with the solvent replaces the intramolecular OH-$\pi$(cis-Mes) hydrogen bonding in a syn C=COH conformation. Such an interaction will probably increase with the increased orthogonality of the $\beta$-Mes and C=C planes and will be maximal in the congested **3d**, with a consequent decrease in $K_{assn}$ in DMSO-$d_6$.

## Experimental Section

**General Methods.** Melting points were determined with a Thomas-Hoover apparatus and are uncorrected. IR spectra were taken with a Perkin-Elmer Model 157G spectrometer and accurate values with the FTIR Bruker ISF 113 V spectrometer. UV spectra were taken with a Baush and Lomb Model 2000 spectrometer and a Kontron Uvikon Model 860 spectrometer. Mass spectra were recorded with a MAT-311 instrument at 70 eV. $^1$H NMR spectra were recorded on a Bruker WH-300 and WP 200 SV pulsed FT spectrometers operating at 300.133 and 200.133 MHz, respectively. $^{13}$C NMR spectra were recorded on a Bruker WP 200 SV spectrometer operating at 50.32 MHz. The reference was tetramethylsilane. Chromatography was on a Si-60 (230–400 mesh) pressure column.

**Solvents and Materials.** Spectroscopic hexane and MeOH (AR Frutarom) were used for the equilibrations. Tetrahydrofuran was distilled from sodium benzophenone ketyl under argon or nitrogen immediately before use. Ether was distilled from $LiAlH_4$ immediately before use. $CH_2Cl_2$ was dried over $MgSO_4$. Distilled $MeNO_2$ was allowed to stand over $CaSO_4$. HMPA and $i$-$Pr_2NH$ were dried over 4A molecular sieves. Commercial (Aldrich) $CS_2$, lithium diisopropylamide (LDA, 1.5 M bistetrahydrofuran in cyclohexane), and MeLi (1.4 M in ether) solutions were used. Enols **3b** and **3c** were prepared according to Fuson.[10]

**X-ray Crystal Structure Analysis of 3d.** The data collection and treatment by MULTAN direct method analysis[45] are as described previously for **1** (R = Ph).[9]

**3d**: space group $P2_1c$, $a$ = 16.489 (5) Å, $b$ = 14.626 (5) Å, $c$ = 16.581 (5) Å, $\beta$ = 90.4 (7)°, $V$ = 3998.7 (9) Å$^3$, $Z$ = 8, $\rho_{calcd}$ = 1.07 g cm$^{-3}$, $\mu$(Mo K$_\alpha$) = 0.16 cm$^{-1}$, no. of unique reflections = 5007, no. of reflections with $I \geq 2.5\ \sigma(I)$ = 2483, $R$ = 0.093.

**1,2-Dimesitylvinyl Trimethylsilyl Ether.** To a stirred solution of LDA (1.5 M, 3.78 mmol) in dry THF (10 mL in an argon atmosphere at −78 °C was added a solution of **4a** (1 g, 3.6 mM) in dry THF (10 mL) dropwise during 10 min. After 1 h of additional stirring at −78 °C, $Me_3SiCl$ (0.77 mL, 6.1 mM) was added during 5 min. The yellow fuming solution was allowed to reach room temperature and after 1 h of additional stirring, the solvent was evaporated. Dry hexane (40 mL) was added and the LiCl precipitate was filtered. This was repeated and then the solvent was evaporated, leaving a light yellow oil (1.14 g). Distillation at 146 °C at 3 Torr afforded a light yellow oil (0.66 g, 53%), which crystallized on standing to a solid, mp 52 °C, which (by NMR) was a 1:7 mixture of two isomers. The compound hydrolyzed slowly to **4a** on standing unless kept under rigorously dry conditions. UV (hexane): $\lambda_{max}$ 197 nm ($\epsilon$ 47 400), 257 (10 300). IR (neat) $\nu_{max}$: 1620 cm$^{-1}$ (C=C, s), 1600 (s). $^1$H NMR ($CDCl_3$) $\delta$: main isomer 0.16 (9 H, s, $Me_3Si$), 1.98, 2.05, 2.18, 2.19 (18 H, 4 s, Mes-Me), 6.06 (1 H, s, CH), 6.70 (4 H, s, Mes-*H*); minor isomer −0.21 (s, $Me_3Si$), 2.29, 2.35, 2.43 (3 s, Mes-Me), 5.49 (s, CH), 6.87 (s, Mes-*H*). Mass spectra (70 eV, room temperature) $m/z$ (relative abundance, assignment): 424 (0.4, M + $SiMe_3$ − H), 352 (80, M), 338 (36, M − $CH_2$), 262 (18, M − $Me_3SiOH$), 247 (81, M − Me − $Me_3SiOH$), 232 (25, M − 2 Me − $Me_3SiOH$), 219 (17, M − $MesCH_2$), 147 (80, MesCO), 143 (30), 128 (21), 119 (80, Mes), 105 (17, PhCO), 103, (64), 91 (45, $C_7H_7$), 73 (100, $SiMe_3$).

Anal. Calcd for $C_{23}H_{32}OSi$: C, 78.35; H, 9.15. Found: C, 78.66; H, 9.10.

(i) When a solution of this ether (10 mg) in $CD_3OD$ (5 mL) was heated to 45 °C or kept for 2 weeks at −20 °C, the NMR spectrum remained unchanged. After reflux for 1, 4, and 6 days, 35%, 63%, and 100% of **4a** completely deuteriated at the methylenic group was formed.

(ii) To a solution of the ether (11 mg, 0.04 mmol) in THF-$d_8$ (0.5 mL) was added dry $Bu_4NF$ (16.4 mg, 0.08 mM), and the mixture was shaken for approximately 5 min. The $^1$H NMR spectrum showed the formation of only **4a**.

**1,2-Dimesityl-3-methylbut-1-en-1-ol (3d).** To a stirred suspension of purified Cu$^I$I (1.95 g, 10.23 mM) in dry ether (40 mL) at 0 °C under Ar was injected a solution of 1.4 M MeLi (14.6 mL, 20.46 mmol). The solution immediately turned yellow, and then a yellow solid precipitated. After additional stirring for 5 min, a solution of **5b** (1 g, 3.4 mM) in dry ether (25 mL) was added. Stirring was continued for an additional 2 h at 0 °C under Ar, at which time the yellow precipitate first dissolved, the yellow solution then turned turbid, and finally a white turbid solution was observed. The mixture was then poured into a stirred saturated aqueous $NH_4Cl$ solution, extracted with ether (3 × 40 mL), and dried ($MgSO_4$), and the ether was evaporated, leaving a yellowish solid (0.88 g). Chromatography with 92.5% petroleum ether–7.5% ether (v/v) as the eluent gave **3d** as a white solid (643 mg, 61%), mp 116.5 °C after crystallization from MeOH–$H_2O$. Spectral data are given in Table I.

Anal. Calcd. for $C_{23}H_{30}O$: C, 85.66; H, 9.38; Found: C, 85.95; H, 9.12.

**Attempted Preparation of 3d from 4a.** To a stirred solution of 1.5 M LDA (7.85 mM) in dry THF (25 mL) at −78 °C under Ar was added a solution of **4a** (2 g, 7.14 mmol) in dry THF (20 mL) dropwise during 10 min. After being stirred for 1 h at −78 °C, $i$-PrCl (0.85 mL, 9.28 mM) was added during 5 min. Stirring was continued for 30 min at −78 °C and for 72 h at room temperature. After being poured into 100 mL of ice–water, TLC and NMR indicated that **4a** was recovered.

**1,2-Dimesityl-3-methyl-2-buten-1-one (5c).** To a solution of **3d** (200 mg, 0.62 mM) in dry $CH_2Cl_2$ (10 mL) was added PDC (513 mg, 1.36 mmol). After being stirred for 2 days under argon, a black precipitate was filtered. Evaporation of the solvent gave a yellowish oily residue (176 mg). Crystallization (petroleum ether) gave **5c** as a white solid, mp 115 °C (103 mg, 52%). Spectroscopic data are given in Table I.

Anal. Calcd for $C_{23}H_{28}O$: C, 86.20; H, 8.81. Found: C, 85.93; H, 8.58.

**1,2-Dimesityl-2-buten-1-one (5b).** This enone[11] was obtained by oxidation of **3c** with 2.1 equiv of PDC in $CH_2Cl_2$ in an argon atmosphere. In the absence of Ar, the major product was MesCOEt.

**1,2-Dimesityl-2-butanone (4c).** To a solution of **3c** (218 mg, 0.71 mM) in MeOH (10 mL), dry HCl was bubbled during 45 min. The mixture was refluxed for 2 days, the MeOH evaporated, the residue dissolved in $CH_2Cl_2$ (15 mL) and washed with saturated aqueous $NaHCO_3$ (10 × 2 mL) and then with water (10 mL) and dried ($MgSO_4$), and the solvent evaporated. Chromatography with 95:5 (v/v) petroleum ether (40–60 °C)/ether gave pure **4c** (104 mg, 48%) and pure **3c** (7 mg). The first fraction was an oil, which solidified on standing, giving **4c**, mp 76 °C. Spectral data are given in table I.

Anal. Calcd for $C_{22}H_{28}$: C, 85.66; H, 9.15. Found: C, 85.80; H, 8.98.

**1,2-Dimesityl-3-methylbutan-1-one (4d). (a) Methyl Mesitylacetate.** A solution of mesitylacetic acid (1.41 g, 7.92 mmol) in MeOH (935 mL) containing concentrated $H_2SO_4$ (6–7 drops) was refluxed overnight. The MeOH was then evaporated and the residue was dissolved in $CH_2Cl_2$ (40 mL) and washed successively with water (2 × 30 mL), saturated aqueous $NaHCO_3$ (25 mL), and water (25 mL). The organic phase was dried ($MgSO_4$) and evaporated, leaving a yellow oil. Distillation at 77–78 °C (0.3 Torr) gave methyl mesitylacetate as a colorless oil. UV (hexane): $\lambda_{max}$ 200 nm ($\epsilon$ 38 800), 211 sh (8300). IR (neat) $\nu_{max}$ 1730–1710 cm$^{-1}$ (C=O, m), 1600 (C=C, s). $^1$H NMR ($CDCl_3$) $\delta$: 2.26 (3 H, s, $p$-Me), 2.29 (6 H, s, $o$-Me), 3.66, 3.67 (5 H, 2 s, $CH_2$ + OMe), 6.87 (2 H, s, Mes-H). Mass spectra (100 eV, 200 °C) $m/z$ (relative abundance, assignment): 192 (25, M), 133 (100, $MesCH_2$), 119 (5, Mes), 77 (3, Ph).

Anal. Calcd for $C_{12}H_{16}O_2$: C, 74.97; H, 8.39. Found: C, 74.67; H, 8.46.

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**(b) Methyl 2-Mesityl-3-methylbutanoate (7).** To a solution of 1.5 M LDA (48 mL, 72 mmol) in dry THF/HMPA (2:1, 90 mL) at 0 °C under Ar was added a solution of methyl mesitylacetate (4.52 g, 24 mM) in dry THF/HMPA (2:1, 30 mL). The mixture was stirred at 0 °C for 165 min, during which time it turns reddish brown. A solution of *i*-PrI (7.2 mL, 72 mmol) in dry THF (10 mL) was then added. Heat was evolved and the solution turned yellow. After being stirred overnight at room temperature, the mixture was poured into ice (200 g), and dilute HCl was added. After extraction with ether (3 × 40 mL), the organic phase was washed with water, dried ($MgSO_4$), and evaporated, leaving a light yellow liquid (7.71 g). Chromatography with 3% ether/97% petroleum ether (v/v) as eluent afforded unreacted methyl mesitylacetate (1.4 g) and a main fraction of pure methyl 2-mesityl-3-methylbutanoate (7) (3.79 g, 69%). Distillation of 1.48 g gave pure ester, bp 89 °C (0.35 Torr) (1.25 g, 84%). UV (hexane): $\lambda_{max}$ 201 nm ($\epsilon$ 50 700), 213 sh (11 900), 218 sh (10 500). IR $\nu_{max}$ (neat): 1730 $cm^{-1}$ (C=O, s). $^1H$ NMR $\delta$ ($CDCl_3$): 0.62, 0.66 (3 H, d, $J$ = 6.9 Hz, CH*Me*Me), 1.12, 1.15 (3 H, d, CHMe*Me*), 2.24 (3 H, s, Mes-*o*-Me), 2.31 (6 H, s, Mes-*o*-Me), 2.60–2.72 (1 H, m, C*H*$Me_2$), 3.60 (3 H, s, MeO), 3.65, 3.68 (1 H, d, $J$ = 10.5 Hz, CHCO), 6.82 (2 H, s, Mes-H). Mass spectra (70 eV, 50 °C) $m/z$ (relative abundance, assignment): 234 (64, M), 191 (53, M – *i*-Pr), 175 (62, MesCH(*i*-Pr)), 159 (93, MesCH(*i*-Pr) – $CH_4$), 133 (100, $MesCH_2$), 119 (35, Mes), 115 (21, M – Mes), 105 (16, PhCO), 91 (26, $C_7H_7$), 77 (11, Ph).

Anal. Calcd for $C_{15}H_{22}O_2$: C, 76.88; H, 9.46. Found: C, 77.11; H, 9.70.

**(c) 2-Mesityl-3-methylbutanoic Acid (8).** A solution of the ester 7 (1.65 g, 7.1 mmol) in 33% NaOH in distilled water (36 mL) was refluxed overnight. The suspension formed was cooled, water (100 mL) was added, and the mixture was warmed until the solid dissolved and then was cooled to room temeprature. Concentrated HCl was added up to a pH of 1–2 and the solution was boiled and then cooled to 0 °C. The white precipitate formed was filtered and dissolved in $CH_2Cl_2$, the solution was dried ($MgSO_4$), and the solvent was evaporated. Crystallization of the residue (0.99 g, 63%) from MeOH–$H_2O$ afforded pure 2-mesityl-3-methylbutanoic acid (8) as a white solid, mp 150–151 °C. UV (hexane): $\lambda_{max}$ 201 nm ($\epsilon$ 34 200), 215 sh (8600). IR $\nu_{max}$ (Nujol): 2500–3100 $cm^{-1}$ (m, COOH), 1690–1710 (C=O, s). $^1H$ NMR $\delta$ ($CDCl_3$): 0.60, 0.62 (3 H, d, $J$ = 6.9 Hz, HC*Me*Me), 1.13, 1.15 (3 H, d, $J$ = 6.3 Hz, CHMe*Me*), 2.24 (3 H, s, Mes-*p*-Me), 2.33 (6 H, s, Mes-*o*-Me), 2.50–2.68 (1 H, m, C*H*$Me_2$), 3.69, 3.72 (1 H, d, $J$ = 10.5 Hz, CHCO), 6.83 (2 H, s, Mes-H). Mass spectra (70 eV, 50 °C) $m/z$ (relative abudance, assignment): 220 (74, M), 177 (63, M – *i*-Pr), 159 (MesCH(*i*-Pr) – $CH_4$), 133 (100, $MesCH_2$), 119 (31, Mes), 115 (12), 105 (12, PhCO), 91 (17, $C_7H_7$), 77 (8, Ph).

Anal. Calcd for $C_{14}H_{20}O_2$: C, 76.33; H, 9.15. Found: C, 76.27; H, 9.18.

**(d) 1,2-Dimesityl-3-methylbutan-1-one (4d).** (i) To the acid 8 (0.70 g, 3.2 mmol) were added $SOCl_2$ (1.9 mL, 25.6 mmol) and $CHCl_3$ (0.5 mL). The mixture was heated to 40 °C for 30 min, then stirred for 3 h at 25 °C, and kept overnight at 0 °C. After evaporation of the $CHCl_3$ and the $SOCl_2$, petroleum ether (40–60 °C) (30 mL) was added to the brown-red liquid and the solvent was evaporated, leaving a yellowish oil (0.72 g, 95%) whose IR showed an acyl halide C=O stretching at 1800 $cm^{-1}$. The compound was not purified.

(ii) To a mixture of $AlCl_3$ (0.69 g, 5.15 mmol) and mesitylene (0.63 mL, 4.55 mmol) in $CS_2$ (15 mL) at 0 °C was added a solution of the acyl halide (0.72 g, 3.03 mM) in $CS_2$ (10 mL) slowly. The yellow mixture, which gradually turned red, was kept for 30 min at 0 °C, for an additional 30 min at room temperature, and then refluxed overnight. The dark brown mixture was poured into ice (70 g)/concnetrated HCl (10 mL), extracted (2 × 30 mL of ether), washed thrice with a dilute aqueous $NaHCO_3$ solution, dried ($MgSO_4$), and evaporated, leaving a black liquid (0.89 g). Purification by flash chromatography with a 45:55 $CH_2Cl_2$–petroleum ether (40–60 °C) mixture gave 0.47 g of products. Addition of EtOH yielded the crude **4d** (0.28 g, 29%). Recrystallization (EtOH) gave **4d** as a white solid, mp 131.5 °C. Spectral data are given in Table I.

Anal. Calcd for $C_{23}H_{30}O$: C, 85.66; H, 9.38. Found: C, 85.57; H, 9.46.

**Enolate of 3d.** The enolate **3d**$^-$ was prepared by addition of **3d** to a solution of dimsylsodium, prepared from NaH (5 molar equiv) and DMSO-$d_6$ followed by heating to dissolution. The $^1H$ NMR and the $^{13}C$ NMR spectra of **3d** and **3d**$^-$ are compared in Table V. The resolution in the $^1H$ NMR spectra of **3d**$^-$ was not so good due to turbidity of the sample.

To the "enolate" solution was added MeI. Heat was evolved and a white precipitate was formed. A saturated aqueous NaCl solution was added, and the mixture was extracted twice with EtOAc, dried ($MgSO_4$), and evaporated. A yellow solid was obtained. A spot with an $R_f$ higher than that of **3d** was observed by TLC on silica, with 90% petroleum ether (40–60 °C)/10% ether as the eluent. The NMR ($CDCl_3$) spectrum [$\delta$: 0.78, 0.82 (6 H, d, CH*Me*$_2$), 2.29, 2.32, 2.37, 2.42 (19 H, 4 s + m, Mes-Me + C*H*$Me_2$), 3.05 (3 H, s, OMe), 6.91, 6.93 (4 H, 2s, Mes-H)] is consistent with formation of the methyl ether of **3d**. The product was not investigated further.

**Equilibration Experiments.** The 3/4 ratio was estimated by integration of the aromatic signals of both species in the $^1H$ NMR spectrum, which display the largest differences.

**With Acid Catalysts.** Solutions of **3** or **4** (8.5–50 mg) in hexane or MeOH (5–25 mL) containing the catalyzing acid were kept either at atmospheric pressure or in vacuo sealed ampules. Samples were analyzed by $^1H$ NMR. Decompositions were more extensive at higher temperature or at a higher acid concentration. Data are given in Table IV, and an experiment is described below.

**Isomerization of 3d and Attempted Isomerization of 4d.** (i) Samples of **3d** or **4d** (10 mg, 0.03 mmol) in cyclooctane (10 mL) containing $CF_3COOH$ (0.04 mL, 0.05 mmol) were kept at 396 K for 6 days. After the usual workup, the sample of **4d** showed (by NMR) a considerable amount of decomposition products (signals at $\delta$ 7.51–7.7) but no **3d**. When starting from **3d** most of **3d** had disappeared, the decomposition product/**3d** ratio was 5, and the **3d**/**4d** ratio was 1.8. TLC analysis showed spots for **3d**, **4d**, and three decomposition products.

(ii) Gaseous HCl was bubbled into a solution of **3d** (100 mg, 0.33 mmol) in EtOH (30 mL), during 90 min. The mixture was refluxed for 2 weeks, during which time HCl was bubbled again into the solution. After 6 days two new aromatic signals started to form. The ratio **3d**/new signals = 5.2:1 after 2 weeks. The solvent was evaporated, the remainder was dissolved in $CHCl_3$ (30 mL), washed with concentrated aqueous $Na_2CO_3$ solution (20 mL) and with water (30 mL) and then dried ($MgSO_4$), and the solvent was evaporated. On chromatography on a preparative TLC Si-60 plate using 90% petroleum ether (40–60 °C)/10% ether as the eluent the main fraction (49 mg) was **3d**. Another fraction was impure **4d**.

**With Basic Catalysts.** Data for isomerization with basic catalysts are given in Table IV.

**Isomerization of 4d to 3d.** **4d** (12 mg, 0.03 mmol) was dissolved in a solution of dimsylsodium in DMSO-$d_6$ (prepared by heating NaH (97%, 15 mg, 0.06 mmol) in DMSO-$d_6$ (2 mL) for 23 min at 70 °C under Ar). The mixture was heated for 1 h at 65 °C under Ar. $^1H$ NMR shows a spectrum different from that of **3d**, **3d**$^-$, or **4d**. $D_2O$ (0.1 mL) was added and the spectrum revealed the presence of **3d**. The mixture was left overnight at room temperature, then poured into a saturated aqueous NaCl solution (5 mL), extracted with EtOAc (3 × 3 mL), and dried ($MgSO_4$), and the solvent was evaporated. An $^1H$ NMR spectrum of the residue consisted of ca. 20:1 of **3d** to **4d**.

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**Registry No.** **3a**, 125640-43-9; **3b**, 117873-83-3; **3c**, 117873-84-4; **3d**, 117873-85-5; **3d**$^-$, 125640-56-4; **3d** methyl ether, 125640-57-5; **3e**, 125640-44-0; **3f**, 77787-79-2; **4a**, 5796-78-1; **4a**-$d_2$, 125640-53-1; **4b**, 125640-45-1; **4c**, 125640-46-2; **4d**, 125640-47-3; **4e**, 125640-48-4; **4f**, 77787-77-0; **5a**, 125640-49-5; **5b**, 125640-50-8; **5c**, 38084-27-4; **7**, 125640-54-2; **8**, 20732-28-9; MesCOEt, 2040-15-5; *i*-PrI, 75-30-9;

1,2-dimesitylvinyl trimethylsilyl ether (isomer 1), 125640-51-9; 1,2-dimesitylvinyl trimethylsilyl ether (isome 2), 125640-52-0; methyl mesitylacetate, 41841-19-4; mesitylacetic acid, 4408-60-0; 2-mesityl-3-methylbutanoyl chloride, 125640-55-3; mesitylene, 108-67-8.

**Supplementary Material Available:** Tables S1-S4 giving bond lengths, bond angles, positional parameters, and thermal parameters for **3d**, Table S6 giving equilibration experiments, and Figures S1 (stereoscopic view of **3d**) and S2 (Meyer's cut of **3d** through the lower methyl group of the $\alpha$-Mes ring) (16 pages); Table S5 giving observed and calculated structural factors for **3d** (14 pages). Ordering information is given on any current masthead page.

# *cis*-Diazenes. Viscosity Effects, One-Bond Scission, and Cis-Trans Isomerization[1,2]

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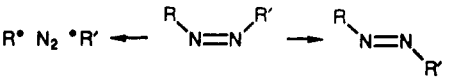
Effects of solvent viscosity on the rates of overall thermal decomposition, deazatization, and isomerization of several symmetric and unsymmetric *cis*-diazenes (*cis*-azoalkanes) have been determined in pure alkanes and mixtures of octane and mineral oil. Increasing viscosity decreases the overall decomposition and deazatization rates for all of these *cis*-diazenes. While isomerization rates also decrease with increasing viscosity for most of the diazenes, that for *cis*-*N*-*tert*-butyl-*N'*-1-norbornyldiazene (1) increases. These results are interpreted in terms of deazatization via one-bond scission and an intermediate diazenyl radical, isomerization via nonradical inversion, and the possibility of isomerization via a diazenyl radical for 1.

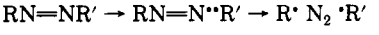
*cis*-Diazenes thermally decompose into radicals and molecular nitrogen in competition with isomerization to their trans isomers (Scheme I).[4] While it has been accepted for some time that highly unsymmetical diazenes (both cis and trans) undergo homolytic scission via one-bond scission to form an intermediate diazenyl radical that subsequently cleaves further to give a radical and molecular nitrogen (Scheme II),[4-6] our proposal[7] that this is also the mechanism for deazatization of symmetrical *cis*-diazenes (R = R') is relatively recent.

The pathway by which these *cis*-diazenes isomerize to their trans isomers has also been the subject of debate. Nonradical routes include rotation about the N=N bond, or inversion at nitrogen (semilinearization);[4,5] while recombination of the diazenyl radical and the R• radical formed by one-bond scission has also been suggested as a possible pathway.[7,8] It is generally accepted that rotation is a much higher energy process than inversion for alkyl diazenes and the latter seems to be the nonradical pathway.[4,5] However, the existence of a radical pathway for isomerization of *cis*-dialkyldiazenes has been controversial.

**Scheme I**



**Scheme II**



**Scheme III**

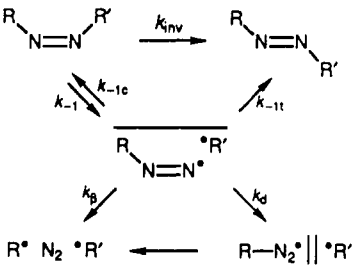
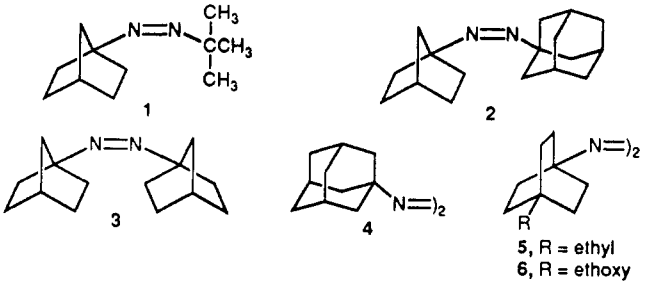


**Chart I**



The results of a detailed study of a series of bridgehead *cis*-diazenes has been interpreted as support for the inversion mechanism and against the radical pathway.[5]

A kinetic scheme including these possibilities is shown as Scheme III. This scheme includes recombination steps ($k_{-1c}$ and $k_{-1t}$) to form both the *cis*- and *trans*-diazene from the proposed intermediate diazenyl radical-R• pair. They would compete with loss of molecular nitrogen ($k_\beta$) and separative diffusion ($k_d$). As a direct consequence of the

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