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Tautomerism

# Tautomerization-Mediated Molecular Switching Between Six- and Seven-Membered Rings Stabilized by Hydrogen Bonding

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**Abstract:** 1,3,4,6-Tetraketones typically undergo keto–enol tautomerism forming bis-enols stabilized by intramolecular hydrogen bonding in two six-membered rings. However, 1,3,4,6-tetraketones derived from the terpene ketone camphor and norcamphor exist as isomers with two distinguishable modes of intramolecular hydrogen bonding, namely, the formation of six- or seven-membered rings. The structural requirements for this so far unknown behavior were investigated in detail by synthesis and comparison of structural analogues. Both isomers of such 1,3,4,6-tetraketones were fully characterized in solution and in the solid state. Intriguingly, they slowly interconvert in solution by means of tautomerism–rotation cascades, as was corroborated by DFT calculations. The influence of temperature and complexation with the transition metals Pd, Rh, and Ir on the interconversion process was investigated.

## Introduction

1,3-Diketones have drawn attention in many fields of modern chemistry. They are easily converted to difluoroboron diketonates that exhibit interesting fluorescence and phosphorescence properties.[1,2] In addition, they are well known to form stable complexes with a variety of metals.[3] Chiral 1,3-diketonate complexes[4] proved to be valuable catalysts, for example, in asymmetric hetero-Diels–Alder reactions.[5]

Unlike their smaller counterparts, 1,3,4,6-tetraketones that consist of two fused 1,3-diketone subunits have been rarely mentioned. The first description of this structural motif dates back to Claisen and Stylos in 1887, who reported the condensation of acetone and diethyl oxalate.[6] In sporadic later studies, tetraketones were used as synthetic intermediates.[7,8] In contrast, they are well-established building blocks in supramolecular coordination chemistry,[9–12] for example, for the formation of metallacrown ethers.[13]

In contrast to the smaller 1,3-diketones, tetraketones almost exclusively form planar bis-enols in solution and in the solid state.[14] Balenovic and Poje first studied the tautomerism of various 1,3,4,6-tetraketones in solution by means of NMR spectroscopy.[15] They realized that the molecular structure and ratio of the tautomers present were strongly solvent dependent. In deuterated chloroform, they exclusively observed the bis-enol structure **1c**. All possible keto–enol tautomers **1a–c** and most interestingly the semiacetal **1d**, product of a ring–chain tautomerism, were observed in deuterated dimethyl sulfoxide (Figure 1 A).[15–16,17]

The multiplicity of coexisting isomeric structures was extended when Noe et al.[18] and Hart[19] independently reported 1,3,4,6-tetracarbonyl **2** derived from natural occurring (+)-(*R*)-camphor. Both reported the simultaneous presence of structurally related isomers that cannot be rationalized by any tautomerism known so far. Hart postulated six possible structures differing in the enol protons position and an *s-cis*/*s-trans* isomerism of the central single bond and suggested $\mathbf{2}_{s\text{-}trans}$ and $\mathbf{2}_{s\text{-}cis}$ (Figure 1 B) as the most probable structures in solution. In the context of our investigations of controllable molecular systems that can coexist in several interconverting states,[20–23] we became aware of this unexplained phenomenon.

## Results and Discussion

We optimized the synthetic protocol to prepare 1,3,4,6-tetraketones by condensation of diethyl oxalate and ketones based on the results of Hart[19] and Noe et al.[18] using **2** as reference substance. We found that the deprotonation of (+)-(*R*)-camphor is the crucial step for the successful conversion to 1,3,4,6-tetraketones and to obtain a high overall yield. Sodium methoxide did not yield any product, and lithium diisopropylamide led to undesired side reaction due to nucleophilic attack of diethyl oxalate. By using sodium hydride to generate the enolate under optimized reaction conditions, the reaction can be performed on a large scale with excellent yield (93%).

To investigate a broad range of tetraketones we additionally prepared compounds **3**–**7** (Figure 2). Besides (+)-(*R*)-camphor, we included (±)-norcamphor, which has an unsubstituted [2.2.1]bicycloheptane core. Compound **3** was prepared in 36% yield due to tedious purification of the *meso* isomer. Literature-known acetone tetraketone **4** was prepared for comparison. Next, we studied the related [3.1.1]bicycloheptanes. (+)-(*R*)-No-

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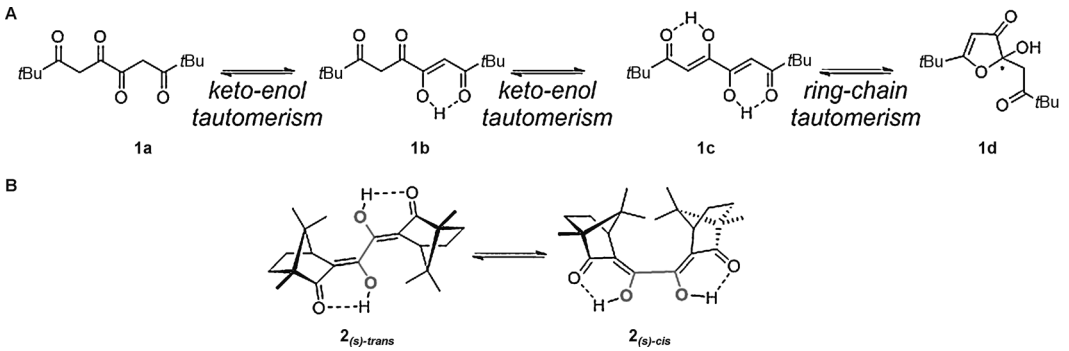


**Figure 1.** Molecular structures of 1,3,4,6-tetraketones reported in literature. A) Tautomers of **1** in deuterated dimethyl sulfoxide solution identified by NMR spectroscopy.[15] B) Additional *s-cis/s-trans* isomerism of **2** proposed by Hart.[19]

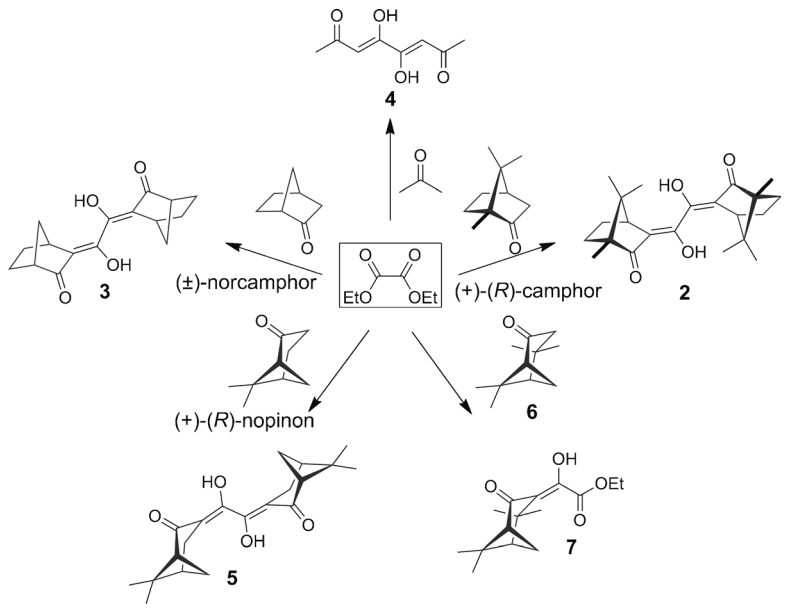


**Figure 2.** Tetraketones investigated in the present study. General reaction conditions: 1.0 equiv diethyl oxalate, 2.0 equiv ketone, 5.5 equiv sodium hydride, THF, reflux, 1–7 d (see Experimental Section for details).

pinone smoothly yielded **5** in 63% yield. The methylated analogue **6** exclusively formed **7** in 70% yield due to increased steric hindrance, which makes nucleophilic attack of a second enolate impossible.

In a first step we investigated the behavior of the obtained 1,3,4,6-tetraketones in the solid state, to have a well-defined starting point for investigations in the solution phase. Therefore, we analyzed crystals of **2**, **3**, and **5** by means of X-ray diffraction. In accordance with **4** and the tetraketone derived from acetophenone,[14] compound **5** exists exclusively as a bis-enol with two six-membered rings stabilized by hydrogen bonding in the solid state (Figure 3 A). Surprisingly, and in sharp contrast to this, we observed two independent molecules as overlapping structures for **2** and **3**. Both are bis-enols, yet a major isomer forms hydrogen-bond-stabilized six-membered rings, while a minor isomer is made up of seven-membered rings (Figure 3 B and C). In the case of **2**, the minor isomer refines to about 13% of the measured crystal. The isomeric ratio observed by X-ray crystallography was highly reproducible when crystalline material prepared under the same conditions was used and is independent of the isomeric ratio of the solid material prior to crystallization.

Samples of **2**, **3**, and **5** were subsequently studied by NMR spectroscopy. As expected, **5** exhibited one distinct signal set in solution irrespective of the solvent used. However, **2** exhibited signal sets for two isomers. They differ most prominently in the chemical shift of the enol proton resonances at 12.53 and 15.54 ppm (in [$D_6$]benzene), respectively. This behavior can easily be rationalized by the simultaneous occurrence of six- and seven-membered ring iso-

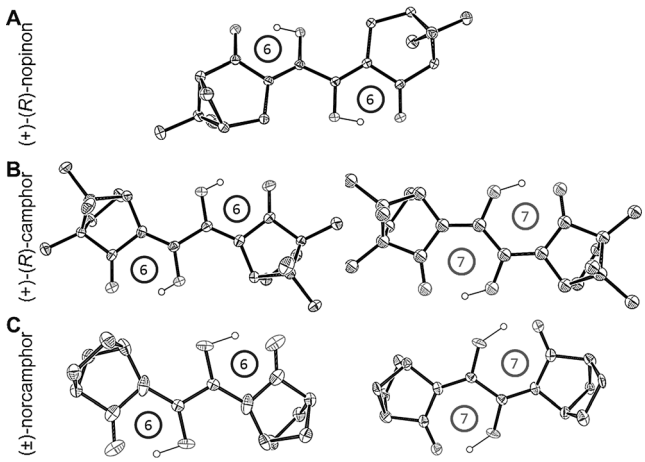


**Figure 3.** X-ray crystal structures of tetraketones **2**, **3**, and **5**. Thermal displacement ellipsoids (30% probability) are shown. Hydrogen atoms except enol protons are omitted for clarity.

mers caused by different intramolecular hydrogen bonding in solution. This isomerism can be described as a coupled *cis*/*trans* isomerism of the keto–enol C=C bond. Although the two isomers are formed by tautomerism (see below), they are not normal tautomers,[24] because there is no rapid interconversion between the isomers due to a migrating group.

NMR spectroscopic analysis of **3** was hampered by the coexistence of ketone tautomers in addition to the six- and seven-membered ring isomers in deuterated chloroform or benzene solution. However, in deuterated dimethyl sulfoxide, compound **3** can almost exclusively (>90%) be transformed into the cyclic semiacetal **3a**. Analysis of 2D NMR spectra indicated that **3a** and not **3b** is the observed isomeric structure (Figure 4, A). This assignment is further corroborated by isolation of the *N*-substituted semiaminal **3c** (Figure 4B, C) on treatment with ammonia.

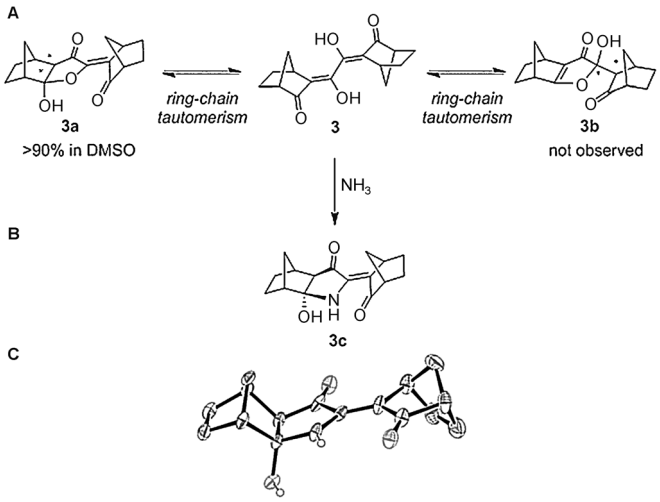


**Figure 4.** Tautomerism of **3**. A) In contrast to dissolution in deuterated chloroform or benzene, **3** is almost exclusively converted to semiacetal **3a** in dimethyl sulfoxide solution. B) Treatment of the 1,3,4,6-tetraketone with ammonia leads to the formation of cyclic semiaminal **3c**, which can be isolated and investigated, for example, in chloroform solution. C) X-ray structure of **3c**. Since *meso*-**3** was used, the depicted structure only represents one stereoisomer. Thermal displacement ellipsoids (30% probability) are shown. Non-acidic hydrogen atoms are omitted for clarity.

To compare the solid-state results with the experiments in solution, our idea was to monitor potential isomerization processes after dissolving crystalline material of known isomeric composition. Thus, larger amounts of crystalline tetraketones **2**, **3**, and **5** were prepared by applying exactly the same conditions that were used to obtain the samples for X-ray crystallography. This material was dissolved in an appropriate deuterated solvent and NMR spectra were recorded at given time intervals. These intervals had to be short in the beginning to quantify any possible isomerization between sample preparation and the first NMR measurement.

As expected, a solution prepared from a crystalline sample of **5** showed only one signal pattern when analyzed after 1 min. Heating of the solution or prolonged waiting did not lead to any isomerization. Unfortunately, crystalline **3** dissolves very slowly in $CDCl_3$ or $C_6D_6$, and hence reliable comparison to the solid-state results impossible.

In contrast, crystalline **2** dissolves very rapidly in $CDCl_3$ and $C_6D_6$. This allowed us to record NMR spectra within 1 min after adding the sample. To confirm that the tautomeric ratio was not significantly altered within this first minute, we repeated the measurement after another minute. Intriguingly, we observed two signal patterns without any change of relative intensity within the first two minutes irrespective of whether $CDCl_3$ or $C_6D_6$ was used. The initial tautomeric ratios were determined as 15:85 ($CDCl_3$) and 18:82 ($C_6D_6$), respectively. It thus can be concluded that the two species observed by NMR spectroscopy are those overlapping in the X-ray structure. In addition, with respect to the isomeric ratio in the solid state, the signals of the minor species in NMR spectroscopy can be identified as $\mathbf{2}_{\text{seven membered}}$.

Surprisingly, recording NMR spectra after 4 h, 24 h and 6 d revealed that the isomeric ratio slowly changed over time and reached solvent-dependent equilibria at 35:65 ($C_6D_6$) and 29:71 ($CDCl_3$) after several days (Figure 5). Thus, a solution of **2** contains significantly larger amounts of $\mathbf{2}_{\text{seven membered}}$.

The slow adjustment of the equilibrium isomeric ratio can be drastically accelerated by heating the solution. Thus, a sample of crystalline **2** was dissolved in 1,2-dideuterotetrachloroethane and an initial 14:86 ratio was determined. NMR spectra were recorded while stepwise heating to 130 °C and after subsequent cooling to room temperature. The equilibrium ratio of 34:66 was reached within less than 3 h (time required to conduct the experiment).

To fully understand the new type of tautomerism-mediated isomerism, we investigated the structures of all above-mentioned tetraketones and mechanistic aspects by DFT calculations at the B3LYP/cc-pvTZ level of theory. First, we compared the relative energies of the hydrogen-bond-mediated six- and seven-membered ring isomers of **2**, **4** and **5**. Preliminary investigation of the relative stabilities of six- and seven-membered ring structures revealed that the latter is less stable for acetone tetraketone **4** ($\Delta G = +26.5\ \text{kJ mol}^{-1}$) and nopinone tetraketone **5** ($\Delta G = +4.9\ \text{kJ mol}^{-1}$), yet favored for camphor derivative **2** ($\Delta G = -9.3\ \text{kJ mol}^{-1}$). Although the overall stability of seven-membered ring isomers seems to be overestimated, this gives a first hint at the anomalous behavior of [2.2.1]bicycloheptane-derived camphor tetraketone **2**. Next, we observed that the *s-cis* isomer $\mathbf{2}_{s\text{-cis}}$ proposed by Hart[19] is already $\Delta G = 17.8\ \text{kJ mol}^{-1}$ higher in energy than *s-trans* isomer $\mathbf{2}_{s\text{-trans}}$ and therefore is not further taken into account.

With regard to the isomerization mechanism, we note that no mixed intermediate with one hydrogen-bond-stabilized six- and one seven-membered ring isomer can be formed. Two independent rotations around formal C=C bonds are ultimately required to transform $\mathbf{2}_{\text{six membered}}$ into $\mathbf{2}_{\text{seven membered}}$ (Figure 6A). In principle, this can be achieved by two mechanistic options: with or without breaking the protochelate structures by keto–enol tautomerism. Since the barrier for keto–enol tautomerism is highly solvent dependent and many different sorts of mechanisms are known and plausible,[25–27] we did not study this

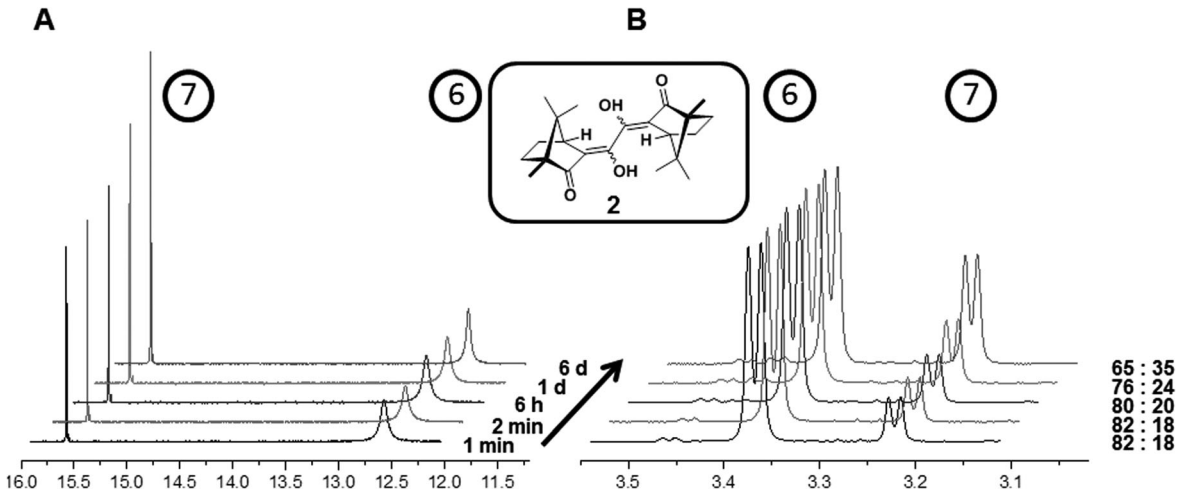


**Figure 5.** Partial $^1$H NMR spectra at given times after dissolution of a crystalline sample of **2** in $C_6D_6$. A) Enol proton region. B) Camphor-backbone bridgehead-proton resonances. The relative integrals are given as ratios on the right. They can be determined for the resonances in A) or B) without divergence.

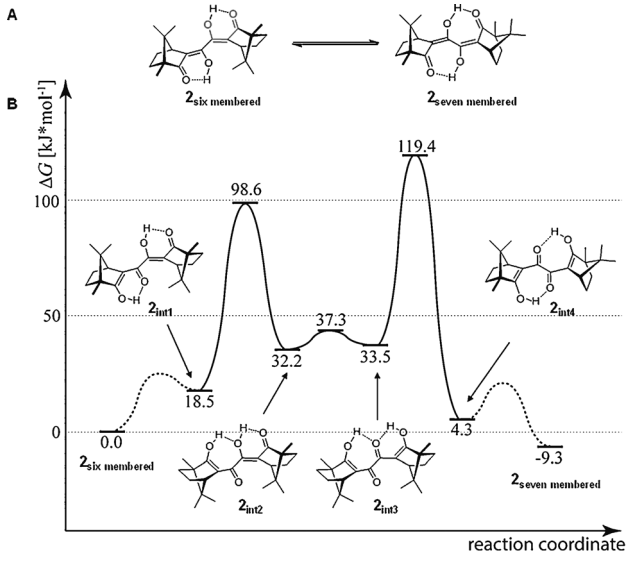


**Figure 6.** Mechanistic investigation of the interconversion of the hydrogen-bond-stabilized six- and seven-membered ring isomers of **2**. A) Isomerization overview. B) Reaction profile. All calculations were performed with Gaussian 09 (Revision D.01). The B3LYP functional was used with a cc-pVTZ basis set. All given values are D3-corrected. Standard ambient temperature and pressure (298 K, 1.0 atm) were applied.

mechanism, which in fact is very similar to that investigated and discussed below.

In a first step, tautomerization of $\mathbf{2}_{\mathbf{six\ membered}}$ to $\mathbf{2}_{\mathbf{int1}}$ lowers the bond order of the formal C=C bond, which facilitates rotation around this bond in a second step. Intermediate $\mathbf{2}_{\mathbf{int2}}$ is stabilized by two intramolecular hydrogen bonds and can readily tautomerize to $\mathbf{2}_{\mathbf{int3}}$, which has an elongated second former C=C double bond. Another rotation to give $\mathbf{2}_{\mathbf{int4}}$ and finally consecutive tautomerization of both enol protons results in $\mathbf{2}_{\mathbf{seven\ membered}}$ (Figure 6, B).

Various cases are known in which transition metals have significant influence on tautomerism. Thus, we were interested in the behavior of the tautomers towards transition metal complexation.[28–30] As expected, **5** readily forms $C_2$-symmetric homobimetallic complexes **8** and **9** with $[\{Rh(nbd)Cl\}_2]$ (nbd = norbornadiene) and $[\{Rh(CO)_2Cl\}_2]$, in which the metal atoms are chelated in six-membered rings. Complexation with $[\{Pd(C_3H_5)Cl\}_2]$ resulted in statistical formation of *endo* and *exo* isomers, and thus **10** was obtained as a 1/2/1 ratio of *endo*/*endo*, *endo*/*exo*, and *exo*/*exo* isomers (Figure 7 A). The geometrical parameters of this class of complexes were studied in detail by means of X-ray crystallographic investigation of $\{\mathbf{2}[Rh(cod)]_2\}$[19] (cod = 1,5-cyclooctadiene) and **9** (Figure 7, B).

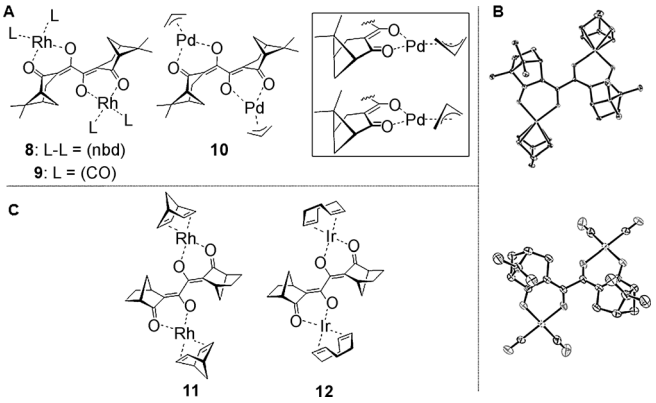


**Figure 7.** Transition metal complexes of 1,3,4,6-tetraketones. A) Homobimetallic complexes of **5** and illustration of the coordination isomers of **10**. B) Molecular structures of $\{\mathbf{2}[Rh(cod)]_2\}$[19] and **9** in the solid state. Thermal displacement ellipsoids (30% probability) are shown and hydrogen atoms are omitted for clarity. C) Rhodium and iridium complexes of **3**.

Since **2** and **5** exclusively form six-membered metal-chelate complexes, we were interested in the properties of *meso*-**3**, which exists as complex mixture of several tautomers. Interestingly, treatment of *meso*-**3** with $[\{Rh(nbd)Cl\}_2]$ or $[\{Ir(cod)Cl\}_2]$ resulted in significant simplification of the NMR spectra by exclusive formation of analogous $C_i$-symmetric complexes **11** and **12** (Figure 7 C).

Interestingly, on decoordination of the tetraketone ligand **2**, for example, by heating the complex in a protic solvent, both hydrogen-bond-mediated six- and seven membered ring isomers are again observed in the described ratios. Thus, metal coordination and decoordination can also be used to control the isomeric equilibrium.

## Conclusion

We have described a novel type of tautomerism-mediated isomerism caused by hydrogen-bond-stabilized six-membered and seven-membered cyclic bis-enol structures. Inspired by camphor derived 1,3,4,6-tetraketone **2**, we identified both isomers in solution and in the solid state. Study of several analogous structures revealed that a [2.2.1]bicycloheptane backbone is crucial for the occurrence of the isomerism, as was proven by experimental data and DFT calculations. One key factor of this new phenomenon is the exceptionally slow rate of isomerization in solution. This process can be accelerated by heating or treatment with transition metals, and the latter form exclusively six-membered metal chelates. Further studies may aim to use the hydrogen-bond-stabilized six-and seven-membered ring isomers as switching units that can be controlled by crystallization, addition of auxiliaries, temporary metal bonding, or temperature.

## Experimental Section

Syntheses were carried out under an atmosphere of argon (5.0 grade) with exclusion of air. All glassware was heated prior to use, and standard Schlenk techniques were applied. THF and $CH_2Cl_2$ were dried in an MB SPS-800 system and stored under argon. NMR spectra were recorded on Bruker Avance 600, 500, and 300 MHz spectrometers. The residual proton signals of the solvent were used as internal standards.[31] Mass spectrometric measurements were performed on a JEOL JMS-700 Magnetic Sector or a Finnigan MAT TSQ700 spectrometer. IR spectra were recorded on a Thermo Scientific Nicolet 6700 FTIR spectrometer. X-Ray crystallographic analysis was done on a Bruker Smart CCD or a Bruker APEX diffractometer. Microanalyses were performed on an Elementar vario MIRKO cube instrument. (+)-(*R*)-Nopinone,[32] 4,4,6,6-tetramethylbicyclo[3.1.1]heptan-2-one,[33] and 2,4,5,7-octanetetraone[34] were prepared by following literature procedures. All other chemicals were obtained from Aldrich, Acros, TCI, or Alfa Aesar and used without further purification. IUPAC nomenclature for **2**, **3**, **5**, and **7** was based on the keto species.

### General procedure for the preparation of tetracarbonyl compounds

In a three-necked flask equipped with a dropping funnel and a reflux condenser, 5.5 equiv of NaH was suspended in THF. The dropping funnel was charged with 2.0 equiv of the carbonyl compound and 1.0 equiv of $(CO_2Et)_2$ dissolved in THF. The NaH suspension was brought to reflux and the reagent mixture was added dropwise. Reaction progress was monitored by TLC and NMR (1–7 d). After complete conversion, the solvent was removed under reduced pressure and the residue partitioned between $H_2O$ and $Et_2O$. The aqueous phase was washed with $Et_2O$ three times, acidified to a pH of 1 with 3 M hydrochloric acid, and extracted with $Et_2O$ three times. These organic extracts were dried over $Na_2SO_4$ and concentrated.

**1,2-Bis[(1*R*,4*R*)-4,7,7-trimethyl-3-oxobicyclo[2.2.1]heptan-2-yl]-ethane-1,2-dione (2)**:[18,19] Purification by flash chromatography (silica, hexanes/ethyl acetate 50/1); bright yellow solid; 93%; $^1$H NMR ($C_6D_6$, 300.51 MHz): seven-membered ring protochelate: $\delta = 0.58$ (s, 6H, $CH_3$), 0.68 (s, 6H, $CH_3$), 0.91 (s, 6H, $CH_3$), 1.19–1.49 (m, 6H, $CH_2$), 1.70–1.90 (m, 2H, $CH_2$), 3.21 (d, $^3J_{H,H} = 3.8$ Hz, 2H, CH), 15.54 ppm (s, 2H, OH); six-membered ring protochelate: $\delta = 0.61$ (s, 6H, $CH_3$), 0.68 (s, 6H, $CH_3$), 0.93 (s, 6H, $CH_3$), 1.19–1.49 (m, 6H, $CH_2$), 1.70–1.90 (m, 2H, $CH_2$), 3.36 (d, $^3J_{H,H} = 3.9$ Hz, 2H, CH), 12.53 ppm (s, 2H, OH); $^{13}$C{$^1$H} NMR ($C_6D_6$, 75.56 MHz): seven-membered ring protochelate: $\delta = 9.7$ (2C, $CH_3$), 18.5 (2C, $CH_3$), 20.4 (2C, $CH_3$), 26.3 (2C, $CH_2$), 31.8 (2C, $CH_2$), 47.9 (2C, $C_q$), 49.5 (2C, CH), 59.7 (2C, $C_q$), 123.8 (2C, *C*=C–O), 158.1 (2C, O–*C*=C), 211.7 ppm (2C, C=O); six-membered ring protochelate: $\delta = 9.0$ (2C, $CH_3$), 18.5 (2C, $CH_3$), 20.6 (2C, $CH_3$), 27.4 (2C, $CH_2$), 30.7 (2C, $CH_2$), 48.9 (2C, $C_q$), 48.9 (2C, CH), 58.0 (2C, $C_q$), 121.1 (2C, *C*=C–O), 155.9 (2C, O–*C*=C), 214.6 ppm (2C, C=O); MS (EI$^+$): *m/z* (%): 179 (100, $[C_{11}H_{15}O_2]^+$), 247 (72, $[M-C_6H_{14}^{\bullet}-CO]^+$), 275 (9, $[M-C_6H_{14}^{\bullet}]^+$), 330 (34, $[M-CO]^{+\bullet}$), 358 (17, $[M]^{+\bullet}$); HRMS (EI$^+$): *m/z* calcd for $C_{22}H_{30}O_4$: 358.2144; found: 358.2140; IR (FT-ATR): $\tilde{\nu} = 2957$, 2870, 1655, 1620, 1574, 1556, 1456, 1377, 1267, 1221, 1145, 1067, 1025 cm$^{-1}$; elemental analysis (%) calcd for $C_{22}H_{30}O_4$: C 73.71, H 8.44; found: C 73.22, H 8.42.

***meso*-1,2-Bis(3-oxobicyclo[2.2.1]heptan-2-yl)ethane-1,2-dione (3)**: Purification by recrystallization from $Et_2O$ and washing with acetone; bright yellow solid; 36%; complex NMR spectra in $CDCl_3$ and $C_6D_6$; MS (EI$^+$): *m/z* (%): 109 (15, $[C_8H_9O_2-C_2H_4]^+$), 137 (100, $[C_8H_9O_2]^+$), 246 (30, $[M-CO]^{+\bullet}$), 274 (2, $[M]^{+\bullet}$); HRMS (EI$^+$): *m/z* calcd for $C_{16}H_{18}O_4$: 274.1205; found: 274.1232; IR (FT-ATR): $\tilde{\nu} =$ 3250, 2961, 2873, 1736, 1694, 1620, 1480, 1456, 1325, 1288, 1262, 1189, 1167, 1085, 1067, 1033 cm$^{-1}$; elemental analysis (%) calcd for $C_{16}H_{18}O_4$: C 70.06, H 6.61; found: C 70.03, H 6.32. NMR characterization for semiacetal structure **3a**: $^1$H NMR ([D$_6$]DMSO, 500.13 MHz): $\delta = 1.18$–1.28 (m, 2H, $CH_2$), 1.30–1.43 (m, 3H, $CH_2$), 1.44–1.51 (m, 1H, $CH_2$), 1.51–1.60 (m, 2H, $CH_2$), 1.61–1.70 (m, 2H, $CH_2$), 1.78–1.92 (m, 2H, $CH_2$), 2.14 (br s, 1H, CH), 2.37 (d, $^3J_{H,H} = 3.1$ Hz, 1H, CH), 2.46 (d, $^3J_{H,H} = 3.6$ Hz, 1H, CH), 2.55 (d, $^3J_{H,H} = 3.5$ Hz, 1H, CH), 3.95 (br s, 1H, CH), 7.59 ppm (s, 1H, OH); $^{13}$C{$^1$H} NMR ([D$_6$]DMSO, 125.76 MHz): $\delta = 22.0$ ($CH_2$), 23.5 ($CH_2$), 27.5 ($CH_2$), 28.2 ($CH_2$), 34.8 ($CH_2$), 37.1 (CH), 37.4 ($CH_2$), 42.1 (CH), 45.9 (CH), 49.3 (CH), 57.9 (CH), 115.3 (C(OH)–O), 116.5 (*C*=C–O), 144.6 (C=*C*–O), 205.2 (C=O), 205.4 ppm (C=O). Characterization of **3c**, obtained by acidification of the aqueous phase with saturated $NH_4Cl$ solution instead of hydrochloric acid and subsequent extraction with $Et_2O$ at pH 7 followed by crystallization from MeOH/$Et_2O$: $^1$H NMR ($CDCl_3$, 300.08 MHz): $\delta = 1.20$–2.10 (m, 12H, $CH_2$), 2.10 (m, 1H, CH), 2.40 (m, 1H, CH), 2.50 (m, 1H, CH), 2.65 (m, 1H, CH), 3.79 (s, 1H, OH), 3.89 (m, 1H, CH), 8.63 ppm (s, 1H, N*H*); $^{13}$C{$^1$H} NMR ($CDCl_3$, 75.46 MHz): $\delta = 22.3$ ($CH_2$), 24.1 ($CH_2$), 28.2 ($CH_2$), 28.9 ($CH_2$), 35.6 ($CH_2$), 37.2 (CH), 40.6 ($CH_2$), 41.8 (CH), 47.4 (CH), 49.8 (CH), 59.6 (CH), 94.5 (N–*C*–C(O)), 108.5 (C=*C*), 139.6 (O–*C*–N), 205.6 (C=O), 211.0 ppm (C=O); MS (EI$^+$): *m/z* (%): 82 (21), 150 (15), 176 (15), 178 (15), 204 (24), 205 (13), 206 (22), 217 (12, $[M-CO-C_2H_4]^{+\bullet}$), 245 (46, $[M-C_2H_4]^{+\bullet}$), 245 (15), 273 (100, $[M]^{+\bullet}$); HRMS (EI$^+$): *m/z* calcd for $C_{16}H_{19}O_3N$: 273.1365; found: 273.1364; IR (FT-ATR): $\tilde{\nu} = 3343$, 3296, 2947, 2870, 1737, 1699, 1660, 1603, 1455, 1396, 1299, 1224, 1199, 1087, 1037, 934 cm$^{-1}$.

**1,2-Bis[(1*R*,5*R*)-6,6-dimethyl-2-oxobicyclo[3.1.1]heptan-3-yl]-ethane-1,2-dione (5)**: Purification by flash chromatography (silica, hexanes/ethyl acetate 10/1); colorless solid; 63%; $^1$H NMR ($CDCl_3$, 300.51 MHz): $\delta = 0.94$ (s, 6H, $CH_3$), 1.35 (s, 6H, $CH_3$), 1.46 (m, 2H,

$CH_2$), 2.26 (m, 2H, CH), 2.58 (m, 4H, CH, $CH_2$), 2.70 (m, 4H, $CH_2$), 14.62 ppm (s, 2H, OH); $^{13}C\{^1H\}$ NMR ($CDCl_3$, 75.56 MHz): $\delta = 21.7$ (2C, $CH_3$), 26.0 (2C, $CH_3$), 26.4 (2C, $CH_2$), 27.8 (2C, $CH_2$), 39.4 (2C, CH), 39.9 (2C, $C_q$), 55.2 (2C, CH), 107.0 (2C, *C*=C–O), 165.4 (2C, C=*C*–O), 210.9 ppm (2C, C=O); MS ($EI^+$): *m/z* (%): 137 (18, $[C_{10}H_{13}O_2-CO]^+$), 165 (100, $[C_{10}H_{13}O_2]^+$), 302 (41, $[M-CO]^{+\bullet}$), 330 (20, $[M]^{+\bullet}$); HRMS ($EI^+$): *m/z* calcd for $C_{20}H_{26}O_4$: 330.1831; found: 330.1837, IR (FT-ATR): $\tilde{\nu} = 2971$, 2956, 2924, 2869, 1607, 1541, 1450, 1337, 1322, 1208, 1192, 1061, 1005 $cm^{-1}$; elemental analysis (%) calcd for $C_{20}H_{26}O_4$: C 72.64, H 7.93; found: C 72.64, H 8.09.

**Ethyl 2-oxo-2-[(1*R*,5*S*)-2,2,6,6-tetramethyl-4-oxobicyclo[3.1.1]-heptan-3-yl]acetate (7)**: Yellow oil; 70% relative to ethyl oxalate; $^1H$ NMR ($CDCl_3$, 300.51 MHz): $\delta = 1.05$ (s, 3H, $CH_3$), 1.24 (s, 3H, $CH_3$), 1.30 (s, 3H, $CH_3$), 1.36 (s, 3H, $CH_3$), 1.39 (t, $^3J_{H,H} = 7.2$ Hz, 3H, $CH_3$), 1.65 (d, $^3J_{H,H} = 10.5$ Hz, 1H, $CH_2$), 1.82 (dd, 1H, $CH_2$), 2.47–2.58 (m, 2H, CH), 4.36 (q, $^3J_{H,H} = 7.2$ Hz, 2H, $CH_2$), 15.83 ppm (s, 1H, OH); $^{13}C\{^1H\}$ NMR ($CDCl_3$, 75.57 MHz): $\delta = 14.1$ ($CH_3$), 25.0 ($CH_3$), 26.8 ($CH_3$), 27.1 ($CH_3$), 27.7 ($CH_3$), 30.4 ($CH_3$), 35.3 ($C_q$), 41.2 ($C_q$), 55.7 (CH), 55.8 (CH), 62.2 ($CH_2$), 113.7 (C=C–O), 163.7 (C–O), 166.9 (C–O), 210.9 ppm (C=O); MS ($EI^+$): *m/z* (%): 83 (59, $[C_5H_7O]^+$), 137 (73, $[C_8H_9O_2]^+$), 193 (100, $[C_{12}H_{17}O_2]^+$), 266 (48, $[M]^{+\bullet}$); HRMS ($EI^+$): *m/z* calcd for $C_{15}H_{22}O_4$: 226.1518; found: 226.1513; IR (FT-ATR): $\tilde{\nu} =$ 2976, 1739, 1712, 1608, 1472, 1388, 1370, 1280, 1247, 1214, 1189, 1008 $cm^{-1}$; elemental analysis (%) calcd for $C_{15}H_{22}O_4$: C 67.64, H 8.33; found: C 67.81, H 8.49.

### General procedure for the preparation of transition metal complexes:

2.0 equiv of KO*t*Bu was added to a solution of 1.0 equiv of tetracarbonyl compound in THF and the mixture was stirred for 15 min at room temperature. Then 1.0 equiv $[\{MLCl\}_2]$ was added and stirring continued over night at room temperature. The solvent was evaporated under reduced pressure and the residue suspended in $CH_2Cl_2$, filtered through Celite, and concentrated. The crude product was washed with a small amount of pentane.

**$Rh^I$(nbd) complex of 5 (8)**: Bright yellow solid; 90%; $^1H$ NMR ($CDCl_3$, 400.18 MHz): $\delta = 0.80$ (s, 6H, $CH_3$), 1.20 (m, 4H, $CH_{2\,(nbd)}$), 1.24 (s, 6H, $CH_3$), 1.27 (d, $^3J_{H,H} = 9.3$ Hz, 2H, $CH_2$), 2.16 (m, 2H, CH), 2.25 (m, 2H, $CH_2$), 2.31–2.44 (m, 6H, $CH_2$, CH), 3.76 (m, 4H, $CH_{(nbd)}$), 3.88 (m, 4H, CH=$C_{(nbd)}$), 3.95 ppm (m, 4H, CH=$C_{(nbd)}$); $^{13}C\{^1H\}$ NMR ($CDCl_3$, 100.63 MHz): $\delta = 21.5$ (2C, $CH_3$), 25.9 (2C, $CH_3$), 27.8 (2C, $CH_2$), 28.2 (2C, $CH_2$), 38.8 (2C, $C_q$), 39.9 (2C, CH), 49.6 (4C, d, $^2J_{C,Rh} = 2.5$ Hz, $CH_{(nbd)}$), 52.1 (2C, d, $^1J_{C,Rh} = 11.1$ Hz, *C*=$C_{(nbd)}$), 52.3 (2C, d, $^1J_{C,Rh} = 10.8$ Hz, *C*=$C_{(nbd)}$), 52.4 (2C, d, $^1J_{C,Rh} = 10.7$ Hz, *C*=$C_{(nbd)}$), 53.2 (2C, d, $^1J_{C,Rh} = 11.0$ Hz, *C*=$C_{(nbd)}$), 54.6 (2C, CH), 60.7 (2C, d, $^3J_{C,Rh} = 6.8$ Hz, $CH_{2\,(nbd)}$), 98.6 (2C, d, $^3J_{C,Rh} = 2.2$ Hz, C=C-O), 179.6 (2C, O–*C*=C), 196.6 ppm (2C, C=O); HRMS ($FAB^+$): *m/z* calcd for $C_{34}H_{40}O_4Rh_2$: 718.1037; found: 718.1027; IR (FT-ATR): $\tilde{\nu} = 2910$, 1558, 1444, 1417, 1375, 1372, 1302, 1240, 1209, 1064, 1012 $cm^{-1}$.

**$Rh^I(CO)_2$ complex of 5 (9)**: Yellow orange solid; quantitative yield; $^1H$ NMR ($CDCl_3$, 500.13 MHz): $\delta = 0.84$ (s, 6H, $CH_3$), 1.32 (s, 6H, $CH_3$), 1.34 (m, 2H, $CH_2$), 2.22 (m, 2H, CH), 2.34 (m, 2H, $CH_2$), 2.48 (m, 4H, $CH_2$), 2.67 ppm (t, $^3J_{H,H} = 5.1$ Hz, 2H, CH); $^{13}C\{^1H\}$ NMR ($CDCl_3$, 125.76 MHz): $\delta = 21.4$ (2C, $CH_3$), 25.8 (2C, $CH_3$), 27.2 (2C, $CH_2$), 28.3 (2C, $CH_2$), 39.3 (2C, $C_q$), 39.7 (2C, CH), 54.3 (2C, CH), 101.4 (2C, d, $^3J_{C,Rh} = 3.0$ Hz, *C*=C-O), 177.6 (2C, O–*C*=C), 183.5 (2C, d, $^1J_{C,Rh} = 74.1$ Hz, RhCO), 183.6 (2C, d, $^1J_{C,Rh} = 72.9$ Hz, RhCO), 198.1 ppm (2C, C=O); HRMS ($FAB^+$): *m/z* calcd for $C_{24}H_{25}O_8Rh_2$ ($[M+H]^+$): 646.9660; found: 646.9648; IR (FT-ATR): $\tilde{\nu} = 2956$, 2922, 2077, 2063, 2018, 1997, 1582, 1559, 1451, 1419, 1367, 1326, 1260, 1244, 1209, 1093, 1065, 1016 $cm^{-1}$.

**$Pd^{II}(C_3H_5)$ complex of 5 (10)**: Bright yellow solid; 93%; air-sensitive; a 1/2/1 ratio of *endo*/*endo*, *endo*/*exo*, and *exo*/*exo* isomers leads to a fourfold (1/1/1/1) signal pattern; $^1H$ NMR ($CDCl_3$, 300.08 MHz): $\delta = 0.87/0.88/0.96/0.97$ (4s, 4×6H, $CH_3$), 1.27/1.28/1.28/1.29 (4s, 4×6H, $CH_3$), 1.34/1.35/1.43/1.45 (4d, $^3J_{H,H} = 9.6$ Hz, 4×2H, $CH_2$), 2.19 (m, 4×2H, CH), 2.30–2.65 (m, 4×8H, $CH_2$, CH), 2.87 (m, 4×4H, $CH_{2\,allyl}$), 3.86 (m, 4×4H, $CH_{2\,allyl}$), 5.51 ppm (m, 4×2H, $CH_{allyl}$); $^{13}C\{^1H\}$ NMR ($CDCl_3$, 75.46 MHz): $\delta = 21.5/21.6/21.7/21.7$ (4×2C, $CH_3$), 26.0/26.0/26.0/26.0 (4×2C, $CH_3$), 27.7/27.8/27.8/27.8 (4×2C, $CH_2$), 28.2/28.2/28.2/28.2 (4×2C, $CH_2$), 38.9/38.9/39.0/39.0 (4×2C, $C_q$), 40.0/40.0/40.1/40.1 (4×2C, CH), 55.2/55.2/55.2/55.2 (4×2C, CH), 55.6/55.6/55.7/55.8 (4×2C, $CH_{2\,allyl}$), 56.0/56.1/56.2/56.2 (4×2C, $CH_{2\,allyl}$), 98.5/98.6/98.6/98.7 (4×2C, *C*=C-O), 112.6/112.6/112.6/112.6 (4×2C, $CH_{allyl}$), 181.2/181.3/181.3/181.3 (4×2C, O-*C*=C), 197.5/197.5/197.5/197.5 ppm (4×2C, C=O); HRMS ($FAB^+$): *m/z* calcd for $C_{26}H_{34}O_4{}^{108}Pd_2$: 626.0548; found: 626.0507.

**$Rh^I$(nbd) complex of 3 (11)**: Bright yellow solid; quantitative yield; $^1H$ NMR ($CD_2Cl_2$, 500.13 MHz): $\delta = 1.21$ (m, 4H, $CH_{2\,(nbd)}$), 1.22–1.28 (m, 6H, $CH_2$), 1.54 (m, 2H, $CH_2$), 1.71–1.76 (m, 4H, $CH_2$), 2.63 (brs, 2H, CH), 2.91 (brs, 2H, CH), 3.80 (brs, 4H, $CH_{(nbd)}$), 3.87 (brs, 4H, CH=$C_{(nbd)}$), 3.90 ppm (brs, 4H, CH=$C_{(nbd)}$); $^{13}C\{^1H\}$ NMR ($CD_2Cl_2$, 125.76 MHz): $\delta = 24.7$ (2C, $CH_2$), 29.3 (2C, $CH_2$), 40.8 (2C, CH), 43.4 (2C, $CH_2$), 50.1 (2C, d, $^2J_{C,Rh} = 2.9$ Hz, $CH_{(nbd)}$), 50.2 (2C, d, $^2J_{C,Rh} = 2.9$ Hz, $CH_{(nbd)}$), 50.3 (2C, CH), 52.5 (2C, d, $^1J_{C,Rh} = 11.1$ Hz, *C*=$C_{(nbd)}$), 52.6 (2C, d, $^1J_{C,Rh} = 11.0$ Hz, *C*=$C_{(nbd)}$), 52.8 (2C, d, $^1J_{C,Rh} = 11.3$ Hz, *C*=$C_{(nbd)}$), 53.2 (2C, d, $^1J_{C,Rh} = 11.3$ Hz, *C*=$C_{(nbd)}$), 60.9 (2C, d, $^3J_{C,Rh} = 6.9$ Hz, $CH_{2\,(nbd)}$), 113.3 (2C, d, $^3J_{C,Rh} =$ 1.9 Hz, *C*=C-O), 173.3 (2C, O–*C*=C), 201.1 ppm (2C, C=O); HRMS ($FAB^+$): *m/z* calcd for $C_{30}H_{32}O_4Rh_2$: 662.0411; found: 662.0392; IR (FT-ATR): $\tilde{\nu} = 2946$, 2866, 1577, 1436, 1381, 1299, 1291, 1270, 1246, 1219, 1097 $cm^{-1}$.

**$Ir^I$(cod) complex of 3 (12)**: Orange solid; quantitative yield; $^1H$ NMR ($CD_2Cl_2$, 300.51 MHz): $\delta = 1.25$–1.41 (m, 6H, $CH_2$), 1.57–1.70 (m, 10H, $CH_2$, $CH_{2\,(cod)}$), 1.82 (m, 4H, $CH_2$), 2.23 (m, 8H, $CH_{2\,(cod)}$), 2.86 (brs, 2H, CH), 3.23 (brs, 2H, CH), 4.00 ppm (m, 8H, CH=$C_{(cod)}$); $^{13}C\{^1H\}$ NMR ($CD_2Cl_2$, 125.76 MHz): $\delta = 24.3$ (2C, $CH_2$), 29.3 (2C, $CH_2$), 31.3 (2C, $CH_{2\,(cod)}$), 31.3 (2C, $CH_{2\,(cod)}$), 31.3 (2C, $CH_{2\,(cod)}$), 31.4 (2C, $CH_{2\,(cod)}$), 40.9 (2C, CH), 43.3 (2C, $CH_2$), 50.4 (2C, CH), 59.1 (2C, *C*=$C_{(cod)}$), 59.2 (2C, *C*=$C_{(cod)}$), 59.4 (2C, *C*=$C_{(cod)}$), 59.7 (2C, *C*=$C_{(cod)}$), 116.7 (2C, *C*=C-O), 171.3 (2C, O*C*=C), 202.2 ppm (2C, C=O); HRMS ($FAB^+$): *m/z* calcd for $C_{32}H_{40}O_4{}^{193}Ir_2$: 874.2185; found: 874.2130; IR (FT-ATR): $\tilde{\nu} = 2938$, 2867, 2829, 1581, 1444, 1375, 1292, 1272, 1249, 1221, 1101, 1000 $cm^{-1}$.

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# FULL PAPER

**Tautomerism**

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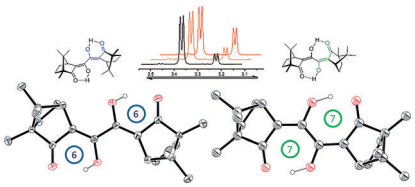
**Tautomerization-Mediated Molecular Switching Between Six- and Seven-Membered Rings Stabilized by Hydrogen Bonding**



**Hydrogen bonding makes the difference!** 1,3,4,6-Tetraketones with unanticipated and so far unknown tautomerism-mediated isomerism due to different modes of intramolecular hydrogen bonding (i.e., six- and seven-membered rings; see figure) are described. Structural requirements and options for switching of the equilibrium isomeric ratio were studied.