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Dynamic behavior of hydrogen bonding in hydrogen 5,6-acenaphthenedicarboxylate

Arno Brück and Kathleen V. Kilway*

Department of Chemistry, University of Missouri-Kansas City, Kansas City, MO 64110-2499, USA

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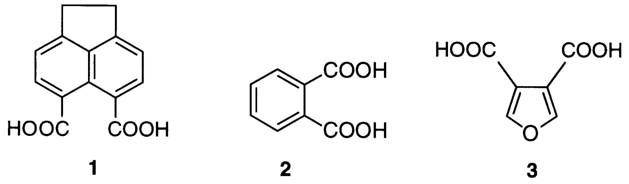
Abstract—The dynamic hydrogen bond behavior of hydrogen 5,6-acenaphthenedicarboxylate has been studied using NMR spectroscopy at variable concentration and temperature. From the concentration experiments, it is clear that there is an equilibrium between monomeric (intramolecularly hydrogen bonded) and aggregated (intermolecularly hydrogen bonded) species at room temperature. Upon cooling, the equilibrium shifts completely toward intramolecular hydrogen bonding, thereby overcoming the steric cost required to form the necessary eight-membered ring. This compound is one of the few examples which exhibits such behavior, and the first within the series of hydrogen dicarboxylates where it has been observed by NMR spectroscopy. © 2001 Elsevier Science Ltd. All rights reserved.

1. Introduction

Hydrogen bonding, an old and important subject in chemistry, has gained renewed attention due to the presumed role in which strong H-bonds have been accounted for the stabilization of transition states in enzymatic catalysis.[1–6] Model compounds for strong intramolecular hydrogen bonding have included hemisalts of dicarboxylic acids. From our results in recent NMR studies on acid salts of dicarboxylic acids,[7] we concluded that stable intramolecular H-bonds in such systems are formed when a minimum strain is imposed on the resulting geometry of the molecule. Even though we studied many acid salts, only hydrogen 5,6-acenaphthenedicarboxylate has exhibited a wide range of dynamic behavior in hydrogen bonding with respect to temperature and concentration.

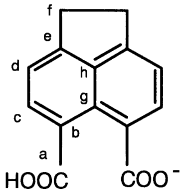
2. Results and discussion

Tetrabutylammonium hydrogen 5,6-acenaphthenedicarboxylate (**1a**) was prepared according to a previously described method used for other diacids.[8] The proton resonance for the remaining carboxyl proton for **1a** (0.15 M in CD_2Cl_2) at room temperature appears at 16 ppm, which is upfield with respect to other half-salts containing strong intramolecular hydrogen bonds.[9–12] Normally, strong intramolecular hydrogen-bonded protons in similar systems (i.e. hydrogen phthalate, **2a**, 20.64 ppm and hydrogen 3,4-furandicarboxylate, **3a**, 20.10 ppm) resonate in a region from 19 to 20 ppm.[7,13] (See Scheme 1.)



Scheme 1.

For intermolecular H-bonded O–H···O systems, it is known that the resonance of the carboxyl proton shifts downfield with increasing concentration[14] due to increased H-bond formation in the aggregated species. In order to determine the type of bonding in this compound, the ^1H NMR spectra were recorded at several concentrations (i.e. 0.15, 0.07 and 0.035 M). (See Table 1 and Scheme 2.) As the concentration decreased, the signal broadened and shifted further upfield, indicative of aggregation and intermolecular hydrogen bonding.[14–16]



Scheme 2.

The signal's width at half-height ($W_{1/2}$) at room temperature broadened with decreasing concentrations. This broadening is either due to a competition for the remaining carboxyl

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Keywords: intramolecular; intermolecular; hydrogen bonding; variable-temperature; hydrogen dicarboxylates.

* Corresponding author. Tel.: +1-816-235-2289; fax: +1-816-235-5502; e-mail: kilwayk@umkc.edu

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Table 1. ^{1}H NMR data of tetrabutylammonium hydrogen 5,6-acenaphthenedicarboxylate at different concentrations in anhydrous CD_2Cl_2

Concentration (M)	(a)		(c)	(d)	(f)				
	$\delta_{\mathrm{COO}H}$	$W_{1/2}$	$\delta_{\mathrm{C}H\mathrm{CCO}}$	$\delta_{\mathrm{C}H\mathrm{CCCO}}$	$\delta_{\mathrm{C}H_2\mathrm{C}}$	$\delta_{\mathrm{NC}H}$	$\delta_{\mathrm{NCC}H}$	$\delta_{\mathrm{NCCC}H}$	$\delta_{\mathrm{NCCCC}H}$
0.15	16.01	73	7.79[a]	7.21[a]	3.36	3.07[b]	1.34[b]	1.17[b]	0.78[a]
0.07	14.87	115	7.80[a]	7.22[a]	3.37	3.08[b]	1.34[b]	1.18[b]	0.78[a]
0.035	14.49	139	7.81[a]	7.23[a]	3.37	3.09[b]	1.36[b]	1.18[b]	0.79[a]

The chemical shift (δ) is in ppm and linewidth at half-height ($W_{1/2}$) and coupling constants (J) are in Hz.

[a] The coupling constant (J) is equal to 7 Hz.

[b] Multiplet.

Table 2. ^{1}H NMR data of tetrabutylammonium hydrogen 5,6-acenaphthenedicarboxylate at different temperatures (0.15 M in anhydrous CD_2Cl_2)

Temperature (K)	(a)		(c)	(d)	(f)				
	$\delta_{\mathrm{COO}H}$	$W_{1/2}$	$\delta_{\mathrm{C}H\mathrm{CCO}}$	$\delta_{\mathrm{C}H\mathrm{CCCO}}$	$\delta_{\mathrm{C}H_2\mathrm{C}}$	$\delta_{\mathrm{NC}H}$	$\delta_{\mathrm{NCC}H}$	$\delta_{\mathrm{NCCC}H}$	$\delta_{\mathrm{NCCCC}H}$
290	16.01	73	7.79[a]	7.21[a]	3.36	3.07[b]	1.34[b]	1.17[b]	0.78[a]
265	16.36	352	7.75[a]	7.20[a]	3.34	2.96[b]	1.25[b]	1.09[b]	0.76[a]
250	16.54	1100	7.73[a]	7.19[a]	3.31	2.88[b]	1.21[b]	1.05[b]	0.74[a]
230	15.75	255	7.88[a]	7.32[a]	3.38	2.88[b]	1.17[b]	1.05[b]	0.77[a]
	18.31	286	7.70[a]	7.18[a]	3.31				
205	18.51	19	7.68	7.18	3.31	2.78	1.17	0.94	0.76
197	18.56	25	7.67	7.17	3.31	2.74	1.12	0.91	0.76

The chemical shift (δ) is in ppm and linewidth at half-height ($W_{1/2}$) and coupling constants (J) are in Hz.

[a] The coupling constant (J) is equal to 7 Hz.

[b] Multiplet.

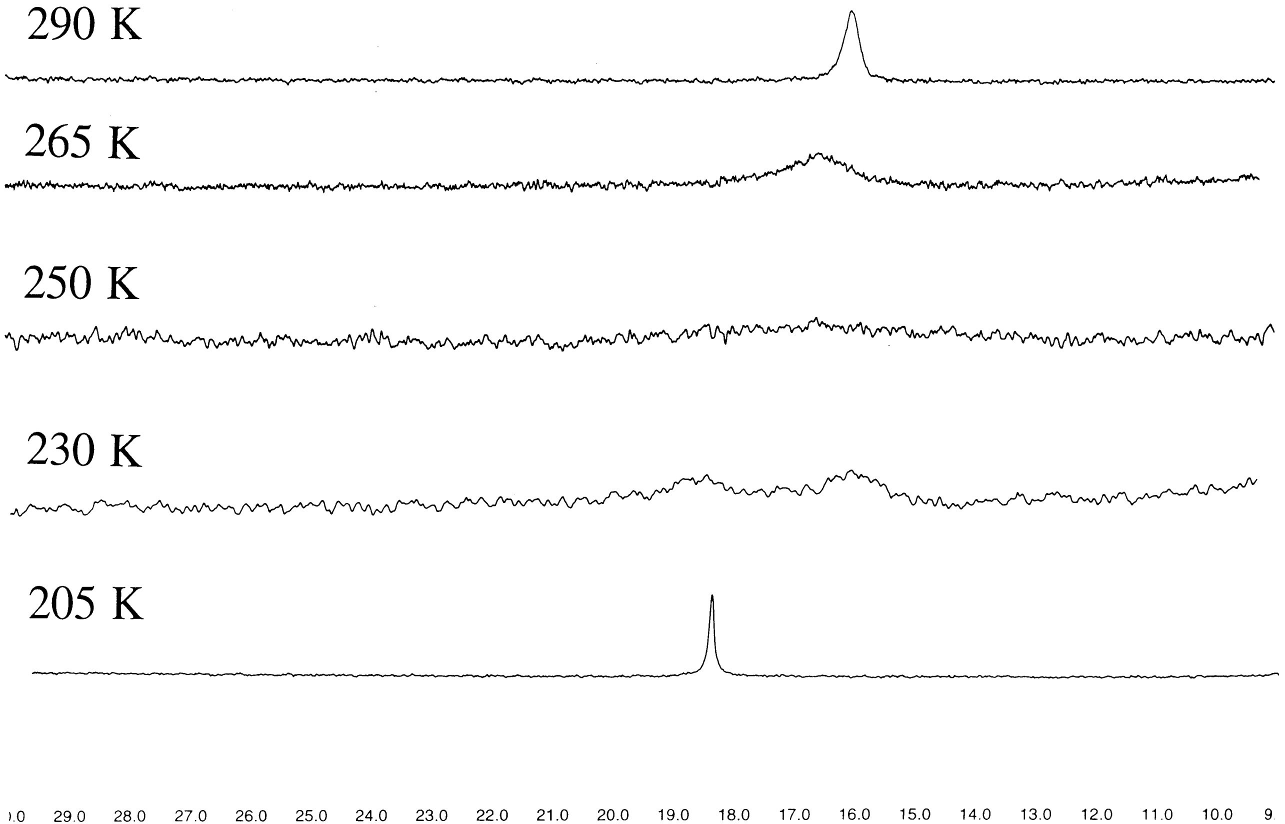

Figure 1. Carboxyl-proton resonance of tetrabutylammonium hydrogen 5,6-acenaphthenedicarboxylate (0.15 M in anhydrous CD_2Cl_2) at different temperatures.

hydrogen by trace amounts of water and the adjacent oxygen atoms or to shifting the equilibrium toward the monomer. In order to test the effect of water on this equilibrium, a small amount of water in THF-d_8 is added to a sample of hydrogen 5,6-acenaphthenedicarboxylate in anhydrous CD_2Cl_2 at room temperature. The low-field proton resonance at around 16.5 ppm is no longer observed, and the corresponding water signal is broadened. From the concentration and water addition studies, it is clear that intermolecular hydrogen bonding is dominant at room temperature, and the intramolecular H-bond of the monomer cannot compete with water.

3. VT-NMR studies

Since the chemical shift of the remaining acidic proton (COO*H*) is shifted upfield with respect to similar systems and is also concentration dependent, further studies were carried out with respect to temperature (Table 2 and Fig. 1). Hydrogen bonding in alcohols or other species is temperature dependent, and the corresponding resonance shifts downfield with decreasing temperature. Normally, the COO*H* chemical shift of hydrogen dicarboxylates sharpens and shifts further downfield up to 0.3 ppm with decreasing temperatures and the extent of the shift is dependent on the linewidth. If $W_{1/2}$ is broad at room temperature as noted in **2a** (i.e. 56 Hz), then the signal shifts to an even greater extent downfield by as much as 0.4 ppm (from 20.64 to 21.05 ppm) upon cooling.

When **1a** (0.15 M in CD_2Cl_2) was cooled to 250 K, the carboxyl proton resonance shifted downfield as expected, but was surprisingly broadened. Instead of a substantial downfield shift of around 20 ppm for the carboxyl proton, typically found for strongly H-bonded systems, a chemical shift of around 16 ppm is observed. This evidence, together with a considerable linewidth, suggests the presence of an inter- rather than intramolecular hydrogen bond. The concentration dependence of the signal at room temperature supports this assumption.

The signal continues to broaden (250 K, δ=16.54 ppm and $W_{1/2}$=1100 Hz) until 230 K, where two broad signals appeared at 18.31 and 15.75 with linewidths of 286 and 255 Hz, respectively. With further cooling, the upfield signal at 15.75 ppm disappears while the signal at 18.31 ppm sharpens and shifts further downfield. At 230 K, the intramolecular/intermolecular equilibrium becomes slow with respect to the NMR time frame, and the two species are distinguishable. Since the ^1H resonance of the COOH group is strongly temperature dependent, it is simpler to evaluate the aromatic and aliphatic hydrogens of the anion. These signals also doubled at 230 K indicating the presence of two different species.

Variable-temperature proton NMR studies at a different concentration (0.07 M in CD_2Cl_2) showed a similar behavior (Table 3). The only difference was that the temperature where both the inter- and the intramolecularly bonded species are visible together increase by 7 K. At 197 K, the carboxyl-proton resonance seems to be concentration independent and appears at exactly the same position as recorded for the 0.15 M solution, corroborating the assumption that at very low temperatures the anion is solely intramolecularly hydrogen bonded. The resonance at room temperature is further upfield and broader, which is the typical behavior for an intermolecularly H-bonded system. Using the Gutowsky–Holm approximation,[17,18]

Table 3. ^1H NMR data of tetrabutylammonium hydrogen 5,6-acenaphthenedicarboxylate at different temperatures (0.07 M in anhydrous CD_2Cl_2)

Temperature (K)	(a)		(c)	(d)	(f)				
	δ_{COOH}	$W_{1/2}$	δ_{CHCCO}	δ_{CHCCCO}	δ_{CH_2C}	δ_{NCH}	δ_{NCCH}	δ_{NCCCH}	δ_{NCCCCH}
298	14.87	115	7.80[a]	7.22[a]	3.37	3.08[b]	1.34[b]	1.18[b]	0.78[a]
261	15.02	239	7.75[a]	7.21[a]	3.34	2.98[b]	1.27[b]	1.12[b]	0.76[a]
249	16.00	750	7.73[a]	7.20[a]	3.33	2.91[b]	1.22[b]	1.06[b]	0.76[a]
240	17.70	1200	7.73[a]	7.19[a]	3.33	2.90[b]	1.22[b]	1.06[b]	0.76[a]
237	15.80	380				2.87	1.21	1.05	0.75
	18.25	430	7.72	7.18	3.32				
197	18.56	22	7.67	7.17	3.31	2.71	1.12	0.88	0.74

The chemical shift (δ) is in ppm and linewidth at half-height ($W_{1/2}$) and coupling constants (J) are in Hz.

[a] The coupling constant (J) is equal to 7 Hz.

[b] Multiplet.

Table 4. $^{13}C\{^1H\}$NMR resonances of tetrabutylammonium hydrogen 5,6-acenaphthenedicarboxylate at different temperatures (0.15 M in anhydrous CD_2Cl_2)

Temperature (K)	(a)	(b)	(c)	(d)	(e)	(f)	(g)	(h)				
	δ_{CO}	δ_{CCO}	δ_{CHCCO}	δ_{CHCCCO}	δ_{CCCCCO}	δ_{CH_2C}	δ_{CCCO}	δ_{CCCCO}	δ_{NC}	δ_{NCC}	δ_{NCCC}	δ_{NCCCC}
290	173.8	126.8	129.2	118.7	146.8	30.6	135.3	140.2	58.7	24.4	20.0	13.9
230	173.9	125.7	131.2	118.8	150.0	30.0	133.7	139.2	57.3	23.2	19.2	13.5
	172.8	125.4	128.4	117.9	146.5	29.9						
205	172.7	125.4	128.3	117.3	146.3	29.6	133.0	138.9	56.5	22.8	18.8	13.4

The chemical shift (δ) is in ppm.

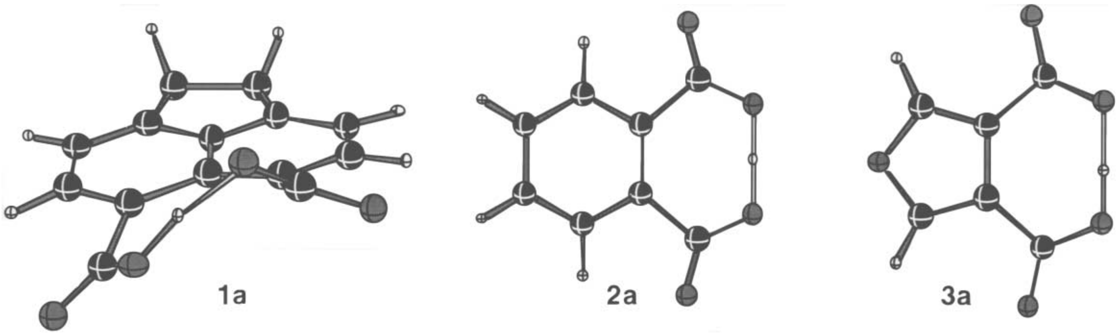

Figure 2. Optimized structures for **1a**, **2a**, and **3a**.

this interconversion is at a cost of 10 kcal/mol ($k_c=1400\ s^{-1}$ at 230 K).

The variable-temperature ^{13}C NMR data for **1a** (0.15 M in CD_2Cl_2) are summarized in Table 4. The VT-behavior observed for the carbon nuclei is identical with the findings from the proton NMR experiments. At both room temperature and low temperature, we observe just one set of signals, and all of the resonances are shifted slightly upfield upon cooling. It can be summarized that the chemical shift change for all other resonances except the hydrogen-bonded proton is rather minor upon cooling. This trend is consistent with the findings from other dilution experiments (see Table 1).

Similar to the results from the proton NMR measurements, all anion signals with the exception of those arising from the two carbons which are part of the ring junction, double and sharpen upon further cooling to one set of signals at 205 K. As observed previously in the ^{1}H NMR spectra, one set is shifted downfield, and the other set upfield with respect to the resonances recorded at room temperature. At this temperature both intra- and intermolecular hydrogen bonds have been 'frozen out' owing to the fact that the corresponding equilibrium between them has become slow on the NMR time scale. At lower temperatures, the set of signals that account for the intermolecular species has vanished while the other set of signals representing the intra-form remains.

4. Computational studies

In order to completely understand the dynamic behavior of this compound in solution, ab initio calculations were utilized. Hydrogen 5,6-acenaphthenedicarboxylate, the dimer of hydrogen 5,6-acenaphthenedicarboxylate (used as an aggregate model), **2a**, and **3a** were calculated using the following methods. Density functional theory (B3LYP) was used to optimize geometries for all of the molecules with standard double zeta basis sets (6-31G(d,p)). Molecular geometries were optimized within the designated symmetry constraints for self-consistent field (SCF) wavefunctions

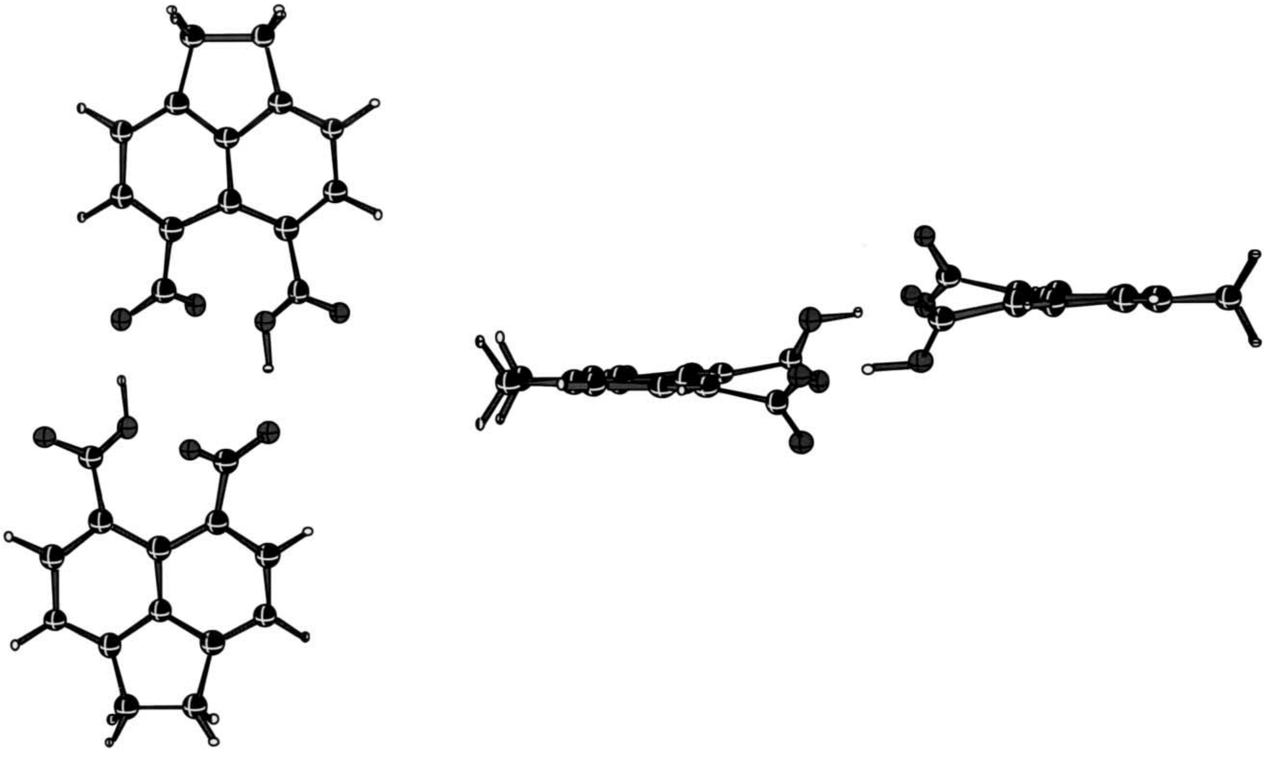

Figure 3. Structure of the dimer of **1a**.

using gradient evaluation techniques and were characterized by harmonic vibrational analysis. To determine the charge distribution and several of the atoms' properties at different steps during the reaction paths, the theory of atoms in molecules implemented in the AIMPAC suites of programs was used. Natural population (NPA) and natural bond orbital (NBO) analyses were performed using the methods of Weinhold implemented in GAUSSIAN 94.[19–21]

The optimized structures of **1a**, hydrogen phthalate (**2a**), and hydrogen 3,4-furandicarboxylate (**3a**) are depicted in Fig. 2. In the absence of another competitor (i.e. water), **2a** and **3a** have ideal orientations for H-bonding because the OHO unit is approximately linear and the molecule is planar. In the case of **1a**, the [O–H–O] entity is *not* coplanar with the remaining part of the molecule but significantly twisted out of plane. Therefore, the intramolecular hydrogen bond would be rather unstable towards other competitors.

Even though the dimer is 22 kcal/mol higher in energy (gas phase), the experimental evidence in aprotic, anhydrous solution clearly shows the presence of intermolecular hydrogen bonding and aggregation at room temperature. (See Fig. 3.) If **1a** does not have other molecules to interact with, then it forms an unfavored eight-membered ring.

5. Conclusions

The equilibrium between monomeric (intramolecularly hydrogen bonded) and aggregated (intermolecularly hydrogen bonded) species of a hydrogen dicarboxylate has been monitored using dynamic NMR spectroscopy. The extent of the downfield shift observed for the carboxyl proton resonance, and the temperature as well as concentration dependence correlates with the assumption that **1a** exists exclusively as a monomer at lower temperatures. At higher temperatures, there is an equilibrium between monomeric (intramolecularly hydrogen bonded) and aggregated (intermolecularly hydrogen bonded) species. Compound **1a** is therefore the first example known where such behavior has been observed by VT-NMR spectroscopy. The hydrogen bonds in such systems are rather weak and are easily disrupted in the presence of other hydrogen-bond donors such as water.

6. Experimental section

6.1. General

Unless otherwise stated, NMR measurements were performed at 20°C on a Bruker AC 250 FT-NMR spectrometer operating at 250 MHz (^{1}H) and 62.9 MHz (^{13}C), respectively. Chemical shifts were referenced against the solvent signal. All chemicals including tetrabutylammonium hydroxide (1.0 M in methanol) and 5,6-acenaphthenedicarboxylic acid were obtained commercially (Aldrich, Salor) and used without further purification. NMR solvents were purchased from Aldrich (CD_2Cl_2, THF-d_8). Dichloromethane-d_2 was dried and distilled from phosphorus pentoxide prior to use.

6.2. Preparation of tetrabutylammonium hydrogen 5,6-acenaphthenedicarboxylate

A suspension of 5,6-acenaphthenedicarboxylic acid (182 mg, 0.75 mmol) in methanol (5 mL) was treated with an equimolar amount of NBu_4OH (0.75 mL of a 1.0 M solution in methanol). The resulting clear solution was stirred for 30 min at room temperature and the solvents were subsequently removed in vacuo. The solid residue was dried for 14 h under high vacuum at 70°C.

6.3. Preparation of NMR samples

NMR samples (0.15 M in 0.5 mL CD_2Cl_2) were prepared and sealed in a glovebox (Vacuum Atmospheres S-40) under nitrogen. After recording the spectra under anhydrous conditions, each sample was treated with aqueous THF-d_8 (3 μL of H_2O in 0.5 mL THF-d_8) and measured again.

6.4. Variable temperature experiments

Temperature dependent measurements were carried out using a Bruker Variable-Temperature Unit. Temperatures were measured by means of a thermocouple, which was inserted directly into the probe head. The samples were left to reach equilibrium at the noted temperature for 30 min before each measurement.

Acknowledgements

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References

1. Warshel, K.; Papazyan, A. *Proc. Natl Acad. Sci. USA* **1996**, *93*, 13665–13670.
2. Scheiner, S.; Kar, T. *J. Am. Chem. Soc.* **1995**, *117*, 6970–6975.
3. Cleland, W. W. *Biochemistry* **1992**, *31*, 317–319.
4. Cleland, W. W.; Kreevoy, M. M. *Science* **1994**, *264*, 1887–1890.
5. Gerlt, J. A.; Gassman, P. G. *J. Am. Chem. Soc.* **1993**, *115*, 11552–11568.
6. Gerlt, J. A.; Gassman, P. G. *Biochemistry* **1993**, *32*, 11943–11952.
7. Brück, A.; McCoy, L. L.; Kilway, K. V. *Org. Lett.* **2000**, *2*, 2007–2009.
8. Perrin, C. L.; Nielson, J. B. *J. Am. Chem. Soc.* **1997**, *119*, 12734–12741.
9. Hibbert, F.; Emsley, J. *Adv. Phys. Org. Chem.* **1990**, *26*, 255.
10. Gunnarsson, G.; Wennerström, H.; Egan, W.; Forsén, S. *Chem. Phys. Lett.* **1976**, *38*, 96–99.
11. Altman, L. J.; Laungani, D.; Gunnarsson, G.; Wennerström, H.; Forsén, S. *J. Am. Chem. Soc.* **1978**, *100*, 8264–8265.

12. Berglund, B.; Vaughan, R. W. *J. Chem. Phys.* **1980**, *73*, 2037–2043.
13. Frey, P. A.; Whitt, S. A.; Tobin, J. B. *Science* **1994**, *264*, 1927–1930.
14. Emsley, J. *Chem. Soc. Rev.* **1980**, *9*, 91–124.
15. Clark, J. H.; Emsley, J. *J. Chem. Soc., Dalton Trans.* **1974**, 1125–1129.
16. Jones, R. G.; Dyer, J. R. *J. Am. Chem. Soc.* **1973**, *95*, 2465–2470.
17. Sandström, J. *Dynamic NMR Spectroscopy*; Academic: London, 1982; p 97.
18. Gutowsky, H. S.; Holm, L. H. *J. Chem. Phys.* **1956**, *25*, 1228–1234.
19. Frisch, M. J.; Trucks, G. W.; Schlegel, H. B.; Gill, P. M. W.; Johnson, B. G.; Robb, M. A.; Cheeseman, J. R.; Keith, T. A.; Pettersson, G. A.; Montgomery, J. A.; Raghavachari, K.; Al-Laham, M. A.; Zakrzewski, V. G.; Ortiz, J. V.; Foresman, H. B.; Cioslowski, J.; Stefanov, B. B.; Nanayakkara, A.; Challacombe, M.; Peng, C. Y.; Ayala, P. Y.; Chem, W.; Wong, M. W.; Andres, J. L.; Replogle, E.S.; Gompers, R.; Martin, R. L.; Fox, D. C.; Binkley, J. S.; Defrees, D. J.; Baker, J.; Stewart, J. P.; Head-Gordon, M.; Gonzalez, C.; Pople, C. GAUSSIAN 94; Revision D.3. Gaussian, Inc.: Pittsburgh, PA, 1996.
20. Stephens, P. J.; Devlin, F. J.; Chabalowski, C. F.; Frisch, M. J. *J. Phys. Chem.* **1994**, *98*, 11623–11627.
21. Becke, A. D. *J. Chem. Phys.* **1993**, *98*, 5648–5652.