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Hindered Rotation around Csp^2–Csp^3 Bonds in the Enol Forms of α-(9-Fluorenyl)-β-diketones and in 3,5-Disubstituted 4-(9-Fluorenyl)pyrazoles. An ^{1}H NMR Study

Marcial Moreno-Mañas,* Asensio Gonzalez, Jorge Marquet, and Francisco Sanchez-Ferrando
Departamento de Química, Universidad Autónoma de Barcelona, Bellaterra, 08193-Barcelona, Spain

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Synopsis. Slow rotation around the Csp^2–Csp^3 bonds of the enol forms of 3-(9-fluorenyl)-2,4-pentanedione, 2-(9-fluorenyl)-1-phenyl-1,3-butanedione, and the corresponding bonds of the derived pyrazoles, was studied by variable temperature ^{1}H NMR. For the pyrazoles, the values T_c=315—320 K ($\Delta G^{\ddagger}_{T_c}$=15.1±0.1 kcal mol^{-1}) and T_c=338±5 K (corresponding to $\Delta G^{\ddagger}_{T_c(\text{sp}\rightarrow\text{ap})}$=18.1±0.2 kcal mol^{-1} and $\Delta G^{\ddagger}_{T_c(\text{ap}\rightarrow\text{sp})}$=16.1±0.2 kcal mol^{-1}) were found, respectively.

Hindered rotation around Csp^2–Csp^3 bonds in 9-arylfluorenes is a well-known phenomenon.[1] However, at the best of our knowledge no examples have been reported in which the group accompanying the fluorene moiety is either a five-membered heterocyclic ring (i.e. pyrazole) or a ring held together by hydrogen bonds (i.e. the enol form of a β-diketone). Some of us have reported a synthetic method, based on the use of cobalt(II) complexes of β-dicarbonyl compounds, which enables us to place bulky substituents in the α-positions of β-dicarbonyl compounds,[2–4] among them the fluorenyl radical.

The ^{1}H NMR spectrum of 3-(9-fluorenyl)-2,4-pentanedione (**1a**) shows in CDCl$_3$ at the ordinary probe temperature two sets of sharp peaks as indicated in Fig. 1. The enol form exhibits hindered rotation since both methyl groups give signals at different chemical shifts. The sharp signal at δ 0.99 is assigned to the methyl group protons placed above the plane of the fluorene moiety.

The major form of 2-(9-fluorenyl)-1-phenyl-1,3-butanedione (**1b**) in solid phase was an enol form (see IR in Experimental). However, in CDCl$_3$ the keto form predominates to an extent of ca. 6:1. The observed enol form exhibits the signal of the methyl group at δ 1.05. Therefore, by comparison with the chemical shift measured for **1a**, we assign the **sp** conformation to the enol form of **1b** (for nomenclature see Ref. 1).

3-(9-Fluorenyl)-5,5-dimethyl-2,4-hexanedione (**1c**) showed only peaks attributed to the keto form, both in KBr (IR) and in CDCl$_3$ (^{1}H NMR).

Due to the interference of the keto⇄enol equilibria we did not attempt any kinetic study of the rotation in compounds **1a** and **1b**. However, compounds **1** were converted into the pyrazoles **2** by conventional methods and the kinetic behavior at different temperatures of these fluorenyl-substituted heterocycles was studied at 80 MHz in a Bruker WP80SY spectrometer.

In the case of exchange between two equally populated, uncoupled sites, the rotational barrier $\Delta G^{\ddagger}$ is customarily determined at the coalescence temperature T_c, using the well-known expressions[5] $k=\pi\Delta\nu/\sqrt{2}$ and $k=(k_BT/h)[\exp(-\Delta G^{\ddagger}/RT)]$, in which $\Delta\nu$ is the frequency separation of the two lines at the slow rotation limit, k_B is the Boltzmann constant, h is the Planck constant, and k is the exchange (interconversion) rate at coalescence. This rather simple approach requires: i) The operation of a single exchange (interconversion) mechanism; ii) the absence of coupling; iii) equal line-widths for both lines; and iv)

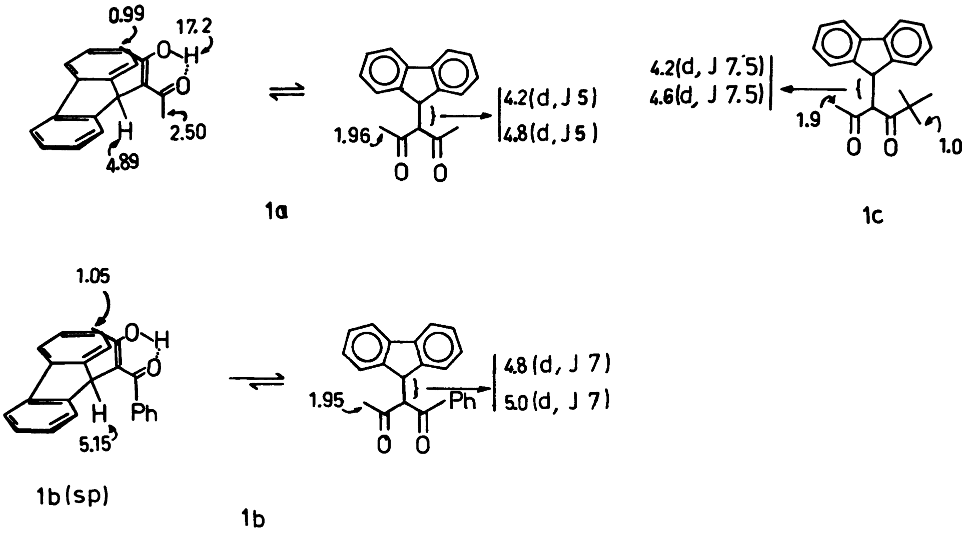

Fig. 1.

linewidths negligible compared with $\Delta\nu$.

The case of exchange between two unequally populated sites has also been solved in much the same simple way.[6] Thus, from the observed coalescence temperature T_c, and the values of $\Delta\nu$ (line separation) and Δp (population difference) obtained at a lower temperature under slow rotation, the mean lifetime at coalescence, $\tau=1/k$ can be obtained using the values tabulated in (Ref. 7), provided conditions i)—iv) above are again met. Of course, validity of this approach depends on the assumption that chemical shift differences and rotamer populations are independent of temperature, assumptions which can often be inadequate. However, if these assumptions are indeed valid, individual rate constants k_A and k_B for the two interconversion processes (A→B and B→A) are derived using the expressions $k_A=2kp_B$ and $k_B=2kp_A$, in which p_A and p_B are the populations of A and B, respectively. Finally, the corresponding barriers at coalescence are calculated in a straightforward manner[8] using the equation $\Delta G^{\ddagger}_{x}=8.31T[23.76+\ln(T/k_x)]$, with SI units throughout. Thus, these simple cases can be studied without using the more sophisticated methods of line shape analysis.[9]

The ^{1}H NMR spectrum of 3,5-dimethyl-4-(9-fluorenyl)pyrazole (**2a**) in $CDCl_3$ at the probe temperature (305 K) shows very broad signals for the two methyl groups. The two signals sharpen to two singlets at δ 2.59 and 1.17 upon cooling at 250 K, while they coalesce to a singlet upon heating at 365 K (Fig. 2). The T_c was found to be between 315—320 K, while the low temperature frequency separation between the two signals was $\Delta\nu=114.3$ Hz. Ignoring the effect of the N(1)–N(2) prototropic shift which is very rapid in our experimental conditions,[10] and applying the pertinent kinetic equations,[5] the degenerate conversion between the two rotamers at T_c has a rate $k=253.9\ s^{-1}$. The rotation barrier at T_c was calculated to be 15.1 ± 0.1 kcal mol^{-1} (63.1 ± 0.4 kJ mol^{-1}).

Three different groups[11–13] have reported a value higher than 25 kcal mol^{-1} (104.5 kJ mol^{-1}) for the rotation barrier in 9-mesitylfluorene. As expected, the smaller angle in the pyrazole ring results in a marked decrease in the rotational barrier.

The ^{1}H NMR spectrum of 4-(9-fluorenyl)-3-methyl-5-phenyl-1*H*-pyrazole (**2b**) in $CDCl_3$ at 305 K shows a single peak for the methyl protons at δ 1.21, but it is not a sharp singlet ($\Delta\nu_{1/2}>5$ Hz). Upon cooling at 263 K, two methyl group signals can be seen at δ 2.58 and 1.13 with a ratio ca. 6:94, attributed respectively to the **ap** and **sp** conformers (Fig. 2). Therefore, the population difference at 263 K is $\Delta p=0.88$, while the measured frequency difference between the two peaks is $\Delta\nu=116.4$ Hz. A series of spectra at increasing temperatures shows that the minor peak at δ 2.58 disappears on heating from 233 to 303 K while both peaks broaden. For $T>303$ K the minor peak is no longer seen, but the major upfield peak continues to broaden. At a temperature between 333 and 343 K this peak reaches maximum broadening (coalescence), and it sharpens at 363 K. Assuming the T_c is 338 ± 5 K and ignoring again the effect of the N(1)–N(2) prototropic shift,[10] we have calculated the barrier to rotation for the unequally populated rotamers by applying the pertinent equations.[6] The individual rates for conversion at T_c of major to minor ($k_{sp\to ap}$) and minor to major ($k_{ap\to sp}$) are 13.38 s^{-1} and 254.2 s^{-1}, and the individual rotation barriers at T_c, $\Delta G^{\ddagger}_{sp\to ap}$ and $\Delta G^{\ddagger}_{ap\to sp}$ are calculated[8] to be 18.1 ± 0.2 kcal mol^{-1} (75.7 ± 0.8 kJ mol^{-1}) and 16.1 ± 0.2 kcal mol^{-1} (67.3 ± 0.8 kJ mol^{-1}).

The ^{1}H NMR spectrum of 3-*t*-butyl-4-(9-fluorenyl)-5-methyl-1*H*-pyrazole (**2c**) shows a single *t*-Bu signal at δ 1.68, both at 308 K and upon cooling at 223 K. Similarly, a single methyl signal is found at δ 1.05 at both temperatures. We conclude that **2c** exists in the **sp** conformation to an extent of more than 99%.

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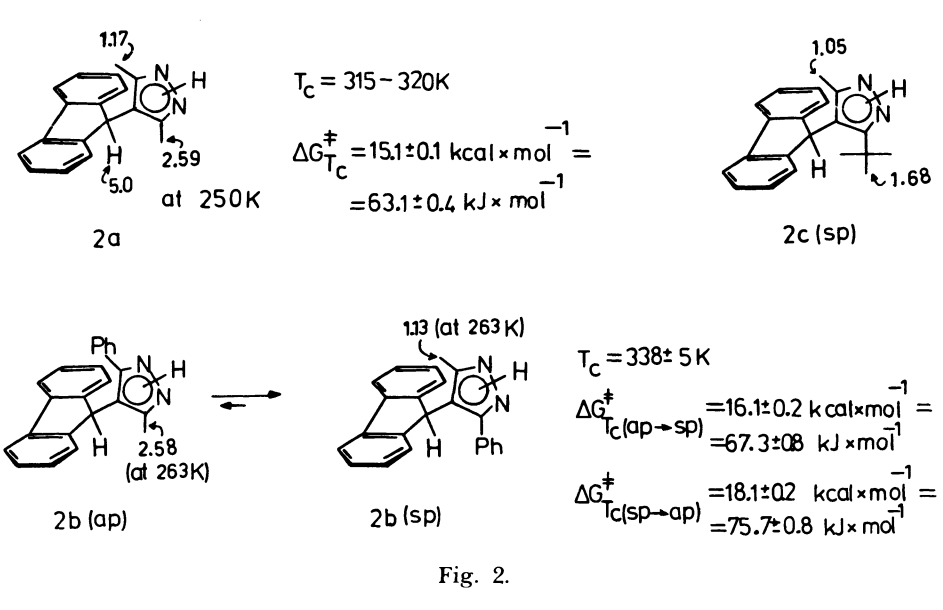

Fig. 2.

for the purchase of the NMR spectrometer, and to "Direcció General d'Ensenyament Universitari (Generalitat de Catalunya)" for the NMR data system.

Experimental

Room temperature 80 MHz ^{1}H NMR spectra were taken at 32 °C, in the FT mode, using a Bruker WP80SY spectrometer, equipped with a 5 mm switchable ^{1}H/^{13}C dual probe, under Aspect 2000 computer control, and are referenced to internal TMS. Variable temperature spectra were obtained under BVT-1000 control. Temperatures were calibrated against methanol peak separation.[14] Solutions of 2—5 mg of sample in $CDCl_3$ were used in all experiments. The pulse conditions used were: spectral width, 1000 Hz; 8 K data points, with quadrature detection; pulse width, 4 μs (60 deg); acquisition time, 4.1 s, with no relaxation delay; digital resolution, 0.25 Hz per point. FIDs were weighted by exponential multiplication (line broadening 0.25 Hz) prior to Fourier transformation.

Compounds 1. Compounds **1** were prepared by treating the corresponding cobalt(II) complexes of the unsubstituted β-diketones with 9-bromofluorene in refluxing chloroform (for **1a** and **1b**) or in refluxing chlorobenzene (for **1c**), following the procedures described in Ref. 2—4.

1a: Mp 72 °C; IR (KBr) 1720, 1690, 1600—1570 (broad) cm^{-1}; MS *m/z* (rel intensity) 264 (M$^+$, 40), 221 (100), 203 (48), 178 (26), 176 (21), 165 (59), 43 (91).

1b: Mp 58 °C; IR (KBr) 1600 (broad) cm^{-1}; MS *m/z* (rel intensity) 326 (M$^+$, 34), 284 (22), 283 (76), 265 (30), 221 (61), 178 (29), 176 (24), 165 (39), 105 (100), 77 (74), 43 (46).

1c: Mp 98—9 °C; IR (KBr) 1710, 1680 cm^{-1}; MS *m/z* (rel intensity) 306 (M$^+$, 11), 221 (100), 165 (57), 57 (22).

Compounds 2. **2a:** Mp 235—6 °C; IR (KBr) 3300—2800 (broad) cm^{-1}; MS *m/z* (rel intensity) 260 (M$^+$, 100), 259 (44), 245 (28), 218 (38), 176 (23), 165 (26), 42 (63).

2b: Mp 97—9 °C; IR (KBr) 3400—2900 (broad) cm^{-1}; MS *m/z* (rel intensity) 322 (M$^+$, 100), 321 (38), 280 (25), 176 (21), 165 (27), 77 (48), 42 (29).

2c: Mp 203—4 °C; IR (KBr) 3500—2800 (broad) cm^{-1}; MS *m/z* (rel intensity) 303 (23), 302 (M$^+$, 100), 287 (78), 245 (22), 165 (62), 57 (23), 42 (30), 41 (37).

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