Kinetics of the Reactions of Flavylium Ions with π-Nucleophiles

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Dedicated to Prof. Dieter Hoppe on the occasion of his 60th birthday

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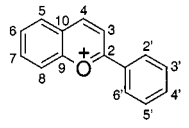
The kinetics of the reactions of the flavylium ion **1a** and the 4′-methoxyflavylium ion **1b** with various π-nucleophiles and tributylstannane were investigated photometrically in dichloromethane. Electrophilicity parameters E(**1a**) = –3.46 and E(**1b**) = –4.96 were derived from the equation log k (20 °C) = $s(E + N)$; these allow the prediction of potential reaction partners of the flavylium ions **1a** and **1b**.

Introduction

Flavylium ions **1** (= 2-aryl-1-benzopyrylium ions), diversely substituted at the 3,3′,4′,5,5′ and 7-positions by OH, OMe, or glycosyloxy groups, form the nucleus of the anthocyanin pigments responsible for a large number of plant colors.[1]



Flavylium Ion, **1**

Some of them have been used as food colorants[2] and, more recently, as laser dyes[3] and sensibilizers for electrophotographic recordings.[4] Presently, their use as a basis for optical memory systems is being investigated.[5]

As ambident electrophiles, flavylium ions may react with nucleophiles at the 2- or 4-position to yield 2-aryl-2*H*- or 2-aryl-4*H*-1-benzopyrans, respectively. Like other 2-substituted 1-benzopyrylium ions, they generally prefer reaction at the 4-position.[1] Detailed kinetic investigations of the hydration of the parent and of 4′-substituted flavylium ions indicated that even hard nucleophiles such as H_2O or ^-OH attack the 4-position somewhat faster than the 2-position.[6] The latter reactions may be reversible, and the pH-dependent equilibrium mixture consists of the 2-aryl-2*H*- and 2-aryl-4*H*-1-benzopyrans and chalcones (or their anions), arising from ring-opening of the 2-hydroxy-2-phenyl-2*H*-1-benzopyran.[6]

Kinetic investigations of the reactions of flavylium ions with *C*-nucleophiles have not been reported. Recently, we have shown that the electrophilicity parameters E defined by Equation (1), provide a general ordering principle for carbocations and related species and allow predictions of the rates of reaction with potential nucleophilic reaction partners.[7]

$$\log k\ (20\ ^\circ\mathrm{C}) = s\,(E + N) \qquad (1)$$

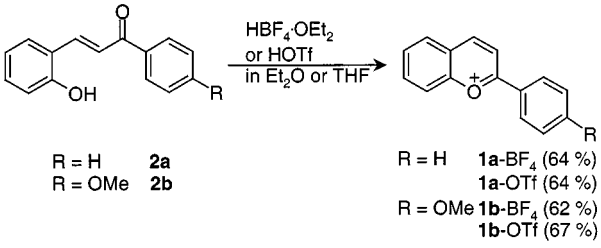
where E = electrophilicity parameter, N = nucleophilicity parameter and s = nucleophile-dependent slope parameter

It was the goal of this work to determine the reactivity parameter E of some flavylium ions and to use these parameters for defining the scope of potential nucleophilic reaction partners. For this purpose, we have studied the kinetics of the reactions of the parent and the 4′-methoxy-substituted flavylium ion with π-nucleophiles.

Results

Synthesis of the Flavylium Salts

By modifying the procedure reported for the preparation of **1a**-ClO_4,[8] the tetrafluoroborate and triflate salts of the flavylium ions **1a** and **1b** were synthesized by refluxing the salicylideneacetophenones **2a** and **2b**,[9] respectively, in either tetrafluoroboric or triflic acid (Scheme 1). An alternative synthetic route for **1b**-BF_4 has been described by Katritzky.[10]



Scheme 1

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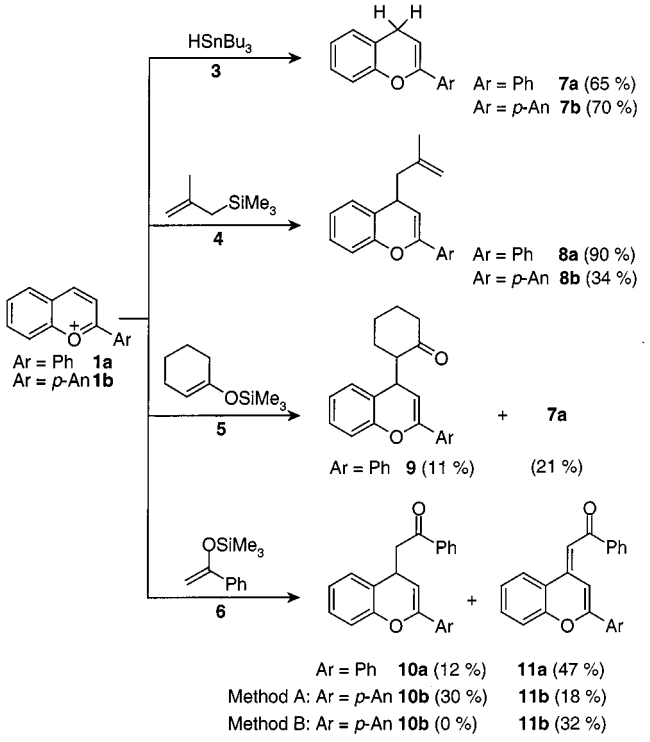
Reactions of Flavylium Salts with Nucleophiles

As described in Scheme 2, the flavylium ions **1a** and **1b** are attacked by the nucleophiles **3**−**6** in the 4-position, analogous to the reactions with other nucleophiles.[1]



Scheme 2

The reactions of the tetrafluoroborate salts of **1a** and **1b** with tributylstannane **3** yielded the flavenes **7a** (65%) and **7b** (70%), respectively, which were identified by comparison of their ^{1}H NMR spectra with those of the products obtained from **1a**-BF_4 and **1b**-BF_4 and sodium borohydride[11a] or lithium aluminum hydride.[11b]

While the reaction of **1a**-BF_4 with (2-methylallyl)trimethylsilane **4** gave **8a** in 90% yield, the yield of **8b** from the corresponding reaction of the 4-methoxy analogue **1b**-BF_4 was only 34% even after prolonged reaction times.

A mixture of product **9** and 4*H*-flavene **7a** was obtained from the reaction of **1a**-BF_4 and 1-(trimethylsiloxy)cyclohexene (**5**) probably due to hydride transfer from **9** to **1a**.

A mixture of **10a** (12%, colorless) and **11a** (47%, yellow) was isolated from the reaction of **1a**-OTf with 1-phenyl-1-(trimethylsiloxy)ethene (**6**). The reaction of **1b**-OTf with **6** proceeded analogously (Scheme 2). When 2.3 equivalents of **6** were added to solutions of **1a**-OTf or **1b**-BF_4 in CD_2Cl_2, observation of the reaction by ^{1}H NMR spectroscopy showed the exclusive formation of **10a** and **10b**, respectively. Therefore, compounds **11a** and **11b** must have been produced by oxidation during the workup process. This interpretation is supported by the finding that **10a** was also observed as the only product in the ^{1}H NMR spectrum of the residue obtained by combining **1a**-BF_4 with **6** in dichloromethane, stirring at room temperature for four hours, and evaporating the solvent. Subsequent attempts to purify the crude sample of **10a** by chromatography (silica gel, chloroform) again gave a mixture of **10a** and **11a**.[12,13,14]

Kinetics

The rate constants of the reactions of the flavylium ions **1a** and **1b** with the nucleophiles **3**−**6** were determined by monitoring the decay of the flavylium absorbances at λ = 410 ± 5 nm (**1a**) or 470 ± 5 nm (**1b**) using the equipment and the data evaluation procedures described previously.[15a] The reactions followed second-order kinetics, first order with respect to flavylium ion and first order with respect to nucleophile.

For unknown reasons, the reproducibility of the second-order rate constants was unusually low with a standard deviation of a factor of 1.14. Rate constants obtained with different counterions (tetrafluoroborate or triflate) agreed within this range, indicating that the counterions come into play after the rate-determining step. This observation is in agreement with the reports that rate constants independent of the counterions were observed for reactions of benzhydrylium salts with allylsilanes[15b] and silylated enol ethers.[15c] For the reaction of **1b** with **4**, the slowest reaction of this series, deviations from the second-order rate law were observed after 20−30% of conversion, probably because of decomposition of **4** by acidic impurities. Second-order kinetics over more than 85% of conversion were obtained, however, when the reaction of **1b**-OTf with **4** was performed in the presence of 2,6-di-*tert*-butylpyridine.

Table 1. Rate constants and activation parameters for the reactions of the flavylium ions **1a** and **1b** with the nucleophiles **3**−**6** in CH_2Cl_2

Reactants	k (20 °C)/L mol^{-1} s^{-1}	$\Delta H^{\ddagger}$/kJ mol^{-1}	$\Delta S^{\ddagger}$/J mol^{-1} K^{-1}
1a + **4**	5.12 ± 0.50	29.62 ± 1.71	−130.16 ± 6.59
5	72.6 ± 10.5	25.84 ± 1.37	−121.01 ± 6.10
6	(5.69 ± 0.50) × 10^2	27.01 ± 0.95	−99.90 ± 4.27
3	(2.12 ± 0.17) × 10^3	27.80 ± 0.96	−86.26 ± 4.01
1b + **4**	(2.56 ± 0.41) × 10^{-1}	−−	−−
5	1.80 ± 0.02	27.94 ± 1.55	−144.60 ± 6.06
6	19.1 ± 1.61	31.85 ± 1.04	−111.62 ± 4.26
3	(2.47 ± 0.10) × 10^2	33.01 ± 0.75	−86.37 ± 2.97

Table 2. Determination of the electrophilicity parameters E of the flavylium ions **1a** and **1b**

Nucleophile	N[a]	s[a]	E(**1a**)	E(**1b**)
(2-Methylallyl)trimethylsilane (**4**)	4.41	0.96	−3.67	−5.03
1-(Trimethylsiloxy)cyclohexene (**5**)	5.21	1.00	−3.35	−4.95
1-Phenyl-1-(trimethylsiloxy)ethene (**6**)	6.22	0.96	−3.35	−4.89
	E (average) =		−3.46	−4.96

[a] From ref.[16]

The rate constants given in Table 1 and the N and s parameters of the π-nucleophiles **4**−**6**[16] listed in Table 2 can be

substituted into Equation (1) to give the *E* parameters for the flavylium ions **1a** and **1b**. The two right-hand columns of Table 2 show that the *E* parameters derived for **1a** and **1b** from reactions with different nucleophiles are very similar, indicating the validity of Equation (1) for describing these reactions.

The potential of Equation (1) to describe the electrophilic reactivities of **1a** and **1b** is further illustrated by the finding that the rate constants calculated for the hydride abstractions from tributylstannane **3** ($N = 9.96$, $s = 0.55$)[16] with **1a** ($k_{calc} = 3.76 \times 10^3$ L mol^{-1} s^{-1}) and **1b** ($k_{calc} = 5.62 \times 10^2$ L mol^{-1} s^{-1}) deviated from the experimental values (Table 1) only by factors of 1.8 and 2.3, respectively. For the attack of H_2O ($N = 5.80$, $s = 0.80$)[7a] at C-4 one calculates first-order rate constants of 74 s^{-1} (20 °C, **1a**) and 4.70 s^{-1} (20 °C, **1b**), which have to be compared with McClelland's experimental values of 8.10 s^{-1} (25 °C, **1a**)[6] and 0.91 s^{-1} (25 °C, **1b**).[6] In view of the wide range of reactivity and structural variety covered by Equation (1), we consider deviations of less than one order of magnitude between calculated and experimental rate constants as quite satisfactory. The averaged *E* parameters given in Table 2, can thus be considered to be a proper representation of the electrophilicities of **1a** and **1b**.

Discussion

The cationic electrophiles characterized so far cover a reactivity range of 19 orders of magnitude, from the highly reactive *tert*-butyl cation ($E = 9$)[17a] to the well-stabilized bis-lilolidin-8-yl-carbenium ion ($E = -10.04$).[16] The flavylium ions **1a** and **1b** are positioned close to the center of the present scale, although somewhat nearer to the low electrophilicity end. Some electrophiles with similar reactivities are depicted in Figure 1, showing that the flavylium ions **1a** and **1b** are comparable to the tropylium ion and acceptor-substituted diazonium ions.

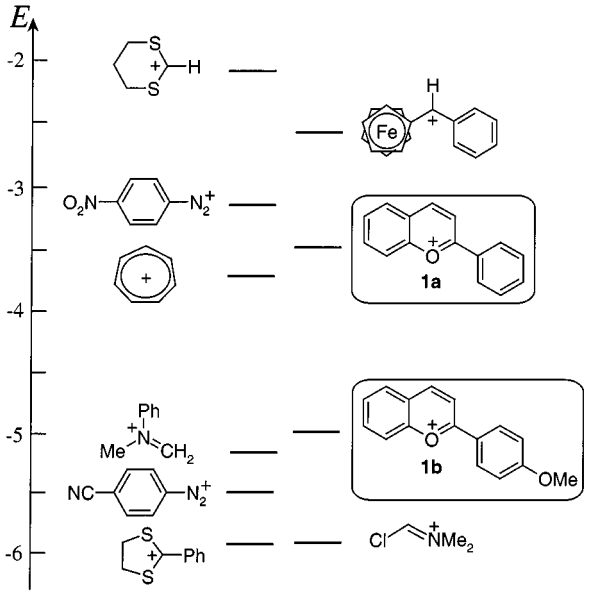
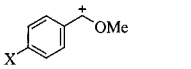
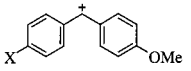
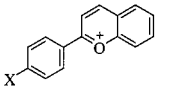


Figure 1. Comparison of the electrophilicities of flavylium ions with reagents of similar reactivity

The electron-donating effect of the *p*-methoxy group reduces the electrophilicity of **1b** relative to **1a** by 1.5 logarithmic units. This effect is slightly smaller than in the more electrophilic carboxonium and benzhydryl cations depicted in Table 3 because of the reduced electron demand of the flavylium ions.

Table 3. The effect of *p*-methoxy substitution on the electrophilicities of phenyl-substituted carbenium ions

Electrophile	*E* (X = H)	*E* (X = OMe)	Δ*E*
	2.98[a]	0.14[b]	2.84
	2.11[b]	0.00[b]	2.11
	–3.46[c]	–4.96[c]	1.50

[a] From rate constants in ref.[17b] using the procedure described in ref.[16] [b] From ref.[16] [c] This work.

We have previously discussed that electrophiles can be expected to react with nucleophiles if $E + N > -5$.[7] From this rule of thumb, one can conclude that **1a** should react with nucleophiles of $N > -1.5$, while **1b** should only be attacked by stronger nucleophiles with $N > 0.0$.

In previous work, flavylium ions have only been combined with strong nucleophiles, for example phenylmagnesium bromide[18a] or lithium phenylacetylide,[18b] to give 4-substituted 4*H*-flavenes. Analogous reactions with carbanions generated in situ from 1,3-diketones, nitromethane, cyanoacetates or malononitriles ($N = 17-22$[19]) have been reported by Kröhnke.[20] It has also been described that enamines generated in situ ($N > 11$[16]) could be trapped by the flavylium salt **1a**-ClO_4.[21] The weakest nucleophiles so far investigated were *N,N*-dialkylanilines[22,23] ($N = 5.6$[24]), which gave 4-aryl-4*H*-flavenes with **1a**-ClO_4, in agreement with the kinetic analysis above. The reactions of **1a** and **1b** described in Scheme 2 therefore include the weakest nucleophiles so far combined with flavylium ions, indicating that the synthetic potential of these electrophiles has not been fully exhausted.

Experimental Section

General: NMR: Varian Mercury 200, Bruker ARX 300, Varian VRX 400S, and Varian INOVA-400. ^{1}H NMR chemical shifts refer to TMS ($\delta_H = 0.00$) and ^{13}C NMR chemical shifts refer to the solvent as internal standard ([D_3]chloroform $\delta = 77.0$; [D_3]acetonitrile $\delta = 1.3$); IR: IR spectrophotometer 325 (Perkin−Elmer). MS: Varian MAT 90 and MAT 95. − Melting points (uncorrected): Reichert Thermovar. All reactions were performed under an atmosphere of dry nitrogen. Dichloromethane was freshly distilled from CaH_2 before use. THF and diethyl ether were dried over KOH and

Na/benzophenone, pentane was dried over KOH and Na. The allylsilane **4** was prepared as described in ref.,[15b] and **2a**, **3**, **5** and **6** are commercially available. The kinetic measurements and the data evaluation were carried out as described previously.[15a]

Flavylium Tetrafluoroborate (1a-BF_4): Salicylideneacetophenone **2a** (1.20 g, 5.25 mmol) was suspended in dry diethyl ether (60 mL) under a nitrogen atmosphere and the mixture was heated to reflux. Upon addition of 10 equiv. $HBF_4{\cdot}OEt_2$ the solid dissolved and the solution turned red. The mixture was heated for 21 h and cooled to ambient temperature to yield a precipitate which was collected under N_2, washed with dry diethyl ether and dried in vacuo. Recrystallization yielded **1a**-BF_4 (1.01 g, 64%) as a yellow powder, m.p. 100 °C (dec., from CH_2Cl_2/pentane). ^{1}H NMR (CD_3CN, 600 MHz): δ = 7.78−7.84 (m, 2 H, 3′-H, 5′-H), 7.93−7.99 (m, 1 H, 4′-H), 8.01−8.06 (m, 1 H, 6-H), 8.37−8.40 (m, 3 H, 5-H, 7-H, 8-H), 8.55−8.59 (m, 2 H, 2′-H, 6′-H), 8.73 (d, J = 9.0 Hz, 1 H, 3-H), 9.50 (d, J = 9.0 Hz, 1 H, 4-H). These data are identical to those described in ref.[25]; ^{13}C NMR (CD_3CN, 150 MHz): δ = 118.5 (d, C-3), 119.9 (d, C-8), 125.3 (C-10), 129.2 (C-1′), 130.9 (d, C-3′), 131.0 (d, C-2′), 131.2 (d, C-6), 131.3 (d, C-5), 138.3 (d, C-4′), 140.8 (d, C-7), 157.2 (C-9), 158.5 (d, C-4), 176.4 (C-2). ^{13}C NMR spectroscopic data are identical to those described in ref.[26]; IR (KBr): $\tilde{\nu}$ = 1620 cm^{-1}, 1590, 1549, 1523, 1456, 1342, 1124, 1084; MS (EI): m/z (%) = 207 (100) [M$^+$], 178 (24).

Flavylium Triflate (1a-OTf): This compound was synthesized as described for **1a**-BF_4 from **2a** (2.00 g, 8.91 mmol) and CF_3SO_3H (2.6 mL, 30 mmol) in diethyl ether (50 mL): 2.03 g (64%) as a yellow powder, m.p. 121−123 °C (dec., from CH_2Cl_2/pentane). The ^{1}H NMR spectrum agreed with that obtained for **1a**-BF_4; $C_{16}H_{11}F_3O_4S$ (356.32): calcd. C 53.93, H 3.11, S 8.99; found C 54.27, H 3.21, S 8.38.

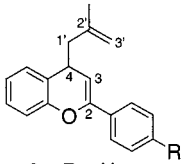
4′-Methoxyflavylium Tetrafluoroborate (1b-BF_4):[10] A suspension of **2b** (0.87 g, 3.4 mmol) in dry THF (40 mL) was heated to reflux under nitrogen atmosphere. Upon addition of 10 equiv. $HBF_4{\cdot}OEt_2$ the solid dissolved and the solution turned red. The mixture was heated for 18 h and cooled to ambient temperature to yield a precipitate which was collected under N_2, washed with dry diethyl ether and dried in vacuo. Recrystallization yielded **1b**-BF_4 (0.684 g, 62%) as an orange powder, m.p. 170 °C (dec., from CH_2Cl_2/pentane). NMR spectroscopic data agreed with those published in refs.[10,26b]; IR (KBr): $\tilde{\nu}$ = 1619 cm^{-1}, 1604, 1589, 1536, 1503, 1456, 1352, 1277, 1184, 1084; MS (EI): m/z (%) = 237 (100) [M$^+$], 222 (7), 194 (17), 165 (9).

4′-Methoxyflavylium Triflate (1b-OTf): This compound was synthesized as described for **1b**-BF_4 from **2b** (2.00 g, 7.87 mmol) and CF_3SO_3H (2.0 mL, 23 mmol) in THF (40 mL): 2.04 g (67%). Orange powder, m.p. 218−219 °C (dec., from CH_2Cl_2/pentane). The ^{1}H NMR spectrum agreed with that obtained from **1a**-BF_4; $C_{17}H_{13}F_3O_5S$ (386.35): calcd. C 52.85, H 3.39, S 8.30; found C 52.55, H 3.41, S 8.04.

2-Phenyl-4*H*-chromene (7a): At −40 °C tributylstannane **3** (0.58 g, 1.99 mmol) was added to a solution of **1a**-BF_4 (0.54 g, 1.84 mmol) in CH_2Cl_2 (10 mL). After 2 min the mixture was quenched with sat. aq. $NaHCO_3$ (20 mL). The organic layer was separated and dried ($MgSO_4$). The solvent was evaporated in vacuo and the residue was purified by column chromatography (alumina I, hexane/diethyl ether = 4:1) to yield **7a** (0.25 g, 65%), m.p. 51−52 °C (ref.:[27] 52−53 °C). The obtained ^{1}H NMR spectrum was in agreement with the data described in ref.[28]

2-(4′-Methoxyphenyl)-4*H*-chromene (7b): At −40 °C tributylstannane **3** (0.40 mL, 0.44 g, 1.5 mmol) was added to a solution of **1b**-BF_4 (522 mg, 1.35 mmol) in CH_2Cl_2 (10 mL). After 1 min the mixture was quenched with sat. aq. $NaHCO_3$ (20 mL). The organic phase was then separated, and the aqueous phase was extracted with CH_2Cl_2 (1 × 10 mL). The combined organic layers were dried ($MgSO_4$) and the solvent was evaporated. The residue was purified by column chromatography (silica gel, hexane/diethyl ether = 8:1) to yield **7b** (225 mg, 70%). The ^{1}H NMR spectrum was in agreement with the data described in ref.[11b]

4-(2-Methylallyl)-2-phenyl-4*H*-chromene (8a): A solution of (2-methylallyl)trimethylsilane (**4**; 52 μL, 38 mg, 0.30 mmol) in 3 mL CH_2Cl_2 was added to **1a**-BF_4 (80 mg, 0.28 mmol). After stirring for 2 h at ambient temperature, the solvent was evaporated. The residue was purified by column chromatography (silica gel, $CHCl_3$) to yield **8a** (70 mg, 90%). ^{1}H NMR (300 MHz, $CDCl_3$): δ = 1.80 (s, 3 H, 2′-CH_3), 2.35 (ddd, ^2J = 13.5 Hz, $^3J_{1A',4}$ = 9.3 Hz, ^4J = 0.8 Hz, 1 H, 1′-H_A), 2.50 (dd, ^2J = 13.5 Hz, $^3J_{1B',4}$ = 5.0 Hz, 1 H, 1′-H_B), 3.75 (ddd, $^3J_{4,1A'}$ = 9.3 Hz, $^3J_{4,1B'}$ = $^3J_{4,3}$ ≈ 4.7 Hz, 1 H, 4-H), 4.72, 4.87 (2 br. s, 2 × 1 H, 3′-H_2), 5.53 (d, J = 4.7 Hz, 1 H, 3-H), 7.00−7.41 (m, 7 H, Ar), 7.67−7.70 (m, 2 H, Ar); ^{13}C NMR (75.5 MHz, $CDCl_3$): δ = 22.7 (q, 2′-CH_3), 32.6 (d, C-4), 48.5 (t, C-1′), 100.2 (d, C-3), 113.2 (t, C-3′), 116.5, 123.2 (2 d, Ar), 124.2 (s, Ar), 124.7, 127.4, 128.26, 128.30, 128.37 (5 d, Ar), 134.5, 142.4, 148.3, 151.7 (4 s, C-2′ and Ar). Signal assignments are based on ^{1}H,^{1}H and ^{1}H,^{13}C-COSY experiments; IR (KBr): $\tilde{\nu}$ = 3070 cm^{-1}, 3037, 2968, 2928, 1646, 1584, 1487, 1456, 1449, 1235, 1114, 1045, 757, 694; MS (EI): m/z (%) = 262 (8) [M$^+$], 207 (100), 178 (26).

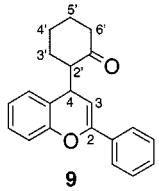


8a, R = H
8b, R = OMe

2-(4-Methoxyphenyl)-4-(2-methylallyl)-4*H*-chromene (8b): A solution of (2-methylallyl)trimethylsilane (**4**; 0.147 mL, 0.109 g, 0.848 mmol) in CH_2Cl_2 (5 mL) was added to **1b**-BF_4 (0.25 g, 0.80 mmol). After stirring for 2 h at ambient temperature, the solvent was evaporated. The residue was purified by column chromatography (silica gel, $CHCl_3$) to yield **8b** (80 mg, 34%). ^{1}H NMR (200 MHz, $CDCl_3$): δ = 1.81 (s, 3 H, 2′-CH_3), 2.34 (ddd, ^2J = 13.0 Hz, $^3J_{1A',4}$ = 9.3 Hz, ^4J < 1 Hz, 1 H, 1′-H_A), 2.50 (dd, ^2J = 13.2 Hz, $^3J_{1B',4}$ = 5.0 Hz, 1 H, 1′-H_B), 3.69−3.83 (m, 4 H, 4-H and OMe), 4.72, 4.86 (2 br. s, 2 × 1 H, 3′-H_2), 5.41 (d, J = 4.6 Hz, 1 H, 3-H), 6.73−7.20 (m, 6 H, Ar), 7.58−7.66 (m, 2 H, Ar).

2-(2-Phenyl-4*H*-chromen-4-yl)cyclohexanone (9): At ambient temperature the silyl enol ether **5** (583 μL, 516 mg, 3.03 mmol) was added to a solution of **1a**-BF_4 (818 mg, 2.78 mmol) in CH_2Cl_2 (15 mL). After stirring for 20 min the solvent was evaporated in vacuo. The residue was purified and separated by column chromatography (silica gel, $CHCl_3$) to yield two fractions: 0.12 g of **7a** (21%) and 0.09 g of **9** (11%, as a mixture of diastereomeric products in a ratio of 79:21, determined by ^{1}H NMR spectroscopy). ^{1}H NMR (400 MHz, CD_3CN): δ = 1.48−1.67, 1.73−1.78 (2 m, 4 H + 1 H, 3′-H_2, 4′-H_2, 5′-H), 1.96−2.04 (m, 1 H, 5′-H), 2.35−2.41 (m, 2 H, 6′-H_2), 2.73−2.78 (m, 1 H, 2′-H), 4.31 (dd, J = 4.7, 3.1 Hz, 1 H, 4-H), 5.61 (d, J = 4.8 Hz, 1 H, 3-H), 7.03−7.12 (m, 2 H, ArH), 7.19−7.26 (m, 2 H, ArH), 7.36−7.44 (m, 3 H, ArH), 7.69−7.74 (m, 2 H, ArH). Additional signals of the minor diastereomer: δ = 2.58−2.62 (m, 1 H, 2′-H), 4.18 (t, J = 4.8 Hz, 1 H,

4-H), 5.66 (d, J = 5.4 Hz, 1 H, 3-H); ^{13}C NMR (100.6 MHz, CD_3CN): δ = 24.73 (t, C-3′ or C-4′), 27.20 (t, C-5′), 27.93 (t, C-3′ or C-4′), 33.59 (d, C-4), 41.96 (t, C-6′), 57.83 (d, C-2′), 98.41 (d, C-3), 116.35 (d, Ar), 122.94 (s, Ar), 124.03, 124.66, 127.94, 128.22, 128.66, 128.76 (6 d, Ar), 134.31, 149.65, 152.75 (3 s, Ar), 211.01 (s, C=O). Additional signals of the minor diastereomer: δ = 24.81 (t), 27.23 (t), 29.31 (t), 33.51 (d), 42.12 (t), 57.94 (d), 101.04 (d), 149.8 (s), 153.01 (s). Signal assignments are based on gDQCOSY and gHSQC experiments; MS (EI, 70 eV), m/z (%) = 305 (8), 304 (11) [M^+], 211 (17), 208 (16), 207 (100), 185 (11).



9

1-Phenyl-2-(2-phenyl-4*H*-chromen-4-yl)ethanone (10a) and 1-Phenyl-2-(2-phenyl-4*H*-chromen-4-ylidene)ethanone (11a): A solution of the silyl enol ether **6** (0.23 mL, 0.22 g, 1.1 mmol) in CH_2Cl_2 (10 mL) was added to **1a**-BF_4 (0.22 g, 0.78 mmol). After stirring for 2 h the solvent was evaporated and the residue was purified and separated by column chromatography (silica gel, $CHCl_3$) to yield **10a** (0.03 g, 12%) and **11a** (0.12 g, 47%).

10a: ^{1}H NMR ($CDCl_3$, 400 MHz): δ = 3.34 (J_{AB} = 17.2 Hz, J_{AX} = 4.7 Hz, 1 H, 1′-H_A), 3.42 (J_{AB} = 17.2 Hz, J_{BX} = 8.8 Hz, 1 H, 1′-H_B), 4.35 (v. quint, J = 4.7 Hz, 1 H, 4-H), 5.70 (d, J = 4.9 Hz, 1 H, 3-H), 7.02−7.57 (m, 14 H, ArH); MS (EI): m/z (%) = 326 (16) [M^+], 325 (16), 324 (55), 274 (53), 207 (100), 105 (13), 77 (7).

11a: ^{1}H NMR ($CDCl_3$, 200 MHz): δ = 7.15 (s, 1 H, 3-H), 7.28−7.62 (m, 10 H, ArH), 7.96−8.08 (m, 4 H, ArH), 8.95 (s, 1 H, 1′-H);[29] MS (EI): m/z (%) = 324 (100) [M^+], 323 (44), 247 (70).

2-(2-(4-Methoxyphenyl)-4*H*-chromen-4-yl)-1-phenylethanone (10b) and 2-(2-(4-Methoxyphenyl)-4*H*-chromen-4-ylidene)-1-phenylethanone (11b):

Method A: Within 10 min a solution of **1b**-BF_4 (163 mg, 0.503 mmol) was added to a solution of the silyl enol ether **6** (305 mg, 1.59 mmol) in CH_2Cl_2 (5 mL). The mixture was stirred for 22 h at ambient temperature, then the solvent was evaporated and the residue was subjected to column chromatography (neutral alumina I, hexane/diethyl ether = 2:1) to yield **10b** (30%) and **11b** (18%) in separate fractions which were still contaminated with acetophenone.

10b: ^{1}H NMR ($CDCl_3$, 200 MHz): δ = 3.24−3.46 (m, 2 H, 1′-H_2), 3.79 (s, 3 H, OMe), 4.31 (m_c, 1 H, 4-H), 5.56 (d, J = 4.9 Hz, 1 H, 3-H), 6.80−7.90 (m, 13 H, ArH); MS (EI): m/z (%) = 356 (3) [M^+], 237 (100).

Method B: A solution of the nucleophile **6** (0.228 mL, 0.214 g, 1.11 mmol) in CH_2Cl_2 (10 mL) was added to neat **1b**-BF_4 (0.30 g, 0.93 mmol). After stirring for 2 h the solvent was evaporated and the residue was purified by column chromatography (silica gel, $CHCl_3$) to yield **11b** (0.12 g, 36%): m.p. 138−140 °C; ^{1}H NMR ($CDCl_3$, 200 MHz): δ = 3.86 (s, 3 H, OMe), 6.95−7.05 (m, 2 H, ArH), 7.10 (s, 1 H, 3-H), 7.26−7.53, 7.93−8.05 (2 m, 6 H + 5 H, ArH), 8.89 (s, 1 H, 1′-H); MS (EI): m/z (%) = 354 (100) [M^+], 353 (40), 277 (58); $C_{24}H_{18}O_3$ (354.14): calcd. C 81.34, H 5.12; found C 81.43, H 5.06.

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[1] C. Czerney, H. Hartmann, in *Methoden Org. Chem. (Houben-Weyl)*, *4th ed.*, Vol. VII/2Ea (Ed.: R. P. Kreher), Thieme Verlag, Stuttgart, **1991**, pp. 30−41.
[2] [2a] G. A. Iacobucci, J. G. Sweeny, *Tetrahedron* **1983**, *39*, 3005−3038; [2b] O. Dangles, H. Elhajji, *Helv. Chim. Acta* **1994**, *77*, 1595−1610.
[3] P. Czerney, G. Graness, E. Birckner, F. Vollmer, W. Rettig, *J. Photochem. Photobiol. A* **1995**, *89*, 31−36.
[4] [4a] S. Maruyama, T. Kubota, K. Kojima, H. Tamura, M. Harada, Ger. Offen. 2,230,303, *Chem. Abstr.* **1973**, *79*, 414; [4b] T. Kubota, K. Kojima, M. Ohta, Ger. Offen. 2,249,448, *Chem. Abstr.* **1974**, *80*, 406.
[5] [5a] F. Pina, M. J. Melo, M. Maestri, P. Passaniti, N. Comaioni, V. Balzani, *Eur. J. Org. Chem.* **1999**, 3199−3207; [5b] F. Pina, M. Maestri, V. Balzani, *Chem. Commun.* **1999**, 107−114; [5c] F. Pina, A. Roque, M. J. Melo, M. Maestri, L. Belladelli, V. Balzani, *Chem. Eur. J.* **1998**, *4*, 1184−1191; [5d] F. Pina, M. H. Melo, M. Maestri, R. Ballardini, V. Balzani, *J. Am. Chem. Soc.* **1997**, *119*, 5556−5561.
[6] R. A. McClelland, S. Gedge, *J. Am. Chem. Soc.* **1980**, *102*, 5838−5848.
[7] [7a] H. Mayr, M. Patz, *Angew. Chem.* **1994**, *106*, 990−1010; *Angew. Chem. Int. Ed. Engl.* **1994**, *33*, 938−957; [7b] H. Mayr, O. Kuhn, M. F. Gotta, M. Patz, *J. Phys. Org. Chem.* **1998**, *11*, 642−654; [7c] H. Mayr, M. Patz, M. F. Gotta, A. R. Ofial, *Pure Appl. Chem.* **1998**, *70*, 1993−2000; [7d] In this work we have used the revised reactivity parameters from ref.[16]
[8] R. J. W. LeFèvre, *J. Chem. Soc.* **1929**, 2771−2774.
[9] [9a] For details of preparation, see: C. Fichtner, *Dissertation*, Ludwig-Maximilians-Universität München 2001; [9b] See also: E. Maccarone, G. Cuffari, A. Passerini, F. Raymo, *J. Chem. Res. (S)* **1991**, 240−241; *J. Chem. Res. (M)* **1991**, 2401−2413.
[10] A. R. Katritzky, P. Czerney, J. R. Levell, W. Du, *Eur. J. Org. Chem.* **1998**, 2623−2629.
[11] [11a] G. A. Reynolds, J. A. VanAllan, *J. Org. Chem.* **1967**, *32*, 3616−3618; [11b] J. W. Clark-Lewis, M. I. Baig, *Aust. J. Chem.* **1971**, *24*, 2581−2592.
[12] A. Cornelson, S. v. Konstanecki, *Ber. Dtsch. Chem. Ges.* **1896**, *29*, 240−244.
[13] J. A. VanAllan, G. A. Reynolds, T. H. Regan, *J. Org. Chem.* **1967**, *32*, 1897−1899.
[14] D. W. Hill, *J. Chem. Soc.* **1934**, 1255−1258.
[15] [15a] H. Mayr, R. Schneider, C. Schade, J. Bartl, R. Bederke, *J. Am. Chem. Soc.* **1990**, *112*, 4446−4454; [15b] G. Hagen, H. Mayr, *J. Am. Chem. Soc.* **1991**, *113*, 4954−4961; [15c] J. Burfeindt, M. Patz, M. Müller, H. Mayr, *J. Am. Chem. Soc.* **1998**, *120*, 3629−3634.
[16] H. Mayr, T. Bug, M. F. Gotta, N. Hering, B. Irrgang, B. Janker, B. Kempf, R. Loos, A. R. Ofial, G. Remennikov, H. Schimmel, *J. Am. Chem. Soc.* **2001**, *123*, 9500−9512.
[17] [17a] M. Roth, H. Mayr, *Angew. Chem.* **1995**, *107*, 2428−2430; *Angew. Chem. Int. Ed. Engl.* **1995**, *34*, 2250−2252; [17b] H. Mayr, G. Gorath, *J. Am. Chem. Soc.* **1995**, *117*, 7862−7868.
[18] [18a] A. Löwenbein, E. Pongracz, E. A. Spiess, *Ber. Dtsch. Chem. Ges.* **1924**, *57*, 1517−1525; [18b] A. V. Koblik, L. A. Murad'yan, E. S. Luk'yanov, *Zh. Org. Khim.* **1996**, *32*, 919−924; *Russ. J. Org. Chem.* **1996**, *32*, 887−892.
[19] R. Lucius, R. Loos, H. Mayr, *Angew. Chem.*, in print.
[20] F. Kröhnke, K. Dickoré, *Chem. Ber.* **1959**, *29*, 46−62.
[21] D. H. Wadsworth, M. R. Detty, B. J. Murray, C. H. Weidner, N. F. Haley, *J. Org. Chem.* **1984**, *49*, 2676−2681.
[22] L. Jurd, *J. Heterocycl. Chem.* **1981**, *26*, 2857−2862.
[23] E. T. Ostensen, *Acta Chem. Scand., Ser. B* **1975**, *29*, 789−790.

[24] M. F. Gotta, H. Mayr, *J. Org. Chem.* **1998**, *63*, 9769−9775.
[25] G. Cardillo, R. Cricchio, L. Morlini, *Tetrahedron Lett.* **1969**, 907−908.
[26] [26a] P. L. Desbene, J. C. Cherton, *Tetrahedron* **1984**, *40*, 3567−3571; [26b] M. Gruner, H. Hartmann, P. Czerney, *J. Prakt. Chem.* **1990**, *332*, 461−469.
[27] T. G. C. Bird, B. R. Brown, I. A. Stuart, A. W. R. Tyrrell, *J. Chem. Soc., Perkin Trans. 1* **1983**, 1831−1846.
[28] M. M. Mishrikey, E. T. Østensen, *Acta Chem. Scand., Ser. B* **1976**, *30*, 329−335.
[29] For analytical data of **11a**, see also: L. A. Murad'yan, A. V. Koblik, D. S. Yufit, Yu. T. Struchkov, V. G. Arsen′ev, S. M. Luk'yanov, *Zh. Org. Khim.* **1996**, *32*, 925−933; *Russ. J. Org. Chem.* **1996**, *32*, 893−901.

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