Dioxirane Oxidation of 3-Arylideneflavanones: Diastereoselective Formation of *trans,trans* Spiroepoxides from the *E* Isomers

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Oxidation of the *E* isomers of the 3-arylideneflavanones **1** by dimethyldioxirane in acetone solution at ambient temperature led to spiroepoxides *trans,trans*-**2** in high yields (≥70%) and complete diastereoselectivity. Steric interaction with the axial aryl group in the 3-arylideneflavanone *E*-**1** directs the attack of the dioxirane to the opposite side during the oxygen transfer to afford exclusively the *trans,trans*-**2** epoxides, which clearly demonstrates the advantage of dimethyldioxirane as oxidant. In comparison, these substrates give under Weitz-Scheffer conditions (alkaline hydrogen peroxide) both diastereomeric epoxides (dr ca. 3:1) in poor yields (≤30%), while *m*-CPBA produces *trans,trans*-**2** spiroepoxides preferentially, but also in low yields (≤40%).[1,2] Attempted epoxidation of the *Z* isomers afforded instead the 3-benzoylflavones **3** and/or 3-benzoylflavanones **4** in low yields. With the much more reactive methyl(trifluoromethyl)dioxirane, the *E*-**1** isomers also gave the *trans,trans*-**2** spiroepoxides diastereoselectively in high yields, but the *Z* isomers suffered complete decomposition. Presumably the sterically hindered *Z* isomers encumber the oxygen atom transfer by the dioxirane and radical-type oxidation dominates for these reluctant substrates.

Introduction

Epoxidation of 3-arylideneflavanones (termed flavindogenides) has been studied by several research groups by using various oxidizing agents. Oxidation of both (*E*)- and (*Z*)-3-arylideneflavanones with alkaline hydrogen peroxide always gave diastereomeric mixtures of epoxides.[1,2] Also the reaction of these α,β-unsaturated ketones with sodium hypochlorite resulted in similar diastereomeric mixtures.[1,3] The epoxidation by *m*-chloroperoxybenzoic acid led generally to mixtures of epoxides from both geometrical isomers of 3-arylideneflavanones.[1,2] These procedures are, therefore, inadequate for the stereoselective epoxidation of such flavanone derivatives.

Dimethyldioxirane[4] (as acetone solution)[5] has proved to be a powerful and selective oxidant not only for the epoxidation of electron-rich but also for electron-poor alkenes such as α,β-unsaturated acids, esters, and ketones[6] and β-oxo enol ethers.[7] This procedure has been advantageously utilized for the epoxidation of chalcones,[5a,8] flavones,[9] aurones, and isoflavones[10] as well. The present paper reports the oxidation of (*E*)-3-arylideneflavanones *E*-**1a-i** and (*Z*)-3-arylideneflavanones *Z*-**1a,c-f** with dimethyldioxirane; good yields of the corresponding epoxides for the *E* isomers were obtained.

Results and Discussion

Product Studies. (*E*)-3-Arylideneflavanones are well-known compounds obtained either by acid- or base-catalyzed condensation of flavanones with aromatic aldehydes. Previously we developed a simple, convenient procedure for the synthesis of (*E*)-3-arylideneflavanones by the piperidine-catalyzed reaction of flavanones with aromatic aldehydes.[11] Consequently, the substrates *E*-**1a-i** used in the present study have been prepared by this method, while their *Z* isomers *Z*-**1a,c-f** were obtained by the established technique of photoisomerization.[12,13] The conformational analysis of the (*E*)- and (*Z*)-3-arylideneflavanones **1** was performed by standard NMR techniques.[14]

Epoxidation of (*E*)-3-arylideneflavanones *E*-**1a-i** with dimethyldioxirane followed the procedure employed on

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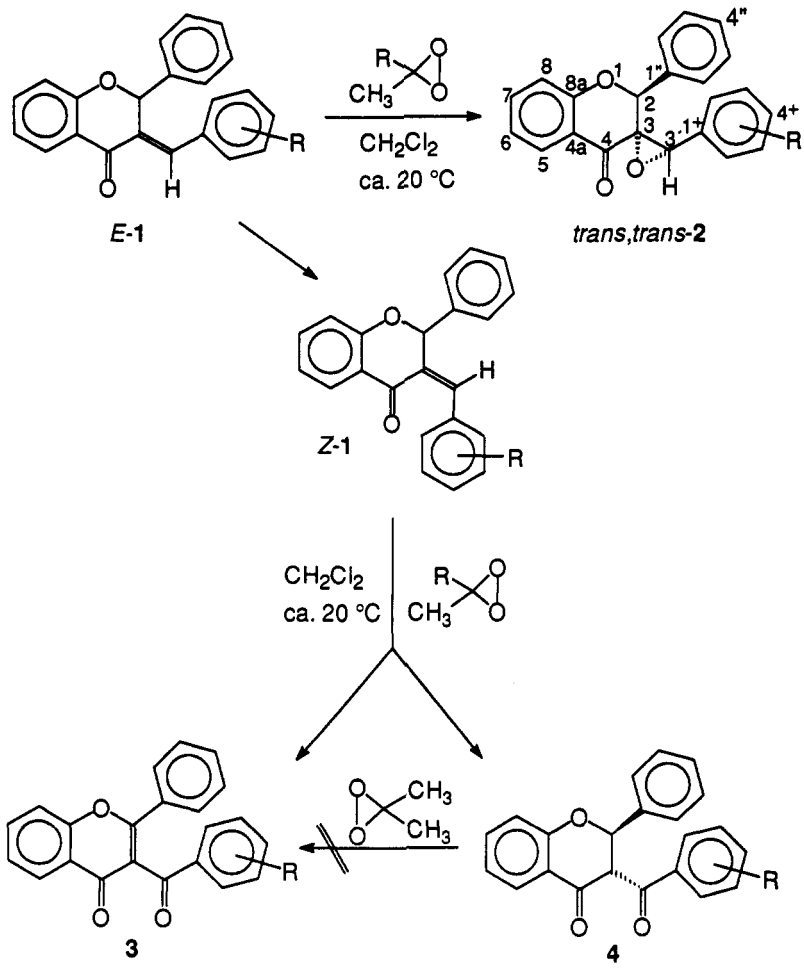
Scheme 1



[a] **a** (R = H), **b** (R = 4-OCH_3), **c** (R = 4-OC_2H_5), **d** (R = 4-CH_3), **e** (R = 4-Cl), **f** (R = 4-Br), **g** (R = 4-CN), **h** (R = 2-OCH_3), **i** (R = 2-CH_3).

the related (*E*)-chalcones[5a,8] and (*E*)-aurones,[10] for which isolated dimethyldioxirane (as a 0.07–0.09 M acetone solution) in anhydrous CH_2Cl_2 at ambient temperature was used. The progress of oxidation was monitored by thin-layer chromatography (TLC) and new batches of dimethyldioxirane solution were added at 24-h intervals until complete consumption of the starting (*E*)-3-arylideneflavanones. In accordance with our previous observations,[5a,9b] with increasing electron-accepting character of the substituent, longer reaction times (from 114 to 552 h) and greater amounts of dimethyldioxirane (from 6 to 23 equiv) were essential for complete epoxidation. TLC analysis of the reaction mixture revealed the presence of only one reaction product for each substrate, namely, the *trans,trans*-**2a-i**, which were isolated in 72–86% yields (Scheme 1). Thus, irrespective of the electronic character of the 3-arylidene substituent, the dimethyldioxirane oxidation of *E*-**1a-i** proceeded in high diastereoselectivity.[15]

For comparison, it is worth mentioning that the peracid epoxidation of *E*-**1a** gave the *trans,trans* epoxide as major product, together with ca. 5% *trans,cis* isomer as byproduct.[1] Presumably, the greater diastereoselectivity obtained by using the dioxirane derives from the greater steric demand of the *gem*-dimethyl group, which obliges this oxidant to attack exclusively opposite from the side of the C-2 phenyl substituent.

When the (*Z*)-3-benzylideneflavanone (*Z*-**1a**) was allowed to react with isolated dimethyldioxirane under the same conditions applied in the epoxidation of its *E* isomer, a complex product mixture resulted in which no epoxide **2a** could be detected. By means of column chromatography, the 3-benzoylflavone (**3a**) (15%) and the 3-benzoylflavanone (*trans*-**4a**) (10%) were isolated. In contrast, oxidation of the *Z*-**1a** with *m*-chloroperoxybenzoic acid afforded a 78:22 mixture of *cis,trans* and *cis,cis* spiroepoxides.[1] Furthermore, while the dimethyldioxirane oxidation of the 4-ethoxy derivative *Z*-**1c** afforded the 3-benzoylflavanone *trans*-**4c** (14%) as the only isolable product, the 3-arylideneflavanones *Z*-**1d-f** led solely to the 3-benzoylflavones **3d-f** in poor yields (15–22%). 3-Benzoylflavones have been prepared previously by the autoxidation of 3-arylideneflavanones.[16,17]

The structures of the 3-benzoylflavones **3a,d-f** and 3-benzoylflavanones **4a,c** were unambiguously elucidated by their ^1H and ^{13}C NMR chemical shifts (Tables 1 and 2). Moreover, the flavones **3** exhibited characteristic $\nu_{C=O}$ bands at 1630 and 1670 cm^{-1} and the flavanones **4** at 1676 and 1689 cm^{-1} in their IR spectra. The 12-Hz coupling constant between the 2-H and 3-H protons unequivocally prove the *trans* stereochemistry of the 3-benzoylflavanones **4a,c**. In solution, slow enolization of the flavanones **4a,c** was detected by NMR spectroscopy.

(15) The first prefix refers to the relative position of the carbonyl and aryl groups of the epoxide ring, while the second prefix describes the relative position of the phenyl group at C-2 and the epoxy oxygen connected to the C-3 atom. It should also be mentioned that all compounds, except **3**, are racemates.

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Table 1. ^{1}H Chemical Shifts of Benzoylflavones 3 and -flavanones 4

proton[a]	3a[b]	3d	3e	3f	4a	4c
2					5.96[c]	5.92[c]
3					5.14	5.13
5	8.24	8.23	8.22	8.23	7.92	7.92
6	7.46	7.44	7.45	7.47	7.06	7.07
7	7.76	7.74	7.75	7.76	7.53	7.53
8	7.59	7.57	7.58	7.56	7.06	7.04
2″,6″	7.66	7.66	7.62	7.62	7.77	7.79
3″,5″	7.36	7.36	7.32–7.40	7.30–7.50	7.36	7.41
4″	7.36	7.30–7.40	7.32–7.40	7.30–7.50	7.48	7.50
2$^+$,6$^+$	7.92	7.82	7.85	7.78	7.48	7.39
3$^+$,5$^+$	7.41	7.19	7.35	7.54	7.30	6.82
4$^+$	7.52				7.28	
others		CH_3 2.35				OCH_2 3.97 CH_3 1.36

[a] For numbering see Scheme 1. [b] Measured at 400 MHz, all others at 250 MHz. [c] ^3J(H-2,H-3) = 12.1 Hz.

Oxidation of the (*E*)-3-arylideneflavanones **1a,d,e** was also carried out with methyl(trifluoromethyl)dioxirane,[18] which afforded exclusively the corresponding *trans,trans* spiroepoxides **2a,d,e** in similar yields as for dimethyldioxirane. The advantage of this more powerful oxidant was the much shorter reaction time (5–8 h) and the lower excess of reagent (1.8–2.8 equiv) necessary for a complete conversion. However, attempted epoxidation of the (*Z*)-3-arylideneflavanones *Z*-**1a,d** by methyl(trifluoromethyl)-dioxirane was unsuccessful. Besides the decomposition of substrates *Z*-**1a,c**, an excess of the methyl(trifluoromethyl)dioxirane reagent was rapidly consumed, which indicated radical-induced decomposition of the latter. Indeed, in the presence of molecular oxygen the decomposition of the dioxirane was substantially suppressed, but also consumption of the substrate was significantly reduced.

The profound differences observed in the dioxirane oxidation of the (*E*)- and (*Z*)-3-arylideneflavanones **1** may be a consequence of steric effects. In the *Z* isomers repulsion between the carbonyl group and the aryl moiety of the *exo* double bond forces the latter to assume a nearly perpendicular arrangement with respect to the plane of the α,β-unsaturated ketone moiety. As a consequence of this stereochemistry, both sides are hindered for the oxygen transfer by the dioxirane. This presumes a transition state with simultaneous bonding at both carbon atoms of the *exo* double bond.

The lack of reactivity of the *Z versus* the *E* isomer in the epoxidation of the 3-arylideneflavanones **1** manifests itself in the much longer reaction times for the former and the formation of the 3-benzoylflavones **3** and -flavanones **4** instead of epoxides **2** (Scheme 1). For such reluctant substrates as the *Z*-**1** isomers toward epoxidation, radical-type oxidation becomes feasible. Indeed, 3-arylideneflavanones are prone to autoxidation and afford 3-benzoylflavones **3**,[16,17] while radical activity has been reported for dioxiranes.[19] Therefore, we propose that the transformation *Z*-**1** → **3** proceeds through dioxirane-initiated radical autoxidation.

More dubious is the origin of the 3-aroylflavanones **4a,c** in the attempted dimethyldioxirane epoxidation of *Z*-**1a,c** (Scheme 1). That the expected epoxides **2a,c** were produced, but through steric compression were too labile to persist, and consequently rearranged by 1,2-H shift to the flavanones **4a,c** is unlikely, because *cis,trans* and *cis,-cis* spiroepoxides **2a** have been isolated in the peracid epoxidation of *Z*-**1a**.[1] Moreover, a control experiment revealed that the 3-aroylflavanones **4** are not further oxidized by DMD under these conditions to the 3-aroylflavones **3**. At this point the mechanism needs clarification.

In conclusion, dioxirane epoxidation of the *E* isomers of the 3-arylideneflavanones **1** proceeded smoothly to afford diastereoselectively the corresponding *trans,trans* spiroepoxides **2** in high yields. Steric interaction with the axial aryl group in the 3-arylideneflavanones *E*-**1** directs the attack of the dioxirane to the opposite side during the oxygen transfer to afford exclusively the *trans,trans*-**2** epoxides. Since epoxidations with *m*-CPBA (≤40%) and Weitz–Scheffer conditions (≤30%) give much lower yields,[1,2] clearly dimethyldioxirane is the reagent of choice. The sterically hindered *Z* isomers, on the other hand, led to the 3-aroylflavones **3** and/or 3-aroylflavanones **4** in low amounts; most of the substrate was converted into undefined, intractable oxidation products. The aryl groups at the C-2 and C-3′ positions in *Z*-**1** encumbers the approach of the dioxirane for epoxidation and radical-type oxidation presumably prevails.

Stereochemistry and NMR Assignment of Spiroepoxides 2. The characteristic ^{1}H and ^{13}C chemical shifts of spiroepoxides **2** are summarized in Tables 3 and 4. Unambiguous assignment of the 2-H (δ 5.31–5.40) and 3′-H (δ 5.05-5.41) singlets has been performed by means of one-dimensional NOE difference experiments (Table 5) and one-dimensional semiselective INEPT measurements (Table 6), optimized for 7-Hz long-range J(C,H) coupling.[20] These latter measurements give the connectivity of the selectively irradiated proton to the carbon atoms which are two or three bonds removed from this proton.

A common characteristic of the proton spectra is the extremely high chemical shift of the 5-H signals as a consequence of the *peri*-positioned C(4)=O carbonyl group. Where necessary, assignments of the 6-H, 7-H, and 8-H signals of the condensed aromatic ring were confirmed by spin-decoupling.

The elucidation of the stereochemistry of spiroepoxides **2** was difficult due to the equilibrium between the two half-chair conformers A and B in Scheme 2. With derivative **2a**, NOE was observed for the protons 2$^+$,6$^+$-H (Table 5) on irradiation of 2-H. This proves that the C(4)=O unit and the phenyl group at C-3′ (marked with $^+$) are *trans*-positioned since spatial proximity of the above-mentioned protons is possible only in the A conformer of the *trans,trans* isomer. Irradiation of 3′-H resulted in an intensity enhancement only of the 2$^+$,6$^+$-H signal, with influence on the 2-H signal.

For the determination of the axial and equatorial arrangement of the phenyl group at C-2, ^3J(C,H) vicinal coupling was advantageously utilized.[14,21] The coupling constant of ca. 8 Hz corresponds to a 180° dihedral angle between 2-H_{eq} and C-8a, while the coupling constant of ca. 1 Hz derives from an 80° angle between the 2-H_{ax} and C-8a atoms.[14,21] The ^3J(2-H_{eq},C-8a) coupling constant, which was determined by the two-dimensional semiselective INEPT method,[22] is 7.2 Hz for **2a** (Table 7).) This

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Table 2. ^{13}C Chemical Shifts of Benzoylflavones 3 and -flavanones 4

carbon[a,b]	3a	3d	3e	3f	4a	4c
2	162.4	162.2	162.5	162.8	81.9	81.6
3	122.6	122.7	122.5 (s)	122.1 (s)	59.6	59.6
4	176.4	176.4	176.2	176.3	189.8	189.9
4a	123.3	123.2	123.4 (m)	132.2 (dd 8.0;6.0)	120.5	120.8
5	126.1	126.0	126.1 (dd 166;8.5)	126.0 (dd 166;8.0)	127.6	127.4
6	125.6	125.5	125.6 (dd 165;7.5)	125.7 (dd 166;7.9)	121.8	121.8
7	134.3	134.6	134.3 (dd 165;8.5)	134.4 (dt 162;7.0)	136.6	136.6
8	118.1	118.1	118.1 (dd 166;7.5)	118.1 (dd 166;7.0)	118.1	118.2
8a	156.1	156.0	156.2	156.1	161.2	161.5
3′	193.5	193.0	192.0 (s)	192.5 (s)	196.0	196.1
1″	131.7	131.7	131.8 (t 7.5)	130.8 (t 7.0)	130.1	138.1
2″,6″	128.5	128.4	128.4 (dt 165;6.5)	128.5 (dt 163;7.5)	127.3	128.5
3″,5″	128.7	128.6	128.8 (dd 164;7.5)	128.8 (dd 164;7.5)	128.5	128.7
4″	131.4	131.3	131.4 (t 7.5)	131.6 (t 7.0)	133.4	133.4
1⁺	137.0	134.6	135.8 (t 7.5)	135.8 (t 7.0)	137.6	129.5
2⁺,6⁺	129.4	129.4	130.7 (dd 162;6.5)	130.7 (dd 162;7.0)	128.7	128.5
3⁺,5⁺	128.7	129.4	129.0 (dd 166;4.5)	132.1 (dd 168;7.0)	128.5	114.6
4⁺	133.7	144.7	140.1	129.1 (t 10.0)	129.5	159.4
others	CH_3 21.7					OCH_2 63.4 CH_3 14.7

[a] For numbering see Scheme 1. [b] Measured at 62.5 MHz; multiplicities and ^1J and ^3J(C,H) coupling constants (in hertz) are given in parentheses.

Table 3. ^1H Chemical Shifts of Spiroepoxides *trans,trans*-2a-i

proton[a]	2a[b]	2b[b]	2c	2d[b]	2e[b]	2f	2g	2h	2i
2	5.36	5.39	5.38	5.38	5.31	5.32	5.31	5.34	5.40
5	7.86	7.84	7.87	7.84	7.86	7.88	7.91	7.94	8.02
6	6.97	6.98	6.89	6.97	6.99	7.01	6.98–7.07	7.05	7.14
7	7.47	7.46	7.50	7.48	7.48	7.50	7.53	7.53	7.59
8	7.05	7.03	7.00	7.04	7.02	7.00–7.10	6.98–7.07	7.07	7.08
3′	5.22	5.18	5.17	5.19	5.12	5.11	5.10	5.41	5.05
2″,6″	7.04	7.06–7.12	7.04–7.14	7.05–7.12	7.05	7.00–7.10	6.98–7.22	7.22	6.85
3″,5″	7.22–7.28	7.06–7.12	7.04–7.14	7.05–7.12	7.08–7.15	7.10–7.17	7.07–7.22	7.15	7.08
4″	7.22–7.28	7.06–7.12	7.04–7.14	7.05–7.12	7.08–7.15	7.10–7.17	7.07–7.22	7.15	7.17
2⁺,6⁺	7.34	7.20	7.27	7.07	7.22	7.18	7.36	7.38	7.30
3⁺,5⁺	7.07–7.11	6.80	6.80	7.25	7.22	7.28	7.51	6.74/6.95	7.03/7.21
4⁺	7.07–7.11							7.26	7.18
others		OCH_3 3.71	OCH_2 3.98 CH_3 1.38	CH_3 2.27				OCH_3 3.75	CH_3 2.03

[a] For numbering see Scheme 1. [b] Measured at 400 MHz, all others at 250 MHz.

Table 4. ^{13}C Chemical Shifts of Spiroepoxides *trans,trans*-2a-i

carbon[a]	2a[b]	2b[b]	2c	2d[b]	2e[b]	2f	2g	2h	2i
2	79.4	79.3	79.5	79.3	79.8	79.5	79.6	80.0	81.0
3	62.4	62.4	62.4	62.5	62.4	62.4	62.6	62.0	62.3
4	186.8	187.0	187.1	187.0	186.7	186.7	186.4	187.1	187.4
4a	121.6	121.6	121.7	121.7	121.5	121.6	121.4	121.8	121.3
5	127.1	127.0	127.2	127.1	127.2	127.2	127.3	127.1	127.2
6	121.8	121.7	121.8	121.8	121.9	121.9	122.2	121.7	121.8
7	137.6	137.1	137.1	138.2	137.3	137.3	137.5	137.0	137.2
8	118.9	118.9	118.9	118.9	118.9	119.0	119.0	119.0	118.8
8a	159.9	159.9	159.0	159.9	159.9	160.0	160.0	159.9	160.6
3′	60.1	60.0	60.1	60.2	58.8	59.9	60.0	57.8	59.8
1″	134.7	134.8	134.9	134.8	134.5	134.5	134.2	135.1	134.7
2″,6″	126.9	126.9	127.0	126.9	126.9	127.0	127.0	127.1	126.8
3″,5″	128.3	128.3	128.4	128.4	128.5[c]	128.5	128.5	128.1	128.2
4″	128.4	128.4	128.4	128.4	128.6	128.7	128.9	128.3	128.6
1⁺	132.9	124.7	124.7	129.9	131.5	132.1	138.4	121.5	131.2
2⁺,6⁺	126.2	127.4	127.5	126.2	127.6	127.9	127.0	157.6/127.1	136.2/125.7
3⁺,5⁺	128.3	113.8	114.4	129.1	128.4[c]	131.5	132.0	109.9/120.2	129.7/125.3
4⁺	126.2	159.6	159.0	138.2	134.3	122.5	112.1	127.1	128.7
others		OCH_3 55.1	OCH_2 63.4 CH_3 14.7	CH_3 21.4		CN 118.3	OCH_3 54.9	CH_3 18.4	

[a] For numbering see Scheme 1. [b] Measured at 100 MHz, all others at 62.5 MHz. [c] Tentative assignment.

fact proves that in the predominant conformer (population of it is ca. 90%) the C-2 phenyl group is axial. A consequence of this steric arrangement is that the 2″,6″-H protons are above the plane of the condensed aromatic ring, so that diamagnetic effects decrease their chemical shift values.

Recently it has been found that in the case of an epoxide ring the *cis* and *trans* ^3J(C,H) coupling constants are different (2.6 Hz/ca. 0 Hz).[23] In derivative **2a** the ^3J(C-2,3′-H) coupling constant is less than 1 Hz, which indicates the *trans* position of these two atoms. For the elucidation

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Table 5. Results of 1D NOE Measurements for Spiroepoxide *trans,trans*-2a

proton irradiated	observed NOE (%)
H-2	H-2″,6″ (2.5); H-2⁺,6⁺ (5.1)
H-3′	H-2⁺,6⁺ (4.1)
H-2⁺,6⁺	H-2 (6.5); H-3′ (5.9)

Table 6. ^{1}H–^{13}C Long-Range Correlations for the Oxidation Products 2–4 Determined by Semiselective 1D INEPT Measurements

compound	proton	carbon
2a	H-2	C-3; C-4; C-8a; C-1″; C-2″,6″
	H-7	C-5; C-8a
	H-3′	C-3; C-4; C-1⁺, C-2⁺,6⁺
	H-2⁺,6⁺	C-3′; C-3⁺,5⁺
2b	H-2	C-3; C-4; C-8a; C-1″; C-2″,6″
	H-7	C-5; C-8a
	H-3′	C-3; C-4; C-1⁺; C-2⁺,6⁺
2d	H-2	C-3; C-4; C-8a; C-1″, C-2″,6″
	H-3′	C-3; C-4; C-1⁺; C-2⁺,6⁺
2e	H-2	C-3; C-4; C-8a; C-1″, C-2″,6″
	H-3′	C-3; C-4; C-1⁺; C-2⁺,6⁺
2f	H-5	C-4; C-7; C-8a
	H-7	C-5; C-8a
2h	H-2	C-3; C-4; C-8a; C-1″, C-2″,6″
	H-7	C-5; C-8a
	H-3′	C-3; C-4; C-1⁺
	H-6⁺	C-3′; C-2⁺; C-4⁺
2i	H-7	C-5; C-8a
	H-3′	C-3; C-1⁺
3d	H-8	C-4a; C-6; C-8a
3f	H-7	C-5; C-8a
4a	H-2	C-4; C-1″, C-2″,6″

Scheme 2

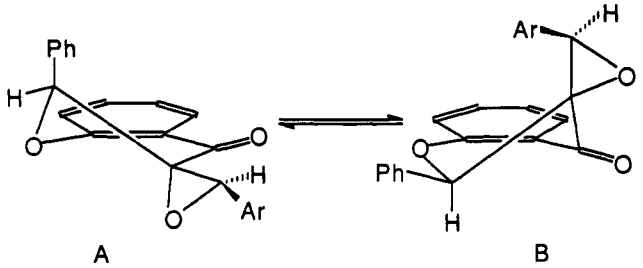


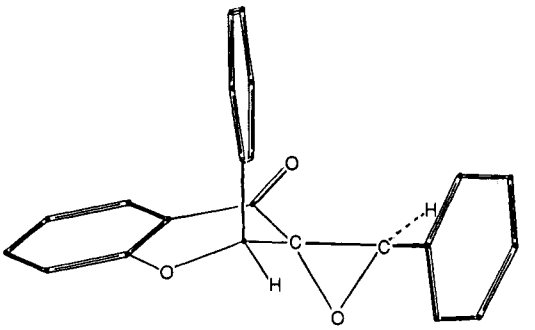
Table 7. Long-Range J(C,H) Coupling Constants (in hertz) for Spiroepoxide *trans,trans*-2a

^{3}J(H-2,C-4)	= 4.5	^{3}J(H-3′,C-2)	< 1.0
^{3}J(H-2,C-8a)	= 7.2	^{3}J(H-3′,C-2⁺,6⁺)	= 2.7
^{3}J(H-2,C-2″,6″)	= 3.2		
^{2}J(H-2,C-3)	= 6.8	^{2}J(H-3′,C-3)	= 3.0
^{2}J(H-2,C-1″)	= 5.1	^{2}J(H-3′,C-1⁺)	= 4.2

of the *trans* and *cis* orientation of the epoxy oxygen with respect to the C-2 phenyl group, the chemical shift value of the 3′-H proton was utilized. In *trans,trans*-**2a** the C-3′ atom is quasi-equatorial for the six-membered ring and, therefore, the 3′-H proton is near and approximately coplanar to the C(4)=O group and its chemical shift is enhanced to δ 5.22 as a result of the *peri* carbonyl group. Spatial proximity and coplanar arrangement are difficult for the *trans,cis*-spiroepoxide and therefore, δ(3′-H) is only 4.46 ppm.[2]

The conformational characteristics of the phenyl groups connected to the C-2 and C-3′ atoms can be assessed on the basis of the ^{3}J(2-H,C-2″,6″) and ^{3}J(3′-H,C-2⁺,6⁺) coupling constants. If the C–H bond and the connecting aromatic ring are coplanar, the coupling constant is 5–6 Hz which decreases gradually together with the decrease of the ratio of this conformer.[14,21,24] On the basis of the measured 3.2- and 2.7-Hz values, the populations of conformers along the C–C (aryl) axis are almost the same.

These results confirm the spatial proximity and nearly coplanar arrangement of the 3′-H and the carbonyl oxygen with a dihedral angle of 12° for O=C(4)—C(3)—(3′) and 1.5° for C(4)—(3)—C(3′)-H. The predominant conformation of compound **2a** has also been determined by AM1



trans,trans-**2a**

calculation,[25] which was in full agreement with the above-mentioned structure. The AM1 calculation of the geometry and total energy of the corresponding *trans,cis*-spiroepoxide **2a** showed that this latter isomer is more stable by 6.4 kcal/mol. The observed diastereoselectivity emphasizes the decisive character of steric requirements in the transition state during oxygen transfer (kinetic control).

Experimental Section

Instrumentation and Materials. ^{1}H and ^{13}C NMR spectra were run at ambient temperature in $CDCl_3$. Chemical shifts are given on the δ scale relative to TMS. Elemental analyses were performed in-house. All solvents were purified by following standard literature methods. Caroate (potassium monoperoxosulfate), the triple salt $2KHSO_5{\cdot}KHSO_4{\cdot}K_2SO_4$, was used as received. Dimethyldioxirane (as acetone solution) and methyl(trifluoromethyl)dioxirane (as CH_2Cl_2 solution) were prepared according to the published procedures,[5,18] and their peroxide content was determined by oxidation of methyl phenyl sulfide, the latter quantitated by ^{1}H NMR. The dimethyldioxirane solutions were stored over molecular sieves (4 Å) at −20 °C. The known substrates *E*- and *Z*-1 were prepared according to known procedures.[11–13] Chromatography was performed on silica gel 60 (Merck) by using hexane:acetone (7:3 v/v) or hexane:benzene (3:2 v/v) as eluents.

Preparation of (*Z*)-3-Arylideneflavanones *Z*-1c,e. (*E*)-3-Arylideneflavanones **1c,e** (3.00 g, ca. 10 mmol) were dissolved in benzene (300 mL) and irradiated with a 250-W mercury arc lamp for 20 h at ambient temperature (ca. 20 °C). The solvent was evaporated under reduced pressure (20 Torr) and the residue purified by column chromatography to afford the products *Z*-1c,e.

(*Z*)-2,3-Dihydro-3-[(4-ethoxyphenyl)methylene]-2-phenyl-4*H*-1-benzopyran-4-one (*Z*-1c) was obtained [1.14 g (38%)] as yellow needles, mp 110–111 °C (from CH_3OH): ^{1}H NMR (250 MHz, $CDCl_3$) δ 1.42 (t, 3H), 4.08 (q, 2H), 6.12 (s, 1H), 6.67 (s, 1H), 6.86–7.95 (m, 13 aromatic H). Anal. Calcd for $C_{24}H_{20}O_3$ (356.4): C, 80.88; H, 5.65. Found: C, 80.62; H, 5.59.

(*Z*)-2,3-Dihydro-3-[(4-chlorophenyl)methylene]-2-phenyl-4*H*-1-benzopyran-4-one (*Z*-1e) was obtained [1.80 g (60%)] as yellow needles, mp 99–100 °C (from CH_3OH): ^{1}H NMR (250 MHz, $CDCl_3$) δ 6.12 (s, 1H), 6.65 (s, 1H), 6.98–7.92 (m, 13 aromatic H). Anal. Calcd for $C_{22}H_{15}ClO_2$ (346.8): C, 76.19; H, 4.35. Found: C, 76.31; H, 4.29.

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Epoxidation of (*E*)-3-Arylideneflavanones 1 by Dimethyldioxirane (as Acetone Solution). General Procedure. The required amount of the dioxirane in acetone (0.07–0.09 M), which was stored over molecular sieves (4 Å) at −20 °C, was added rapidly to a cooled and stirred solution of the particular (*E*)-3-arylideneflavanone 1 (1.78–2.24 mmol) in absolute CH_2Cl_2 (10 mL). The stirring was continued for 24 h and a new quantity of dimethyldioxirane solution was rapidly added. The dioxirane administration was continued in 24-h intervals until complete conversion of starting material *E*-1. The solvent was then evaporated under reduced pressure (ca. 20 Torr) and the residue recrystallized from CH_3OH to afford the corresponding spiroepoxides 2. Substrates *E*-**1a,d,e** were also allowed to react according to the above general procedure with methyl(trifluoromethyl)dioxirane (1.8–2.8 equiv in CH_2Cl_2 solution) at 0 °C for 5–8 h to give the respective spiroepoxides 2 in similar yield as obtained with the dimethyldioxirane.

***trans,trans*-(±)-2,3′-Diphenylspiro[chroman-3,2′-oxiran]-4-one (*trans,trans*-2a).** The epoxidation of *E*-**1a** (0.700 g, 2.24 mmol) by dimethyldioxirane (280 mL of 0.08 M acetone solution) at ambient temperature for 240 h afforded 0.580 g (79%) of *trans,trans*-**2a** as white powder, mp 144–146 °C (from CH_3OH) (lit.[2] mp 149-150 °C): IR (KBr) $\nu_{C=O}$ 1684 cm^{-1}. Anal. Calcd for $C_{22}H_{16}O_3$ (328.4): C, 80.47; H, 4.91. Found: C, 80.59; H, 4.89.

***trans,trans*-(±)-3′-(4-Methoxyphenyl)-2-phenylspiro[chroman-3,2′-oxiran]-4-one (*trans,trans*-2b).** Epoxidation of *E*-**1b** (0.700 g, 2.04 mmol) by dimethyldioxirane (175 mL of a 0.07 M acetone solution) at ambient temperature for 144 h gave 0.570 g (78%) of *trans,trans*-**2b** as white powder, mp 170–171 °C (from CH_3OH) (lit.[2] mp 176 °C): IR (KBr) $\nu_{C=O}$ 1680 cm^{-1}. Anal. Calcd for $C_{23}H_{18}O_4$ (358.4): C, 77.08; H, 5.06. Found: C, 77.17; H, 5.12.

***trans,trans*-(±)-3′-(4-Ethoxyphenyl)-2-phenylspiro[chroman-3,2′-oxiran]-4-one (*trans,trans*-2c).** Epoxidation of *E*-**1c** (0.700 g, 1.96 mmol) with dimethyldioxirane (196 mL of a 0.07 M acetone solution) at ambient temperature for 168 h afforded 0.580 g (79%) of *trans,trans*-**2c** as white powder, mp 149–150 °C (from CH_3OH): IR (KBr) $\nu_{C=O}$ 1689 cm^{-1}. Anal. Calcd for $C_{24}H_{20}O_4$ (372.4): C, 77.40; H, 5.41. Found: C, 77.53; H, 5.47.

***trans,trans*-(±)-3′-(4-Methylphenyl)-2-phenylspiro[chroman-3,2′-oxiran]-4-one (*trans,trans*-2d).** Epoxidation of *E*-**1d** (0.700 g, 2.15 mmol) by dimethyldioxirane (241 mL of a 0.08 M acetone solution) at ambient temperature for 216 h gave 0.630 g (86%) of *trans,trans*-**2d** as white powder, mp 186–187 °C (from CH_3OH): IR (KBr) $\nu_{C=O}$ 1684 cm^{-1}. Anal. Calcd for $C_{23}H_{18}O_3$ (342.4): C, 80.68; H, 5.30. Found: C, 80.67; H, 5.37.

***trans,trans*-(±)-3′-(4-Chlorophenyl)-2-phenylspiro[chroman-3,2′-oxiran]-4-one (*trans,trans*-2e).** Epoxidation of *E*-**1e** (0.700 g, 2.02 mmol) with dimethyldioxirane (429 mL of a 0.08 M acetone solution) at ambient temperature for 408 h afforded 0.630 g (86%) of *trans,trans*-**2e** as white needles, mp 176–177 °C (from CH_3OH): IR (KBr) $\nu_{C=O}$ 1681 cm^{-1}. Anal. Calcd for $C_{22}H_{15}ClO_3$ (362.8): C, 72.83; H, 4.16. Found: C, 72.97; H, 4.12.

***trans,trans*-(±)-3′-(4-Bromophenyl)-2-phenylspiro[chroman-3,2′-oxiran]-4-one (*trans,trans*-2f).** Epoxidation of *E*-**1f** (0.700 g, 1.79 mmol) by dimethyldioxirane (380 mL of a 0.08 M acetone solution) at ambient temperature for 408 h gave 0.600 g (82%) of *trans,trans*-**2f** as white needles, mp 184–185 °C (from CH_3OH): IR (KBr) $\nu_{C=O}$ 1680 cm^{-1}. Anal. Calcd for $C_{22}H_{15}BrO_3$ (407.3): C, 64.88; H, 3.71. Found: C, 64.78; H, 3.66.

***trans,trans*-(±)-3′-(4-Cyanophenyl)-2-phenylspiro[chroman-3,2′-oxiran]-4-one (*trans,trans*-2g).** Epoxidation of *E*-**1g** (0.600 g, 1.78 mmol) by dimethyldioxirane (455 mL of a 0.08 M acetone solution) at ambient temperature for 552 h gave 0.500 g (80%) of *trans,trans*-**2g** as white powder, mp 162–163 °C (from CH_3OH): IR (KBr) $\nu_{C=O}$ 1691 cm^{-1}. Anal. Calcd for $C_{23}H_{15}NO_3$ (353.4): C, 78.18; H, 4.28. Found: C, 78.08; H, 4.29.

***trans,trans*-(±)-3′-(2-Methoxyphenyl)-2-phenylspiro[chroman-3,2′-oxiran]-4-one (*trans,trans*-2h).** Epoxidation of *E*-**1h** (0.700 g, 2.04 mmol) by dimethyldioxirane (332 mL of a 0.08 M acetone solution) at ambient temperature for 312 h afforded 0.530 g (73%) of *trans,trans*-**2h** as white powder, mp 151–152 °C (from CH_3OH): IR (KBr) $\nu_{C=O}$ 1694 cm^{-1}. Anal. Calcd for $C_{23}H_{18}O_4$ (358.4): C, 77.08; H, 5.06. Found: C, 76.97; H, 5.09.

***trans,trans*-(±)-3′-(2-Methylphenyl)-2-phenylspiro[chroman-3,2′-oxiran]-4-one (*trans,trans*-2i).** Epoxidation of *E*-**1i** (0.700 g, 2.15 mmol) by dimethyldioxirane (332 mL of a 0.08 M acetone solution) at ambient temperature for 312 h afforded 0.550 g (75%) of *trans,trans*-**2i** as white powder, mp 153–154 °C (from CH_3OH): IR (KBr) $\nu_{C=O}$ 1684 cm^{-1}. Anal. Calcd for $C_{23}H_{18}O_3$ (342.4): C, 80.68; H, 5.30. Found: C, 80.55; H, 5.28.

Oxidation of (*Z*)-3-Arylideneflavanones 1 by Dimethyldioxirane (as Acetone Solution). General Procedure. The *Z* isomers were allowed to react with dimethyldioxirane (0.07–0.09 M acetone solution) as described above for the *E* isomers. After the disappearance of the (*Z*)-3-arylideneflavanone, as monitored by TLC, the solvent was evaporated under reduced pressure (ca. 20 Torr) and the residue was submitted to column chromatography to yield the oxidation products 3 and/or 4.

The substrates *Z*-**1a,d** were also allowed to react with methyl(trifluoromethyl)dioxirane (1–6 equiv in CH_2Cl_2 solution). The reaction progress was monitored by TLC until complete consumption of the starting material, but on usual workup no definitive oxidation products could be isolated.

3-Benzoyl-2-phenyl-4*H*-1-benzopyran-4-one (3a). Oxidation of *Z*-**1a** (0.700 g, 2.24 mmol) with dimethyldioxirane (392 mL of a 0.08 M acetone solution) at ambient temperature for 336 h afforded 0.110 g (15%) of **3a** as yellow powder, mp 131–132 °C (from CH_3OH) (lit.[16] mp 132–133 °C): IR (KBr) $\nu_{C=O}$ 1634 and 1674 cm^{-1}. Anal. Calcd for $C_{22}H_{14}O_3$ (326.4): C, 80.97; H, 4.32. Found: C, 80.81; H, 4.28.

3-(4-Methylbenzoyl)-2-phenyl-4*H*-1-benzopyran-4-one (3d). Oxidation of *Z*-**1d** (0.700 g, 2.15 mmol) with dimethyldioxirane (323 mL of a 0.08 M acetone solution) at ambient temperature for 288 h gave 0.150 g (21%) of **3d** as yellow powder, mp 144–145 °C (from CH_3OH): IR (KBr) $\nu_{C=O}$ 1636 and 1666 cm^{-1}. Anal. Calcd for $C_{23}H_{16}O_3$ (340.4): C, 81.16; H, 4.74. Found: C, 81.10; H, 4.81.

3-(4-Chlorobenzoyl)-2-phenyl-4*H*-1-benzopyran-4-one (3e). Oxidation of *Z*-**1e** (0.700 g, 2.02 mmol) with dimethyldioxirane (519 mL of a 0.07 M acetone solution) at ambient temperature for 432 h gave 0.110 g (15%) of **3e** as yellow powder, mp 157–158 °C (from CH_3OH) (lit.[16] mp 151–153 °C): IR (KBr) $\nu_{C=O}$ 1628 and 1680 cm^{-1}. Anal. Calcd for $C_{22}H_{13}ClO_3$ (360.8): C, 73.24; H, 3.63. Found: C, 73.21; H, 3.72.

3-(4-Bromobenzoyl)-2-phenyl-4*H*-1-benzopyran-4-one (3f). Oxidation of *Z*-**1f** (0.700 g, 1.79 mmol) with dimethyldioxirane (358 mL of a 0.09 M acetone solution) at ambient temperature for 432 h gave 0.140 g (19%) of **3f** as yellow needles, mp 159–160 °C (from CH_3OH): IR (KBr) $\nu_{C=O}$ 1636 and 1676 cm^{-1}. Anal. Calcd for $C_{22}H_{13}BrO_3$ (405.3): C, 65.21; H, 3.23. Found: C, 65.38; H, 3.27.

***trans*-3-Benzoyl-2,3-dihydro-2-phenyl-4*H*-1-benzopyran-4-one (*trans*-4a)** was isolated as a second product in the dimethyldioxirane oxidation of substrate *Z*-**1a**, 70.0 mg (10%), as white needles, mp 161–162 °C (from CH_3OH) (lit.[26] mp 155 °C): IR (KBr) $\nu_{C=O}$ 1674 and 1698 cm^{-1}. Anal. Calcd for $C_{22}H_{16}O_3$ (328.4): C, 80.47; H, 4.91. Found: C, 80.35; H, 4.38.

***trans*-2,3-Dihydro-3-(4-ethoxybenzoyl)-2-phenyl-4*H*-1-benzopyran-4-one (*trans*-4c).** Oxidation of *Z*-**1c** (0.700 g, 1.96 mmol) by dimethyldioxirane (343 mL of a 0.08 M acetone solution) at ambient temperature for 336 h gave 0.100 g (14%) of *trans*-**4c** as a white powder, mp 97–98 °C (from CH_3OH): IR (KBr) $\nu_{C=O}$ 1672 and 1694 cm^{-1}. Anal. Calcd for $C_{24}H_{20}O_4$ (372.4): C, 77.40; H, 5.41. Found: C, 77.50; H, 5.37.

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