

**Intramolecular Photocyclization of 2-Acylphenyl Methacrylates:
a Convenient Access to 4,5-Dihydro-1,4-epoxy-2-benzoxepin-3(1*H*)-ones
(= Benzo[*c*]-6,8-dioxabicyclo[3.2.1]octan-7-ones**

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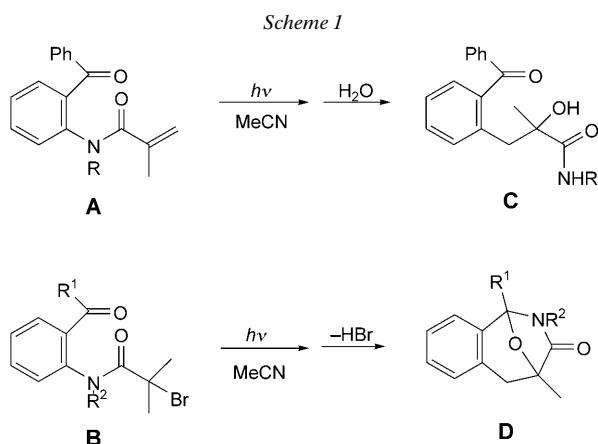
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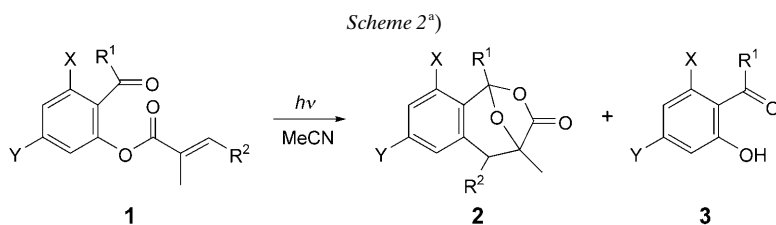
The photochemical reactions of 2-acylphenyl methacrylates (=2-acylphenyl 2-methylprop-2-enoates) **1** were investigated. Irradiation of 2-acylphenyl methacrylates **1a–d** in MeCN gave the tricyclic lactones **2a–d** in good yields, together with a small amount of O–C=O bond cleavage product, the 2-acylphenols **3a–d** (*Scheme 2, Table*). The formation of the tricyclic lactones **2** probably follows a mechanism involving a 1,7-di-radical through ζ -H abstraction (1,8-H transfer) by the excited carbonyl O-atom (*Scheme 3*). Irradiation of 2-acylphenyl tiglate (=2-acylphenyl (2*E*)-2-methylbut-2-enoate) **1e** and 2-acylphenyl methacrylates **1g–i**, substituted by a MeO group (δ -H) at the 3,5-positions of the phenyl group, also gave the tricyclic lactones **2e** and **2g–i**, but in low yields. On the other hand, no H-abstraction products were observed on irradiation of 2-(ethoxycarbonyl)phenyl methacrylate **1f**, of 2-acylphenyl methacrylate **1j** which is substituted by a Me group (γ -H) at the 3,5-positions of the phenyl group, and of **1k** with an OH group at the 3-position of the phenyl group.

1. Introduction. – Intramolecular H-abstraction reactions by the excited carbonyl group have been extensively investigated from synthetic and mechanistic viewpoints [1–3]. Generally, γ -H-atoms are abstracted most rapidly through six-membered cyclic transition states (1,5-H-transfer), as in the *Norrish*-Type-II reaction. This γ -H abstraction is greatly facilitated by favorable stereoelectronic or geometric requirements [2]. Abstraction from remote positions involving 1,6- and greater H-transfers is one of the most attractive subjects in the photochemistry of carbonyl groups [3–9], while these reactions are disfavored for medium and large cyclic transition states both statistically and energetically. Abstraction from such long-range positions has been observed in the photochemistry of imides [10], amino ketones [11], and S-containing glyoxylates [12] associated with electron-transfer character. In the course of our studies on the photochemistry of amide derivatives [13], we have reported that the long-range H-abstraction was observed in the photochemistry of *N*-(2-acylphenyl)prop-2-enamides and *N*-(2-acylphenyl)propanamides [13c,d]. For example, irradiation of *N*-(2-acylphenyl)-2-methylprop-2-enamides (**A**) [13c] and *N*-(2-acylphenyl)-2-bromo-2-methylpropanamides (**B**) [13d] afforded the open-chain amides **C** and the tricyclic lactams **D**, respectively, *via* ζ -H abstraction (1,8-H transfer) by the excited carbonyl O-atom through a nine-membered transition state (*Scheme 1*). We now report a new example of a ζ -H abstraction reaction in the photochemistry of 2-acylphenyl methacrylates **1**, whereby



cyclization, followed by rearrangement of the resulting 1,7-biradicals, leads to the formation of the unexpected tricyclic lactones **3**.

2. Results and Discussion. – Irradiation of 2-acylphenyl methacrylates **1a–d** in MeCN with a high-pressure Hg lamp under Ar atmosphere (Pyrex filter, room temperature) gave tricyclic lactones, *i.e.*, 4,5-dihydro-1,4-epoxy-2-benzoxepin-3(1*H*)-ones (=benzo[*c*]-6,8-dioxobicyclo[3.2.1]octan-7-ones) **2a–d** in high yields (74–98%), along with a small amount of 2-acylphenols **3a–d**, produced by cleavage of the O–C(=O) bond (Scheme 2, Table). The tricyclic lactone **2a** was also obtained when **1a** was irradiated in benzene or MeOH, but in low yield. Irradiation of 2-benzoylphenyl tiglate (=2-benzoylphenyl (*2E*)-2-methylbut-2-enoate; **1e**) afforded the tricyclic lactone **2e**, and the possible isomeric lactone **2e'** (see below, Scheme 3) was not detected. Irradiation of 2-(ethoxycarbonyl)phenyl methacrylate **1f** gave no H-abstraction product. The formation of the tricyclic lactone **2a** was completely quenched by the addition of triplet quenchers such as 2,5-dimethylhexa-2,4-diene, cyclohexa-1,3-diene, and O₂, suggesting that this reaction proceeds *via* an $n\text{-}\pi^*$ triplet state.



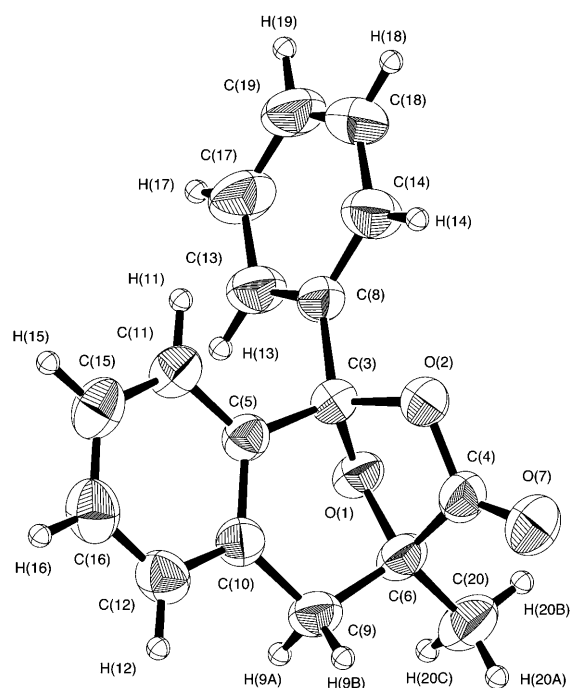
^{a)} For R¹, R², X, and Y, see Table.

The structures of the photoproducts **2** described above were assigned on the basis of spectral and analytical evidence. In the case of the tricyclic lactone **2a**, assignment was further confirmed by an X-ray crystal structure analysis (Fig.).

Table 1. Photochemical Reactions of the 2-Acylphenyl Methacrylates **1** in MeCN

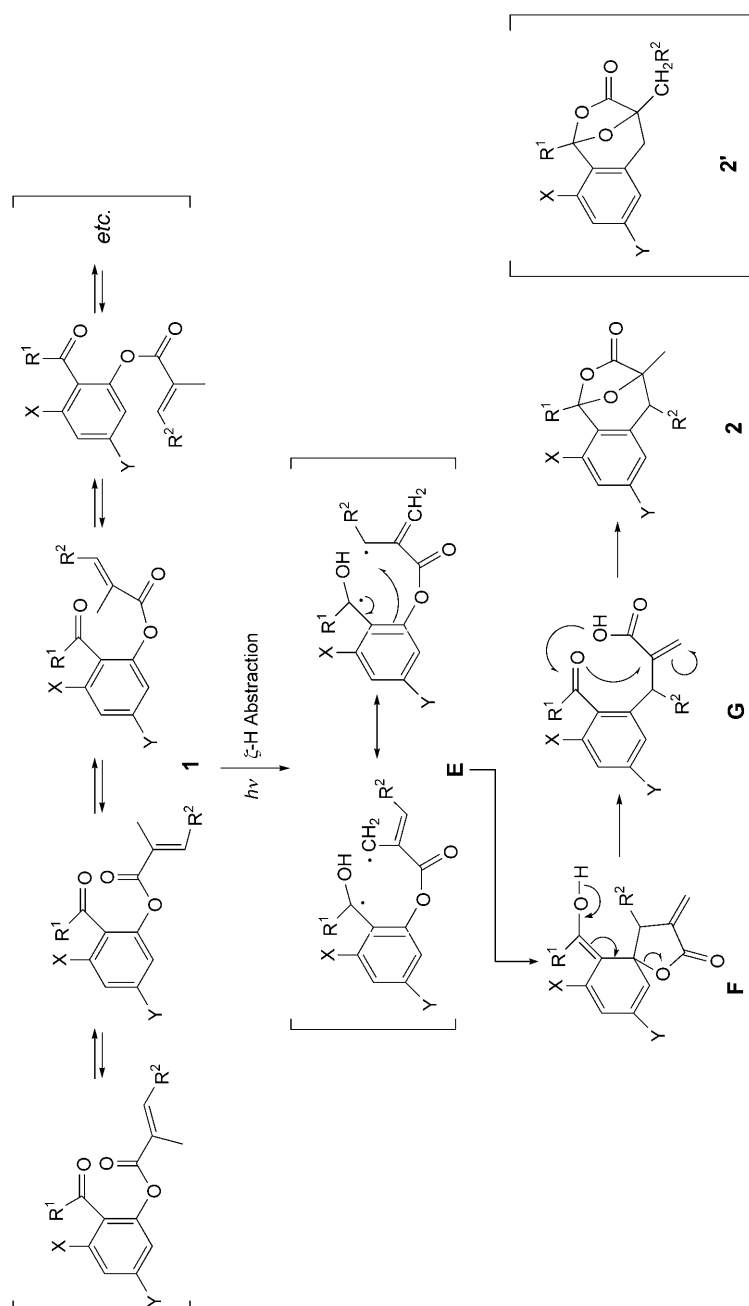
Entry	Starting material	Substituents				Isolated yield [%] of products	
		R ¹	R ²	X	Y	2	3
1	1a	Ph	H	H	H	98	1
2 ^{a)}	1a	Ph	H	H	H	42	14
3 ^{b)}	1a	Ph	H	H	H	12	43
4	1b	Ph	H	H	MeO	84	12
5	1c	Me	H	H	H	70	1
6	1d	Et	H	H	H	74	5
7	1e	Ph	Me	H	H	14 ^{c)}	2
8	1f	EtO	H	H	H	– ^{d)}	6
9	1g	Ph	H	MeO	MeO	trace	13
10	1h	Me	H	MeO	MeO	44	23
11	1i	Et	H	MeO	MeO	20	25
12	1j	Ph	H	Me	Me	– ^{d)}	11
13	1k	Me	H	OH	H	– ^{d)}	– ^{d)}

^{a)} Solvent: benzene. ^{b)} Solvent: MeOH. ^{c)} 2 : 1 Mixture of two diastereoisomers. ^{d)} Not detected.

Figure. X-Ray crystal structure of compound **2a**. ORTEP view.

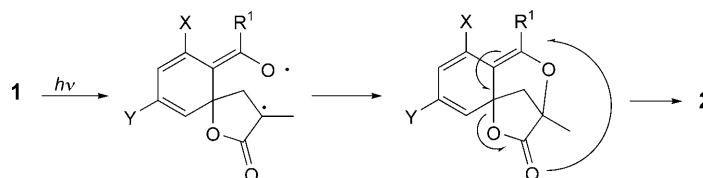
A plausible mechanism for the formation of the tricyclic lactones **2** is depicted in *Scheme 2*. ζ -H (Allylic-H) abstraction by the excited carbonyl O-atom via a nine-membered transition state would result in the 1,7-biradical **E**. Subsequent ring closure yields the spiro lactone **F**, which may undergo ring opening to the oxo-carboxylic acid **G**, and then ring closure yields the tricyclic lactone **2**. The intramolecular *ortho* photocycliza-

Scheme 3



tion mechanism was reported in the photochemistry of 4-phenoxybut-1-enes [14]. A similar mechanistic sequence could also be considered, *i.e.*, *ipso*-cyclization of the olefinic C(β)-atom at the phenolic C-atom of the aromatic ring, followed by 1,6-cyclization of the formed biradical, and then 3,3-sigmatropic rearrangement yielding the final tricyclic products (*Scheme 4*)¹⁾. However, no cyclization product could be formed from 2-(ethoxycarbonyl)phenyl methacrylate **1f** as mentioned above, and irradiation of the parent phenyl methacrylate and 2-methoxyphenyl methacrylate resulted in the recovery of unchanged starting materials. Further, we recently proposed the analogous H-abstraction reaction of N-analogues, *i.e.*, of *N*-(2-acylphenyl)-2-methylprop-2-enamides [13c]. From these facts, we propose the long-range H-abstraction mechanism.

Scheme 4



Subsequently, to examine the intramolecular competition between δ -H (1,6-H transfer) and ζ -H abstraction (1,8-H transfer), and γ -H (1,5 H transfer) and ζ -H abstraction, we carried out the photoreaction of **1g–i** having MeO substituents (δ -hydrogen) at the *m*-positions of the phenyl group and **1j** having Me substituents (γ -hydrogen) at the *m*-positions of the phenyl group. Irradiation of **1g–i** in MeCN under the same conditions gave the tricyclic lactones **2g–i** (trace–44%), accompanied by the corresponding 2-acylphenols **3g–i** (13–25%), and benzofuran derivatives, which are expected to be produced *via* δ -H abstraction [2a][15], could not be observed. When **1j** was irradiated, no H-abstraction product was formed, only a small amount of the corresponding phenol **3j** was isolated. This is probably due to the lack of favorable stereoelectronic or geometric requirements [2]. Irradiation of 2-acyl-3-hydroxyphenyl methacrylate **1k** resulted in the recovery of unchanged starting material, probably due to intramolecular H-bonding between OH and the acetyl C=O of **1k**.

The H-abstraction reaction by the excited carbonyl O-atom is generally facilitated by favorable stereoelectronic and geometric requirements [2]. Long-range H-atom abstraction reactions are rare [3]. Our results herein establish the potential of long-range H-abstraction reactions in case of favorable conformation.

Experimental Part

General. Flash chromatography (FC): *Wakogel-C-300* silica gel. M.p.: *Yanaco-MP-J3* micro-melting point apparatus; uncorrected. B.p.: *Shibata-GTO-350-RD* glass-tube-oven distillation apparatus. IR Spectra: *Jasco-FT/IR-300* spectrophotometer; in cm^{-1} . ^1H - and ^{13}C -NMR Spectra: *Jeol-JNM-EX-270* (270 MHz) or *Varian-Gemini-200* (200 MHz) spectrometer; in CDCl_3 , with Me_4Si as internal standard; δ in ppm, J in Hz.

Irradiation of 2-Acylphenyl Methacrylates 1: General Procedure. A soln. of the **1** (1 mmol) in MeCN (70 ml), unless otherwise noted, was irradiated in a Pyrex tube with a high-pressure Hg lamp (*Halos EHP*

¹⁾ We thank a referee for suggesting this mechanism.

500 W; Eikosha) under Ar for 5–15 h at r.t. After removal of the solvent, the residue was subjected to FC (SiO₂, toluene/AcOEt 50 : 1 → 19 : 1) to give the photoproducts **2** and **3** (see Table). The structures of the 2-acylphenols **3** were confirmed by direct comparison of their spectral properties with those of commercially available materials.

4,5-Dihydro-4-methyl-1-phenyl-1,4-epoxy-2-benzoxepin-3(1H)-one (2a): M.p. 141–142°. IR (KBr): 1795. ¹H-NMR: 1.73 (s, 3 H); 3.13 (d, *J* = 17.5, 1 H); 3.28 (d, *J* = 17.5, 1 H); 6.70 (d, *J* = 7.9, 1 H); 7.06 (t, *J* = 7.6, 1 H); 7.18 (d, *J* = 7.3, 1 H); 7.24–7.34 (m, 1 H); 7.54–7.58 (m, 3 H); 7.62–7.66 (m, 2 H). ¹³C-NMR: 21.2; 35.4; 79.7; 108.6; 126.1; 126.3; 126.4; 128.4; 128.9; 129.6; 131.7; 134.7; 136.4; 175.0. Anal. calc. for C₁₇H₁₄O₃: C 76.67, H 5.30; found: C 76.37, H 5.32.

4,5-Dihydro-4-methyl-1-phenyl-7-methoxy-1,4-epoxy-2-benzoxepin-3(1H)-7-one (2b): M.p. 130–131°. IR (KBr): 1794. ¹H-NMR: 1.71 (s, 3 H); 3.09 (d, *J* = 17.4, 1 H); 3.27 (d, *J* = 17.4, 1 H); 3.77 (s, 3 H); 6.58–6.72 (m, 2 H); 7.36 (s, 1 H); 7.46–7.52 (m, 3 H); 7.60–7.66 (m, 2 H). ¹³C-NMR: 20.6; 35.3; 54.7; 79.0; 108.2; 110.9; 113.7; 125.7; 127.0; 127.8; 129.0; 132.9; 134.4; 159.9; 174.7. Anal. calc. for C₁₈H₁₆O₃: C 72.96, H 5.44; found: C 73.16, H 5.44.

4,5-Dihydro-1,4-dimethyl-1,4-epoxy-2-benzoxepin-3(1H)-7-one (2c): M.p. 67–68°. IR (KBr): 1783. ¹H-NMR: 1.67 (s, 3 H); 2.05 (s, 3 H); 3.01 (d, *J* = 17.5, 1 H); 3.13 (d, *J* = 17.5, 1 H); 7.12–7.36 (m, 4 H). ¹³C-NMR: 20.1; 21.2; 35.3; 79.4; 107.4; 123.2; 126.6; 129.1; 129.7; 131.4; 135.4; 175.5. Anal. calc. for C₁₂H₁₂O₃: C 70.57, H 5.96; found: C 70.67, H 5.97.

1-Ethyl-4,5-dihydro-4-methyl-1,4-epoxy-2-benzoxepin-3(1H)-one (2d): M.p. 62–63°. IR (KBr): 1790. ¹H-NMR: 1.13 (t, *J* = 7.4, 3 H); 1.67 (s, 3 H); 2.35–2.49 (m, 2 H); 3.00 (d, *J* = 17.4, 1 H); 3.14 (d, *J* = 17.4, 1 H); 7.12–7.36 (m, 4 H). ¹³C-NMR: 6.1; 20.6; 24.9; 35.1; 78.7; 108.5; 122.9; 126.2; 127.9; 129.2; 131.6; 134.3; 175.3. Anal. calc. for C₁₃H₁₄O₃: C 71.54, H 6.47; found: C 71.30, H 6.47.

4,5-Dihydro-4,5-dimethyl-1-phenyl-1,4-epoxy-2-benzoxepin-3(1H)-one (2e; 2:1 diastereoisomer mixture): B.p. 185–187°/3 Torr. IR (film): 1797. ¹H-NMR: 1.46 (d, *J* = 7.3, 2 H); 1.47 (d, *J* = 7.3, 1 H); 1.63 (s, 1 H); 1.71 (s, 2 H); 3.05 (q, *J* = 7.3, 1/3 H); 3.42 (q, *J* = 7.3, 2/3 H); 6.66 (d, *J* = 7.9, 1 H); 6.99–7.06 (m, 1 H); 7.22–7.35 (m, 2 H); 7.46–7.50 (m, 3 H); 7.59–7.67 (m, 2 H). ¹³C-NMR (nonarom. signals): 15.3; 17.8; 19.0; 19.9; 36.9; 39.5; 82.0; 82.6; 108.2; 108.9; 173.1; 175.9. MS: 280 (*M*⁺).

4,5-Dihydro-7,9-dimethoxy-1,4-dimethyl-1,4-epoxy-2-benzoxepin-3(1H)-one (2h): M.p. 32–33°. IR (KBr): 1790. ¹H-NMR: 1.63 (s, 3 H); 2.14 (s, 3 H); 2.91 (d, *J* = 17.3, 1 H); 3.08 (d, *J* = 17.3, 1 H); 3.78 (s, 3 H); 3.79 (s, 3 H); 6.23 (d, *J* = 2.3, 1 H); 6.29 (d, *J* = 2.3, 1 H). ¹³C-NMR: 21.3; 24.1; 36.2; 55.3; 55.4; 78.8; 97.3; 105.2; 108.1; 116.9; 157.7; 160.9; 176.0. Anal. calc. for C₁₄H₁₆O₅: C 63.38, H 6.01; found: C 63.62, H 6.01.

1-Ethyl-4,5-dihydro-7,9-dimethoxy-4-methyl-1,4-epoxy-2-benzoxepin-3(1H)-one (2i): M.p. 43–44°. IR (KBr): 1787. ¹H-NMR: 1.03 (t, *J* = 7.3, 3 H); 1.62 (s, 3 H); 2.31–2.42 (m, 1 H); 2.69–2.79 (m, 1 H); 2.90 (d, *J* = 17.3, 1 H); 3.10 (d, *J* = 17.3, 1 H); 3.77 (s, 3 H); 3.79 (s, 3 H); 6.24 (d, *J* = 2.3, 1 H); 6.29 (d, *J* = 2.3, 1 H). MS: 278 (*M*⁺).

X-Ray Crystal-Structure Determination²⁾. A crystal of **2a** was grown from CH₂Cl₂/hexane. The intensity data were collected on a MacScience-MXC-18 diffractometer, with graphite-monochromated CuK_α radiation (λ = 1.54178 Å), in the ω -2 θ scan mode (2θ < 69.99°). Out of 2844 total reflections, 2204 reflections with intensities greater than 3 σ (*I*) were used. No absorption correction was made. The structure was solved by direct methods with the maXus program. Least-square refinements were performed, including anisotropic thermal parameters for non-H-atoms and isotropic refinement of H-atoms located in difference Fourier synthesis.

Crystal data for **2a**: C₁₈H₁₄O₃; *M* 266.296; *V* = 1353.4 (10) Å³, *Z* = 4, *D*_x = 1.307 Mg cm^{−3}; monoclinic, space group *P*2₁/*c*, *a* = 10.295 (3) Å, *b* = 8.355 (3) Å, *c* = 17.400 (10) Å, α = 90.00°, β = 115.27°, γ = 90.00°; *R* = 0.071, *R*_w = 0.066.

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²⁾ CCDC-269753 contains the supplementary crystallographic data for this paper. These data can be obtained free charge from the Cambridge Crystallographic Data Centre via (www.ccdc.cam.ac.uk/data_request/cif).

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