Benzoyl radicals from (hetero)aromatic aldehydes. Decatungstate photocatalyzed synthesis of substituted aromatic ketones†

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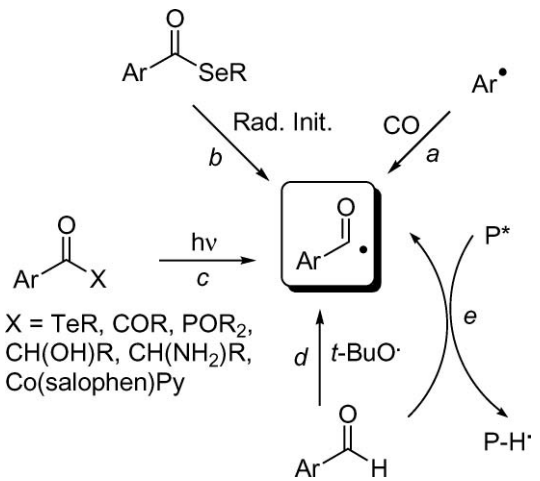
Benzoyl radicals are generated directly from (hetero)aromatic aldehydes upon tetrabutylammonium decatungstate ($(n\text{-}Bu_4N)_4W_{10}O_{32}$), TBADT) photocatalysis under mild conditions. In the presence of α,β-unsaturated esters, ketones and nitriles radical conjugate addition ensues and gives the corresponding β-functionalized aryl alkyl ketones in moderate to good yields (stereoselectively in the case of 3-methylene-2-norbornanone). Due to the mild reaction conditions the presence of various functional groups on the aromatic ring is tolerated (*e.g.* methyl, methoxy, chloro). The method can be applied to hetero-aromatic aldehydes whether electron-rich (*e.g.* thiophene-2-carbaldehyde) or electron-poor (*e.g.* pyridine-3-carbaldehyde).

Introduction

Carbon centered radicals are a versatile tool for the formation of C–C bonds in organic synthesis.[1] As an example, ketones have been obtained from the reaction of nucleophilic acyl radicals with a double or a triple C–C bond.[2,3] Preparing aromatic ketones by this strategy requires the generation of benzoyl radicals (ArC(=O)•). Only in rare instances these have been formed by carbonylation of aryl radicals (Scheme 1, path *a*),[4] while the main approach involves the homolytic cleavage of a suitable ArC(=O)–X bond as illustrated in Scheme 1.



Scheme 1 Literature pathways for the generation of benzoyl radicals.

Acyl selenides (X = SeR) have been largely exploited for this purpose, but require the use of a radical chain carrier, usually a toxic tin containing compound, *e.g.* Bu_3SnH (Scheme 1, path *b*).[5] The photochemical cleavage of a ArC(=O)–X bond is a viable alternative, as shown with acyl tellurides (X = TeR)[6] and benzoylphosphine oxides (X = $P(=O)Ph_2$, path *c*),[7] as well as starting from α-hydroxy or α-amino ketones,[7a–b,8] cyclic ketones (*via* the Norrish type I cleavage)[9] or esters (*via* the photo-Fries rearrangements).[10] Moreover, Pattenden and coworkers have developed acylcobalt salophen reagents (X = Co(salophen)Py, path *c*)[11] that have the advantage to generate acyl radicals by means of ambient light. The generation of benzoyl radicals in this way has been demonstrated in spectroscopical or kinetic studies and has found application for polymerization initiation,[7a] as well as in synthesis, limitedly to Se and Te derivatives. Phenyl selenoesters, however, required the use of benzene as the solvent and of an excess of alkene (up to 2.5 equiv.) and variable amounts of dimers were usually formed as side products.[5] In addition, acylcobalt reagents led in most cases to mixtures of alkylated ketones and conjugated enones.[11b]

Se or Te esters have to be prepared, however, and thus cleaving directly the C–H bond in benzaldehydes would be an obvious step forward.[12] This extension should be viable since the homolytic H abstraction from aromatic aldehydes has been demonstrated with electrophilic radicals, such as t-BuO• [12b] or nitrate[12c] (path *d*). However, synthetic applications reported are limited to a few radical-chain hydroacylation reactions where thiols were added to make the propagation of the chain reaction efficient.[13] Photocatalysis[14,15] offers a peculiar alternative. This method is based on the ability by a photocatalyst of abstracting a hydrogen atom from a reagent when in the excited state (P* in Scheme 1, path *e*) and of being regenerated by back H transfer to an intermediate of the reaction, so that light is a stoichiometric reagent.[14a] Decatungstate salts (*e.g.* the tetrabutylammonium salt, TBADT) are emerging as convenient photocatalysts.[16,17] Indeed, Orfanopoulos *et al.* used TBADT to activate a few aromatic aldehydes for the benzoylation of [60]Fullerene,[18a] but this required a large excess both of the aldehyde (*ca.* 100 equiv.) and of TBADT (2 equiv.) with respect to the fullerene used (that appeared to be one of the absorbing species).[18] In contrast, acylation occurred under synthetically more sensible conditions with *aliphatic* aldehydes and yielded dialkyl ketones.[19,20] As a matter of fact, the BDE for

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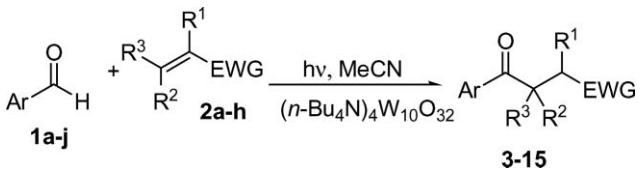
† Electronic supplementary information (ESI) available: Selected absorption spectra of starting aldehydes, TBADT and reaction mixture and ^1H NMR and ^{13}C NMR data for compounds **3–9**, **11–15**. CCDC reference numbers 784807. For ESI and crystallographic data in CIF or other electronic format see DOI: 10.1039/c0ob00066c

Table 1 Photocatalyzed synthesis of substituted aromatic ketones.[a]



Aromatic aldehydes	Olefins	Products (yields, %)[b]
1a (Ar = 4-MeO-C_6H_4)	**2a**	**3**; 75, 77[c], 70[d]
1a	**2b**	**4**; 62
1a	**2c**	**5**; 53, 39[c]
1b (Ar = Ph)	**2d**	**6**; 36, 65[c]
1c (Ar = 4-Cl-C_6H_4)	**2e**	**7**; 82, 59[c]
1d (Ar = 2-Cl-C_6H_4)	**2f**	**8**; 55
1e (Ar = 3-Me-C_6H_4)	**2f**	**9**; 58
1f (Ar = 4-HO-C_6H_4)	**2f**	**10**;[e]
1g (Ar = 4-*t*-BuMe$_2$SiO–C_6H_4)	**2e**	**11**; 81[f]
1h (Ar = 3-OHC-C_6H_4)	**2c**	**12**; 78
1i (Ar = 2-thienyl)	**2g**	**13**; 51[f]
1j (Ar = 3-pyridyl)	**2h**	**14**; 48
1j	**2f**	**15**; 41

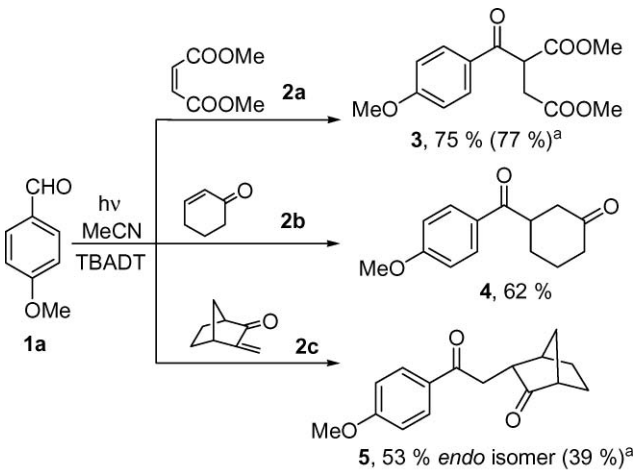
[a] Reaction conditions: ArCHO (**1a–j**, 0.1 M), **2a–h** (0.12 M), TBADT (2×10^{-3} M) in MeCN irradiated at 310 nm (unless otherwise stated). [b] Isolated yields. [c] Reaction performed in acetone/water 4 : 1 v/v mixture. [d] **1a**, (0.2 M), **2a** (0.25 M). [e] Compound not isolated but detected by GC-MS analysis after 50% conversion of **1f**. [f] Solution irradiated at 366 nm wavelength.

the C–H bond in the formyl moiety is known to change little in benzaldehyde (PhC(O)–H = 87 kcal mol^{-1})[21a] in comparison with aliphatic aldehydes (*e.g.* $CH_3C(O)$–H = 87.3 kcal mol^{-1}.[21b] Correspondingly, the rate constants for H abstraction by the *t*-butoxyl[12b] and nitrate radicals[12c] is likewise similar (k_H ca $2–7 \times 10^7$ M^{-1} s^{-1}) for aliphatic aldehydes and benzaldehyde. Thus, extension of the above reaction to aromatic aldehydes should be possible, except for two possible limitations. The first one is the strong dependence of the hydrogen abstraction rate on ring substituents (the k_H values by OH and NO_3 radicals drop over three order of magnitude in passing from electron-donating to the less reactive electron-withdrawing substituted benzaldehydes).[12c] The second is the strong absorption in the near UV by aromatic aldehydes that may preclude excitation of the photocatalyst.

Results and discussion

We report below a range of photocatalytic reactions of (hetero)aromatic aldehydes. The work aimed to establish if—and within which limits—a synthesis of arylketones characterized by a good atom economy could be achieved in this way. The results obtained are reported in Table 1.

A number of (un)substituted olefins (α,β-unsaturated esters, ketones, nitriles) and various functionalized aromatic aldehydes have been tested to explore the scope of the reaction. 4-Anisaldehyde (**1a**), known to be highly reactive towards hydrogen abstraction (k_H 1.2×10^9 M^{-1} s^{-1} by the nitrate radical),[12c] was first tested by adopting the same reaction protocol used for aliphatic derivatives,[19] *viz* the irradiation (310 nm) of an equimolar solution (0.1 M) of **1a** and dimethyl maleate (**2a**) in acetonitrile in the presence of a catalytic amount of TBADT (2% equiv.). The hoped for ketone (dimethyl 2-(4-methoxybenzoyl)succinate, **3**) was indeed obtained, but the conversion of the starting aldehyde was incomplete. Prolonging somewhat the irradiation time (30 h) and using a slight excess (20%) of the olefin led to total conversion and formation of **3** in 75% isolated yield (Scheme 2). Moreover, the spectrum of the reaction mixture well fitted with the addition of those of the identified components (see Figure S2, ESI†). A larger excess of the olefin caused the formation of oligomers, as indicated by GC analysis. On the other hand, the formation of ketone **3** was satisfactory when using an excess (20%) of **1a**. The rate of the reaction is unaffected when increasing the amount of the photocatalyst (up to 4% equiv.); on the contrary when using 1% equiv. the reaction became too sluggish and thus unpractical for synthesis.



Scheme 2

Blank experiments showed that irradiation of a 0.1 M solution of **1a** in neat acetonitrile (24 h, 310 nm) did not cause appreciable consumption of the aromatic aldehyde; on the contrary, when an acetonitrile mixture of **1a** and TBADT was likewise irradiated a partial consumption of the aldehyde (*ca.* 40%) was measured with no concomitant detection by GC-MS analysis of significant amounts of byproducts. Substituting MeCN with a more eco-friendly medium (acetone/water 4 : 1) gave likewise **3** in 77% yield. Increasing the amount of **1a** (up to 0.2 M) and **2a** (up to 0.25 M) allowed the photocatalyzed formation of **3** in a somewhat lower yield (70%, See Experimental section).

1,4-Diketones **4** (62% yield) and **5** (53% yield) were also prepared by the reaction of **1a** with 2-cyclohexen-1-one (**2b**) and 3-methylene-2-norbornanone (**2c**), respectively. Compound **5** was obtained as a single diastereoisomer. The norbornane configuration issue was investigated by NMR through 2D-COSY and NOESY experiments (see ESI†) and the data supported an *endo* structure, although not conclusively (see Fig. 1).[22]

The *endo* configuration was confirmed, however, by a X-ray structure determination (see Fig. 2). This demonstrated that the hydrogen back-donation from the reduced photocatalyst (TBADT-H$^{\bullet}$) to the radical adduct intermediate took place as expected from the less hindered side of the norbornanone moiety and formed the *endo* isomer (see below).

In the synthesis of **5**, changing to aqueous acetone was inappropriate, however, since the yield decreased (39%, Scheme 2). On the contrary, the photocatalyzed addition of parent benzaldehyde (**1b**) to methyl crotonate (**2d**) afforded the aromatic ketone **6** in a

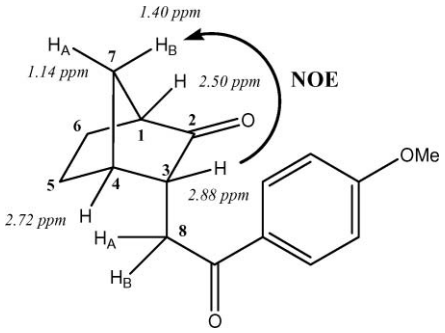


Fig. 1

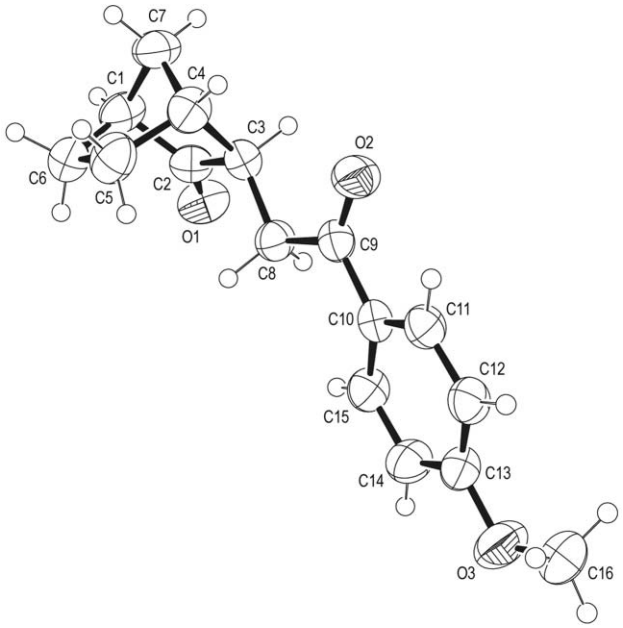
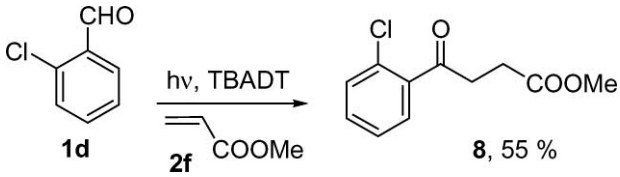


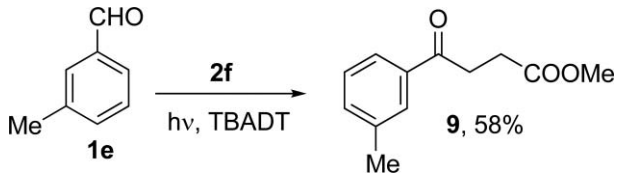
Fig. 2 Perspective view of **5**. Thermal ellipsoids are drawn at 50% probability level.

low yield (36%) that was increased in acetone/water mixture (65%, Scheme 3, right part).

The less H donating 4-chlorobenzaldehyde[12c] (**1c**) was tested in the reaction with methyl vinyl ketone (**2e**) and gave diketone **7** in a high yield (82%, Scheme 3, left part). Isomeric 2-chlorobenzaldehyde (**1d**) and methyl acrylate (**2f**) gave ketoester **8** in a lower yield (55%), presumably due to sterical hindering (Scheme 4). Methyl 4-oxo-4-*m*-tolylbutanoate (**9**) was obtained in 58% yield starting from 3-methylbenzaldehyde (**1e**) and **2f** (Scheme 5).

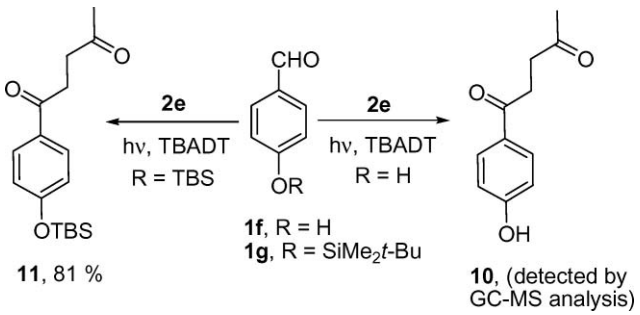


Scheme 4



Scheme 5

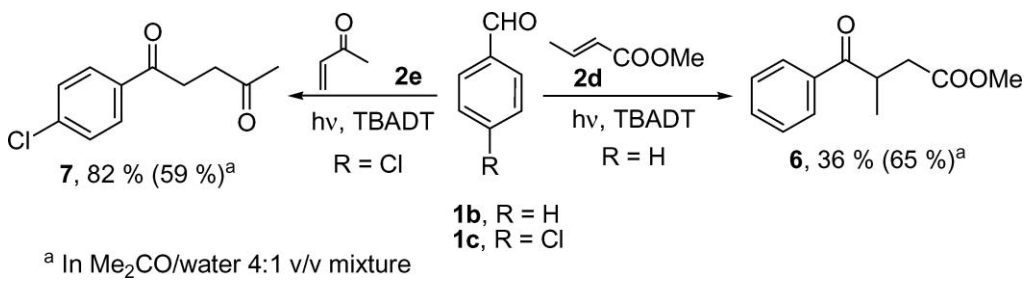
Under the conditions above, 4-hydroxybenzaldehyde (**1f**) did react, though slowly (50% conversion after 30 h irradiation), despite the presence of a reactive phenolic OH group, and gave the expected ketone **10** with **2e**. However, protection of this group as a silyl ether (-OTBS, compound **1g**) and shifting to irradiation at 366 rather than 310 nm allowed the completion of the reaction and afforded 1,4-dione **11** in 81% isolated yield (Scheme 6).



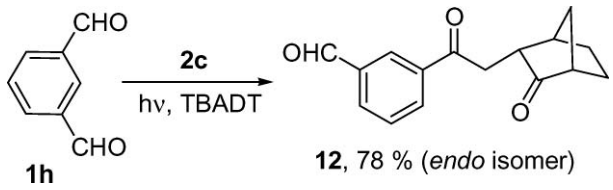
Scheme 6

Interesting was the case of isophthalaldehyde (**1h**) where two equivalent formyl groups were present. The activation of a single group was achieved, as demonstrated in the reaction with **2c**, where substituted benzaldehyde **12** was formed in 78% yield as the exclusive product (Scheme 7). In analogy with compound **5**, the *endo* isomer was exclusively obtained.[23]

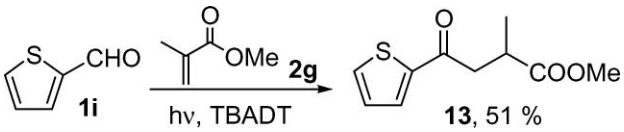
The extension of the method to heteroaromatic aldehydes was next considered. Thiophene-2-carbaldehyde (**1i**) strongly absorbed around 310 nm. Accordingly, 366 nm irradiation was adopted and acylated thiophene **13** was prepared in 51% yield in the reaction with methyl methacrylate (**2g**, Scheme 8).



Scheme 3

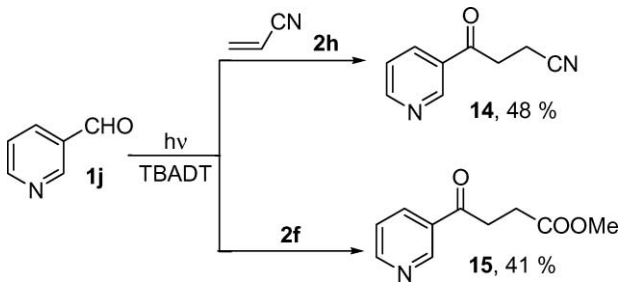


Scheme 7



Scheme 8

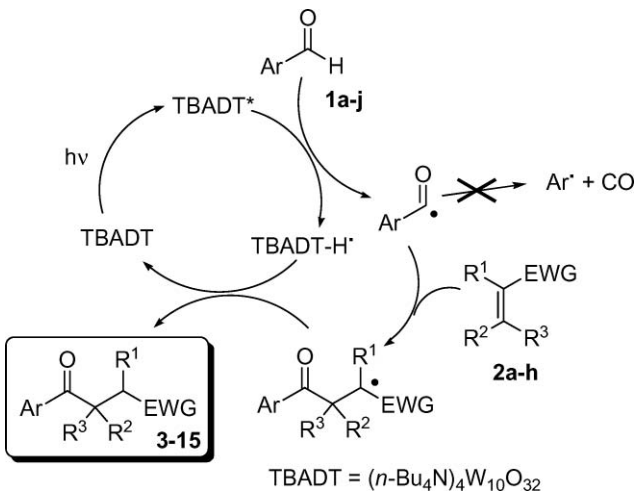
Positive results were obtained also with pyridine-3-carbaldehyde (**1j**), and the reactions with nitrile **2h** and ester **2f** allowed the isolation of the corresponding 3-pyridine ketones **14** and **15** in 48 and 41% yield, respectively (Scheme 9).



Scheme 9

However, when using aromatic aldehydes having a strong absorption also at 366 nm, such as 4-*N*,*N*-dimethylbenzaldehyde, 4-nitrobenzaldehyde or naphthaldehyde no acylation occurred.

The data above show that the generation of substituted benzoyl radicals is in fact viable through a short path by decatungstate photocatalyst from easily available aldehydes (see Scheme 10), avoiding the preparation of Se or Te esters.



Scheme 10 TBADT Photocatalyzed aroylation of olefins.

TBADT photocatalysis is efficient and chemoselective[17,18] even when other labile C–H bonds are present in the starting aldehyde, as in compounds **1a** or **1e**. No competitive paths from the acyl radical (*e.g.* decarbonylation)[27] or from the radical adduct (*e.g.* polymerization) has been evidenced.

Noteworthy, a de-symmetrization of isophthalaldehyde has been achieved maintaining one of the two formyl groups free for further elaboration.

The only condition required for the success of the method with the use of a photocatalyst was that this absorbed light. The maximum of TBADT is at *ca.* 323 nm,[17] but under the conditions of the experiment the absorbance extends almost to 400 nm.[28] Competitive light absorption by most of the aromatic aldehydes considered somewhat slows down, but does not hinder, the acylation, except when arriving at really high-absorbing molecules, such as benzaldehydes with push-pull structure (the 4-dimethylamino derivative), or to polycondensed aromatic (*e.g.* naphthalenes, see Figure S1, ESI†). In the other cases the yield of benzoylation was little dependent on the aldehyde structure. As for the olefin used, α,β-unsaturated esters such as maleate **2a** and crotonate **2d** showed to be the best acyl radical trap for an efficient and clean reaction. α,β-Unsaturated ketones (*e.g.* **2c**, **2e**), however, are likewise good reaction partners providing that their concentration does not exceed 0.1 M. Apart is the case of nitrile **2h**, from which negligible yield of the end aromatic ketones are obtained in most cases. This piece of evidence, along with the fact that direct irradiation of the aldehydes in the absence of the catalyst did not lead to significant reaction on the time scale considered, support the role of TBADT as shown in Scheme 10. Both key steps, H abstraction from the aldehydes and benzoylation of the alkenes level to about the same rate at the relatively high concentration used (*ca.* 0.1 M for both reagents).

The reaction is distinguished by several favorable features. In contrast to many radical processes, no toxic or foul-smelling additives (such as a tin hydride or a thiol[13]) were required. Since an ArC(=O)–H rather than an ArC(=O)–X bond is cleaved, no competitive addition of the X radical to the olefin occurs and thus no incorporation of that group in the end product (in contrast to what commonly observed with acyl tellurides).[6] The acylation yields were mostly moderate. In many cases MeCN was employed as the solvent; aqueous acetone, however, was likewise satisfactory in several cases, though not with enones. For the environmental point of view, the process seemed more desirable than competing radicalic processes[29] that make use of *toxic* organoselenium compounds.

In fact, atom economy is good since *ca.* equimolar amounts of the two reagents are used and TBADT is present in 2% molar amount. Moreover, the method is simple since solutions were irradiated in quartz tubes with no need of stirring. As for the last point, 366 nm irradiation could be conveniently adopted in all the synthesis described in this work and in the most favourable cases the aldehyde concentration could be raised up to 0.2 M.

The end products are versatile 1,4 difunctionalized compounds. 1,4 Diketones, in particular, find large application in the synthesis of five membered rings, such as cyclopentenones, furans, pyrroles, thiophenes and related compounds.[30] Pyridine derivatives are likewise useful intermediates; in particular ketonitrile **14** has been used as intermediate for the synthesis of Myosmine (a nicotiana alkaloid)[31a] or nicotine-2-carboxamide[31b] and related derivatives of **15** were detected as nicotine[31c] or tobacco-specific nitrosamine[31d] metabolites.

Experimental section

General

NMR spectra were recorded on a 300 MHz spectrometer. The structure attributions were made on the basis of ^{1}H and ^{13}C NMR, as well as DEPT experiments; chemical shifts are reported in ppm downfield from TMS. Acetonitrile (HPLC purity grade), acetone (purum for synthesis) and water (HPLC purity grade) were purchased from Carlo Erba and used as received. The photochemical reactions were performed by using nitrogen-purged solutions in quartz tubes (diameter: 1 cm). Compounds **1a–f**, **1h–j**, **2a–h** were commercially available, and were freshly distilled or crystallized before use.

Compound **1g** was prepared following the procedure previously described by Aizpurua *et al.*[32] starting from 4-hydroxybenzaldehyde (**1f**) and *tert*-butyldimethylsilyl chloride in the presence of 1,8-diazabicyclo[5.4.0]undec-7-ene (DBU) (solvent: benzene; temperature: 25 °C; reaction time: 90 min; purification by distillation under vacuum; yield: 95%; spectroscopic data of compound **1g** in accordance with literature data[33]).

General procedure for the photocatalyzed acylation of electron-poor olefins

A solution (30 mL) of an aromatic aldehyde (**1**, 0.1 M) and an olefin (**2**, 0.12 M) in the presence of 200 mg of TBADT[28] (2×10^{-3} M) in MeCN (except when otherwise noted) was poured in quartz tubes and purged for 10 min with nitrogen, serum capped and irradiated for 30 h with ten (emission centered at 310 nm) or twelve (366 nm) 15-W phosphor-coated lamps. The solvent was removed *in vacuo* from the photolyzed solution and the products isolated by purification of the residue by column chromatography (cyclohexane/ethyl acetate as eluents).

Synthesis of dimethyl 2-(4-methoxybenzoyl)succinate (3)

365 μL of 4-anisaldehyde (**1a**, 3.0 mmol, 0.1 M), 450 μL of dimethyl maleate (**2a**, 3.6 mmol, 0.12 M) and 200 mg of TBADT (0.06 mmol, 2×10^{-3} M) were dissolved in 30 mL of acetonitrile and irradiated at 310 nm. Purification of the raw product by column chromatography (silica gel, eluent: cyclohexane : ethyl acetate = 8 : 2) gave 315 mg of dimethyl 2-(4-methoxybenzoyl)succinate (**3**, 75%) as a colorless oil.

The same reaction, when performed using a 0.2 M amount of **1a** and a 0.25 M amount of **2a** gave **3** in 70% yield whereas when adopting an acetone-water (4 : 1 v/v) mixture as the solvent, afforded again **3** in 77% yield.

3: ^{1}H NMR ($CDCl_3$) d 3.0 (d, 2 H, J = 7 Hz), 3.6 (s, 6 H), 3.8 (s, 3 H), 4.8 (t, 1 H, J = 7 Hz), 6.9–8.0 (AA'BB' system, 4 H); ^{13}C NMR ($CDCl_3$) d 33.0 (CH_2), 48.8 (CH), 51.9 (CH_3), 52.6 (CH_3), 55.4 (CH_3), 113.8 (2 CH), 128.5, 131.2 (2 CH), 164.0, 169.3, 171.7, 192.2; IR, (neat) n/cm^{-1} 1739, 1677, 1602; Anal. Calcd. for $C_{14}H_{16}O_6$: C, 59.99; H, 5.75. Found: C, 60.1; H, 5.7.

Synthesis of 3-(4-methoxybenzoyl)cyclohexanone (4)

365 μL of 4-anisaldehyde (**1a**, 3.0 mmol, 0.1 M), 350 μL of 2-cyclohexen-1-one (**2b**, 3.6 mmol, 0.12 M) and 200 mg of TBADT (0.06 mmol, 2×10^{-3} M) were dissolved in 30 mL of acetonitrile and irradiated at 310 nm. Purification by column chromatography (silica gel, eluent: cyclohexane : ethyl acetate = 9 : 1) afforded 216 mg of 3-(4-methoxybenzoyl)cyclohexanone (**4**, 62%) as a colorless oil.

4: ^{1}H NMR ($CDCl_3$)[34] d 1.0–1.2 (m, 2 H), 1.8–2.0 (m, 2 H), 2.0–2.2 (m, 2 H), 2.4–2.5 (m, 2 H), 2.7–2.8 (m, 1 H), 3.8 (s, 3 H), 7.0–7.9 (AA'BB' system, 4 H); ^{13}C NMR ($CDCl_3$) d 24.6 (CH_2), 28.4 (CH_2), 40.8 (CH_2), 43.1 (CH), 44.6 (CH_2), 55.4 (CH_3), 113.9 (2 CH), 128.0, 130.6 (2 CH), 163.7, 198.9, 210.6; IR, (neat) n/cm^{-1} 1712, 1672, 1601; Anal. Calcd. for $C_{14}H_{16}O_3$: C, 72.39; H, 6.94. Found: C, 72.2; H, 7.1.

Synthesis of 3-(2-(4-methoxyphenyl)-2-oxoethyl)bicyclo[2.2.1]-heptan-2-one (5, *endo* isomer)

365 μL of 4-anisaldehyde (**1a**, 3.0 mmol, 0.1 M), 440 μL of 3-methylenebicyclo[2.2.1]heptan-2-one (**2c** - 3-methylene-2-norbornanone -, 3.6 mmol, 0.12 M) and 200 mg of TBADT (0.06 mmol, 2×10^{-3} M) were dissolved in 30 mL of acetonitrile and irradiated at 310 nm. Purification by column chromatography (silica gel, eluent: cyclohexane : ethyl acetate = 9 : 1) yielded 205 mg of 3-(2-(4-methoxyphenyl)-2-oxoethyl)bicyclo[2.2.1]heptan-2-one (**5**, 53%, *endo* isomer) as a colorless oil which solidified upon standing (mp 81–84 °C). The same reaction, when performed using an acetone-water (4 : 1 v/v) mixture as the solvent, afforded again **5** in 39% yield.

5: ^{1}H NMR ($CDCl_3$) d 1.3–1.8 (m, 4 H), 1.9–2.0 (m, 2 H), 2.7–2.9 (m, 4 H), 3.3 (dd, 1 H, J = 17, 2 Hz), 3.8 (s, 3 H), 6,9–8,0 (AA'BB' system, 4 H); ^{13}C NMR ($CDCl_3$) d 21.3 (CH_2), 25.6 (CH_2), 34.5 (CH_2), 37.2 (CH_2), 38.9 (CH), 49.8 (CH), 50.0 (CH), 55.4 (CH_3), 113.7 (2 CH), 129.5, 130.2 (2 CH), 163.5, 196.6, 219.3; IR, (KBr) n/cm^{-1} 1737, 1676, 1601; Anal. Calcd. for $C_{16}H_{18}O_3$: C, 74.39; H, 7.02. Found: C, 74.2; H, 7.0. The ^{1}H NMR spectrum was recorded also in C_6D_6 (see text) d 1.14 (bd, 1H, J = 10 Hz), 1.25–1.50 (m, 5H), 2.49 (m, 1H), 2.71 (dd, 1 H, J = 17.5, 10 Hz), 2.72 (m, 1H), 2.88 (m, 1H), 3.30 (s, 3 H), 3.50 (dd, 1 H, J = 17.5, 3 Hz), 6.73 and 7.95 (AA'BB' system, 4 H).

Synthesis of methyl 3-methyl-4-oxo-4-phenylbutanoate (6)

305 μL of benzaldehyde (**1b**, 3.0 mmol, 0.1 M), 385 μL of methyl crotonate (**2d**, 3.6 mmol, 0.12 M) and 200 mg of TBADT (0.06 mmol, 2×10^{-3} M) were dissolved in 30 mL of acetonitrile and irradiated at 310 nm. After purification by column chromatography (silica gel, eluent: cyclohexane : ethyl acetate = 9 : 1), 111 mg of methyl 3-methyl-4-oxo-4-phenylbutanoate (**6**, 36%) were obtained as a colorless oil. The same reaction, when performed using an acetone–water (4 : 1 v/v) mixture as the solvent, afforded again **6** in 65% yield. Spectroscopic data of **6** in accordance with literature data.[35]

Synthesis of 1-(4-chlorophenyl)pentane-1,4-dione (7)

422 mg of 4-chlorobenzaldehyde (**1c**, 3.0 mmol, 0.1 M), 300 μL of methyl vinyl ketone (**2e**, 3.6 mmol, 0.12 M) and 200 mg of TBADT (0.06 mmol, 2×10^{-3} M) were dissolved in 30 mL of acetonitrile and irradiated at 310 nm. Purification of the residue by column chromatography (silica gel, eluent: cyclohexane : ethyl acetate = 9 : 1) gave 259 mg of 1-(4-chlorophenyl)pentane-1,4-dione (**7**, 82%)

as a colorless oil, which solidified upon standing (mp 69–71 °C, lit[33] 70–72 °C). The same reaction, when performed using an acetone–water (4 : 1 v/v) mixture as the solvent, afforded again **7** in 59% yield. Spectroscopic data of **7** in accordance with literature.[36]

Synthesis of methyl 4-(2-chlorophenyl)-4-oxobutanoate (8).[37]

340 μL of 2-chlorobenzaldehyde (**1d**, 3.0 mmol, 0.1 M), 325 μL of methyl acrylate (**2f**, 3.6 mmol, 0.12 M) and 200 mg of TBADT (0.06 mmol, 2×10^{-3} M) were dissolved in 30 mL of acetonitrile and irradiated at 310 nm. Purification by column chromatography (silica gel, eluent: cyclohexane : ethyl acetate = 9 : 1) yielded 187 mg of methyl 4-(2-chlorophenyl)-4-oxobutanoate (**8**, 55%) as a colorless oil.

8: ^{1}H NMR ($CDCl_3$) d 2.7 (t, 2 H, J = 7 Hz), 3.2 (t, 2 H, J = 7 Hz), 3.6 (s, 3 H), 7.1–7.3 (m, 3 H), 7.4–7.5 (m, 1 H); ^{13}C NMR ($CDCl_3$) d 28.1 (CH_2), 37.4 (CH_2), 51.7 (CH_3), 126.8 (CH), 129.1 (CH), 130.4 (CH), 130.7, 131.8 (CH), 138.6, 172.9, 200.9; IR, (neat) n/cm^{-1} 1737, 1702; Anal. Calcd. for $C_{11}H_{11}ClO_3$: C, 58.29; H, 4.89. Found: C, 58.3; H, 4.8.

Synthesis of methyl 4-oxo-4-*m*-tolylbutanoate (9)[38]

355 μL of 3-methylbenzaldehyde (**1e**, 3.0 mmol, 0.1 M), 325 μL of methyl acrylate (**2f**, 3.6 mmol, 0.12 M) and 200 mg of TBADT (0.06 mmol, 2×10^{-3} M) were dissolved in 30 mL of acetonitrile and irradiated at 310 nm. After purification of the residue by column chromatography (silica gel, eluent: cyclohexane : ethyl acetate = 9 : 1), 182 mg of methyl 4-oxo-4-*m*-tolylbutanoate (**9**, 58%) were obtained as a colorless oil.

9: ^{1}H NMR ($CDCl_3$) d 2.4 (s, 3 H), 2.8 (t, 2 H, J = 7 Hz), 3.3 (t, 2 H, J = 7 Hz), 3.8 (s, 3 H), 7.3–7.4 (m, 2 H), 7.8–7.9 (m, 2 H); ^{13}C NMR ($CDCl_3$) d 21.2 (CH_3), 27.9 (CH_2), 33.3 (CH_2), 51.7 (CH_3), 125.1 (CH), 128.4 (CH), 128.5 (CH), 133.9 (CH), 136.5, 138.3, 173.3, 198.1; IR, (neat) n/cm^{-1} 1740, 1687; Anal. Calcd. for $C_{12}H_{14}O_3$: C, 69.88; H, 6.84. Found: C, 70.0; H, 6.9.

Synthesis of 1-(4-(*tert*-butyldimethylsilyloxy)phenyl)pentane-1,4-dione (11)

709 mg of 4-(*tert*-butyldimethylsilyloxy)benzaldehyde (**1g**, 3.0 mmol, 0.1 M), 300 μL of methyl vinyl ketone (**2e**, 3.6 mmol, 0.12 M) and 200 mg of TBADT (0.06 mmol, 2×10^{-3} M) were dissolved in 30 mL of acetonitrile and irradiated at 366 nm. Purification by column chromatography (silica gel, eluent: cyclohexane : ethyl acetate = 9 : 1) afforded 372 mg of 1-(4-(*tert*-butyldimethylsilyloxy)phenyl)pentane-1,4-dione (**11**, 81%) as a colorless oil. When the reaction was performed by using 4-hydroxybenzaldehyde (**1f**) in place of **1**g, the consumption of the aldehyde was *ca.* 50% after 30 h irradiation. The formation of 1-(4-hydroxyphenyl)pentane-1,4-dione (**10**) was confirmed by GC-MS analysis: MS (m/z) 192 (10, M$^+$), 177 (20), 121 (100), 93 (10), 66 (10).

11: ^{1}H NMR ($CDCl_3$) d 0.2 (s, 6 H), 1.0 (s, 9 H), 2.2 (s, 3 H), 2.8 (t, 2 H, J = 7 Hz), 3.2 (t, 2 H, J = 7 Hz), 6.8–7.8 (AA'BB' system, 4 H); ^{13}C NMR ($CDCl_3$) d -4.5 (2 CH_3), 18.1 (C), 25.4 (3 CH_3), 29.9 (CH_3), 31.9 (CH_2), 36.9 (CH_2), 119.8 (2 CH), 130.1 (2 CH), 130.2 (C), 160.1 (C), 196.9, 207.2; IR, (neat) n/cm^{-1} 1719, 1681, 1600, 842; Anal. Calcd. for $C_{17}H_{26}O_3Si$: C, 66.62; H, 8.55. Found: C, 66.7; H, 8.5.

Synthesis of 3-(2-(3-oxobicyclo[2.2.1]heptan-2-yl)acetyl)-benzaldehyde (12, *endo* isomer)

402 mg of isophtalaldehyde (**1h**, 3.0 mmol, 0.1 M), 440 μL of 3-methylenebicyclo[2.2.1]heptan-2-one (**2c** - 3-methylene-2-norbornanone -, 3.6 mmol, 0.12 M) and 200 mg of TBADT (0.06 mmol, 2×10^{-3} M) were dissolved in 30 mL of acetonitrile and irradiated at 310 nm. Purification of the residue by column chromatography (silica gel, eluent: cyclohexane : ethyl acetate = 8 : 2) gave 300 mg of 3-(2-(3-oxobicyclo[2.2.1]heptan-2-yl)acetyl)benzaldehyde (**12**, 78%, *endo* isomer) as a colorless oil, which solidified upon standing (mp 72–74 °C).

12: ^{1}H NMR ($CDCl_3$) d 1.3–1.7 (m, 4 H), 1.8–2.0 (m, 2 H), 2.7–3.0 (m, 4 H), 3.3 (dd, 1 H, J = 17, 2 Hz), 7.7 (t, 1 H, J = 8 Hz), 8.1 (dt, 1 H, J = 8, 2 Hz), 8.3 (dt, 1 H, J = 8, 2 Hz), 8.5 (t, 1 H, J = 2 Hz), 10.1 (s, 1 H); ^{13}C NMR ($CDCl_3$) d 21.3 (CH_2), 25.7 (CH_2), 35.2 (CH_2), 37.2 (CH_2), 39.0 (CH), 49.5 (CH), 49.9 (CH), 129.2 (CH), 129.5 (CH), 133.4 (CH), 133.5 (CH), 136.6 (C), 137.2 (C), 191.3, 197.0, 218.8; IR, (KBr) n/cm^{-1} 1740, 1699; Anal. Calcd. for $C_{16}H_{16}O_3$: C, 74.98; H, 6.29. Found: C, 75.1; H, 6.3.

Synthesis of methyl 2-methyl-4-oxo-4-(thiophen-2-yl)butanoate (13)[39]

280 μL of thiophene-2-carbaldehyde (**1i**, 3.0 mmol, 0.1 M), 385 μL of methyl methacrylate (**2g**, 3.6 mmol, 0.12 M) and 200 mg of TBADT (0.06 mmol, 2×10^{-3} M) were dissolved in 30 mL of acetonitrile and irradiated at 366 nm. Purification of the residue by column chromatography (silica gel, eluent: cyclohexane : ethyl acetate = 95 : 5) yielded 162 mg of methyl 2-methyl-4-oxo-4-(thiophen-2-yl)butanoate (**13**, 51%) as a colorless oil.

13: ^{1}H NMR ($CDCl_3$) d 1.2 (d, 3 H, J = 7 Hz), 2.9–3.5 (2 H, AB part of an ABX system), 3.0–3.2 (X part of an ABX system), 3.7 (s, 3 H), 7.1 (m, 1 H), 7.7 (m, 1 H), 7.8 (m, 1 H); ^{13}C NMR ($CDCl_3$) d 17.1 (CH_3), 34.8 (CH), 42.3 (CH_2), 51.8 (CH_3), 128.0 (CH), 131.9 (CH), 133.6 (CH), 143.7 (C), 176.1, 190.8; IR, (neat) n/cm^{-1} 1735, 1634; Anal. Calcd. for $C_{10}H_{12}O_3S$: C, 56.58; H, 5.70. Found: C, 56.6; H, 5.6.

Synthesis of 4-oxo-4-(pyridin-3-yl)butanenitrile (14)

280 μL of pyridine-3-carbaldehyde (**1j**, 3.0 mmol, 0.1 M), 235 μL of acrylonitrile (**2h**, 3.6 mmol, 0.12 M) and 200 mg of TBADT (0.06 mmol, 2×10^{-3} M) were dissolved in 30 mL of acetonitrile and irradiated at 310 nm. Purification by column chromatography (silica gel, eluent: cyclohexane : ethyl acetate = 1 : 1) gave 115 mg of 4-oxo-4-(pyridin-3-yl)butanenitrile (**14**, 48%) as a colorless oil, which solidified upon standing (mp 65–67 °C, lit[40] 74 °C). Spectroscopic data of **14** in accordance with literature data.[40]

Synthesis of methyl 4-oxo-4-(pyridin-3-yl)butanoate (15)

280 μL of pyridine-3-carbaldehyde (**1j**, 3.0 mmol, 0.1 M), 325 μL of methyl acrylate (**2f**, 3.6 mmol, 0.12 M) and 200 mg of TBADT (0.06 mmol, 2×10^{-3} M) were dissolved in 30 mL of acetonitrile and irradiated for 30 h at 310 nm. Purification of the residue by column chromatography (silica gel, eluent: cyclohexane : ethyl acetate = 6 : 4) yielded 119 mg of methyl 4-oxo-4-(pyridin-3-yl)butanoate

(**15**, 41%) were obtained as a colorless oil, which solidified upon standing (mp 69–71 °C).

15: ^{1}H NMR ($CDCl_3$)[41] d 2.8 (t, 2 H, J = 7 Hz), 3.3 (t, 2 H, J = 7 Hz), 3.7 (s, 3 H), 7.4 (dd, 1 H, J = 8, 4 Hz), 8.2 (dt, 1 H, J = 8, 2 Hz), 8.8 (dd, 1 H, J = 4, 2 Hz), 9.2 (d, 1 H, J = 2 Hz); ^{13}C NMR ($CDCl_3$)[41] d 27.6 (CH_2), 35.5 (CH_2), 51.8 (CH_3), 123.5 (CH), 131.7 (C), 135.2 (CH), 149.5 (CH), 153.6 (CH), 172.9, 196.9; IR, (neat) n/cm^{-1} 1734, 1686; Anal. Calcd. for $C_{10}H_{11}NO_3$: C, 62.17; H, 5.74. Found: C, 62.2; H, 5.8.

Acknowledgements

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