EurJOC European Journal of Organic Chemistry

FULL PAPER

DOI: 10.1002/ejoc.201402447

Ruthenium-Catalyzed Synthesis of 1,2-Diketones from Alkynes

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Keywords: Synthetic methods / Oxidation / Ruthenium / Alkynes / Green chemistry

The ruthenium-catalyzed synthesis of 1,2-diketones through the oxidation of alkynes by using sodium hypochlorite has been investigated. RuO_4 was generated in situ from inexpensive $RuCl_3 \cdot xH_2O$, and NaOCl as the oxidant demonstrated high performance at room temperature in the solvent diethyl carbonate. A variety of diketones were prepared in good yields by using this environmentally friendly procedure.

Introduction

1,2-Diketones are useful building blocks in organic synthesis, especially the synthesis of heterocyclic compounds of biological interest.[1] 1,2-Dicarbonyl compounds are also precursors for the syntheses of N-heterocyclic carbenes (NHC), a prominent class of ligands in organometallic chemistry and catalysis.[2] During the past 15 years, many examples of catalytic syntheses of 1,2-diketones have emerged, and in particular the oxidation of internal alkynes has received the most attention, because a wide variety of these substrates can be obtained through Sonogashira cross-coupling reactions. These catalytic methods demonstrate undeniable progress, as these protocols are environmentally more friendly than stoichiometric oxidation protocols that employ, for instance, thallium, manganese, chromium, or mercury salts.[3]

A variety of transition metals have been used for the oxidation of alkynes into 1,2-diketones. Rhenium-[4] and palladium-catalyzed[5] processes that employ either hydrogen peroxide, dioxygen, sulfoxides, or pyridine *N*-oxide as the oxidant have been reported. These catalysts generally perform very well with diarylalkynes, but their procedures require high catalyst loadings (5–10 mol-%) and/or high temperatures (60–140 °C).[6] An interesting Au/Ag catalytic system that uses diphenyl sulfoxide as the oxidant was recently reported as an efficient system for the synthesis of benzil derivatives and α-oxo imides.[7] However, the best results were obtained in refluxing dichloroethane, a solvent that is no longer used by the pharmaceutical industry.[8] Iron catalysts have been reported since Sawyer's early work in 1990,[9,10] and recently $FeCl_3$ (5 mol-%)/H_2O_2 was found to be an efficient catalyst for a room-temperature oxidation of electron-rich diarylalkynes.[11] Recently, an interesting copper catalyst was disclosed that operates under mild conditions with O_2/H_2O as the oxidant. However, the use of Selectfluor to generate the active catalyst might hamper this approach.[12] Ruthenium catalysts, in particular RuO_4, play a major role in oxidation catalysis.[13] In fact, with regard to the oxidation of alkynes to diketones, a survey of the literature shows that the RuO_4/$NaIO_4$ oxidation of an alkyne to a diketone is the most widespread procedure,[14] despite the requirement of a highly toxic solvent (CCl_4) and oxidant. For these reasons, decreasing the environmental impact of Ru-catalyzed oxidation reactions is of great interest. In 2010, Wan reported a very efficient catalyst that was composed of $[RuCl_2(p\text{-cymene})]_2$ (0.001 mol-%)/I_2 (10 mol-%) and used *tert*-butyl hydroperoxide (TBHP) as the oxidant.[15] However, this system required several hours in dioxane at 80 °C. Later, the same group reported a room-temperature catalytic process that consisted of a complex mixture of $[RuCl_2(p\text{-cymene})]_2$, 2,2,6,6-tetramethyl-1-piperidinyloxy (TEMPO), Oxone, and $NaHCO_3$ in nitromethane and water as the reaction media.[16]

All these examples demonstrate that the oxidation of alkynes to 1,2-diketones still suffers in many cases from harsh conditions, high catalyst loadings, and the use of oxidants and solvents that have a high environmental impact. Herein, we present our studies that are aimed at decreasing the environmental impact of the ruthenium-catalyzed oxidation of alkynes. In particular, we have focused on the use of carbonate solvents and sodium hypochlorite as the oxidant.

Results and Discussion

In our ongoing efforts on the subject of sequential transformation reactions that involve an initial metathesis transformation, we have been investigating tandem metathesis/oxidation reactions. Although our initial goals were not

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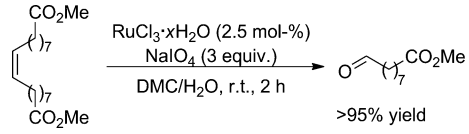
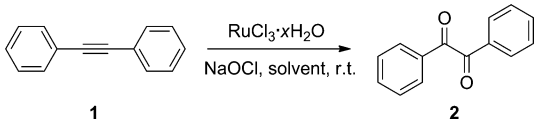
Supporting information for this article is available on the WWW under http://dx.doi.org/10.1002/ejoc.201402447.

achieved, we observed, as reported by Dragojlovic,[17] that dimethyl carbonate (DMC), a solvent recently introduced as a greener alternative to toluene and dichloromethane in olefin metathesis transformations,[18,19] was truly compatible with the oxidants in our studies.[20] This is especially highlighted by the high yielding oxidative cleavage of an alkene to an aldehyde, a reaction that is usually carried out in CCl_4/H_2O (see Scheme 1).



Scheme 1. Oxidative cleavage of alkene in DMC/H_2O.

As a result, we turned our attention to the $RuCl_3{\cdot}xH_2O$-catalyzed oxidation of diphenylacetylene (tolane) and employed DMC as the solvent (see Scheme 2). NaOCl was initially determined to be the "greenest" oxidant that can be used without special equipment,[21] as H_2O_2 is not an appropriate oxidant to generate RuO_4 from $RuCl_3{\cdot}xH_2O$.



Scheme 2. $RuCl_3{\cdot}xH_2O$/NaOCl oxidation of tolane (**1**).

Initial attempts were carried out in DMC with a low catalyst loading of $RuCl_3{\cdot}xH_2O$ (0.5 mol-%) and 4 equiv. of sodium hypochlorite. Under these conditions, the reaction proceeded with full conversion, but diketone **2** was isolated in only 69% yield (see Table 1, Entry 1). Careful analysis of the reaction mixture showed the presence of benzoic acid, a side product that was previously encountered in several studies of the oxidation of alkynes, including an early report of the oxidation of an alkyne by using $RuO_2/NaOCl/CCl_4/H_2O$.[22] Reducing the excess amount of oxidant did not effectively suppress the formation of benzoic acid. In addition to benzoic acid, the dichloro derivative PhClC=CClPh was also detected by GC–MS analysis. The formation of a chlorinated product is often encountered when NaOCl is used, but this issue can be resolved by using a buffered solution with a pH > 10.[23] Indeed, when the reaction media was buffered at pH = 12, the formation of the chlorinated product was suppressed, and the yield of **2** increased (see Table 1, Entries 2 and 3). Water was not a suitable solvent for this reaction (see Table 1, Entry 4), but the replacement of dimethyl carbonate with diethyl carbonate (DEC) resulted in a reduction in the amount of the benzoic acid side product to give **2** in 86 and 82% yield after 4 and 2 h, respectively, at room temperature (see Table 1, Entries 7 and 8). Interestingly, no chlorinated product was formed when diethyl carbonate was used as the solvent. Further optimization attempts were carried out to improve the selectivity of the reaction. Hence, low-temperature experiments were performed (see Table 1, Entry 9). As expected, the reaction rate decreased, but benzoic acid was still detected. Decreasing the catalyst loading or altering the concentration of the reagents did not suppress the formation of benzoic acid either (see Table 1, Entries 10–12).

Table 1. Oxidation of tolane.[a]

Entry	Solvent	NaOCl [equiv.]	*t* [h]	Conversion [%][b]	Yield [%][c]
1	DMC	4	4	>98[d]	69
2	DMC	3	4	76	34
3[e]	DMC	3	4	65	51
4[f]	H_2O	4	4	0	0
5	DEC	4	4	>98[d]	86
6	DEC	2	4	46	n.d.[g]
7	DEC	3	4	>98[d]	86
8	DEC	3	2	>98	82
9[h]	DEC	3	8	46	n.d.[g,i]
10[j]	DEC	3	5.5	>98[d]	86
11[k]	DEC	3	2	62	39
12[l]	DEC	3	2	83	59
13[m]	DEC	3	2	0	0

[a] **1** (0.5 mmol), $RuCl_3{\cdot}3H_2O$ (0.5 mol-%), [**1**] = 0.1 M, room temp., argon. [b] Monitored by GC with hexadecane as the internal standard. [c] Isolated yields. [d] **1** was not detected by GC analysis. [e] Buffer solution was $Na_2HPO_4/NaOH$ (pH = 12). [f] No reaction. [g] n.d. = not determined. [h] T = 5 °C. [i] Benzoic acid was detected. [j] $RuCl_3{\cdot}3H_2O$ (0.1 mmol-%). [k] [**1**] = 0.5 M. [l] [**1**] = 0.02 M. [m] No catalyst.

Despite the accessibility and low cost of $RuCl_3{\cdot}xH_2O$, several ruthenium catalyst precursors, which include olefin metathesis catalysts, were evaluated to improve the catalytic performance. As shown in Table 2, none of the examined precursors yielded improved results. Of note, the complex $[RuCl_2(p\text{-cymene})]_2$, which afforded the best results under Wan's conditions,[16] did not reach the level of performance of $RuCl_3{\cdot}xH_2O$.

Table 2. Screening of catalyst precursors.[a]

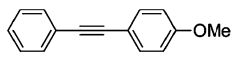
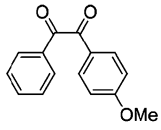
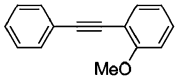
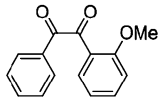
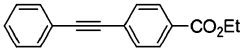
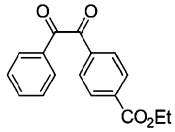
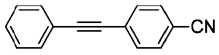
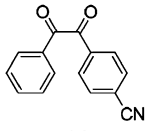
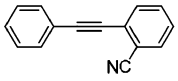
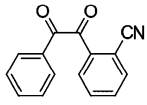
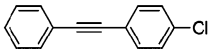
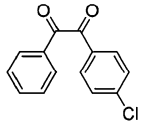
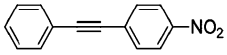
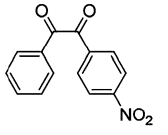
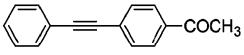
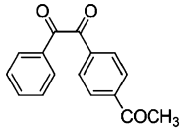
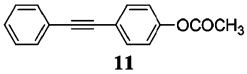
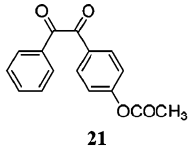
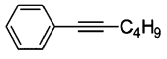
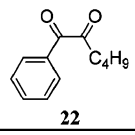
Entry	Catalyst	Conversion [%][b]	Yield [%][c]
1	$RuCl_3{\cdot}xH_2O$	>98[d]	82
2	$[Ru(COD)Cl_2]_n$[e]	90	79
3	$Ru(dppe)_2Cl_2$[e]	73[f]	n.d.[g]
4	$[RuCl_2(p\text{-cymene})]_2$[h]	>98[d]	74
5	$RuCl_2(p\text{-cymene})PPh_3$	77	68
6	$RuCl_2(PCy_3)_2(=CHPh)$[e]	90	79
7	$RuCl_2(SIMes)(PCy_3)(=CHPh)$[e]	68	n.d.[g]
8	$IrCl_3{\cdot}3H_2O$	0	0

[a] **1** (0.5 mmol), catalyst (0.5 mol-%), NaOCl (3 equiv.), DEC (5 mL), room temp., 2 h. [b] Determined by GC analysis with hexadecane as the internal standard. [c] Isolated yield. [d] **1** was not detected by GC analysis. [e] COD = 1,5-cyclooctadiene, dppe = 1,2-bis(diphenylphosphino)ethane, Cy = cyclohexyl, Mes = 2,4,6-trimethylphenyl. [f] After 6 h. [g] n.d. = not determined. [h] 0.25 mol-%.

The scope of the reaction was then explored with a variety of internal alkynes that were easily prepared by using a palladium-catalyzed Sonogashira coupling reaction. In particular, the effects of steric and electronic parameters were

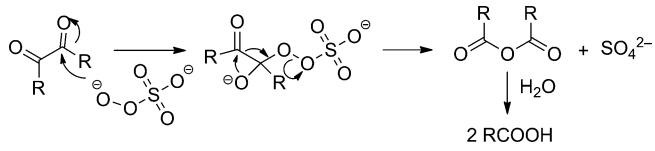
evaluated. Good yields were obtained by using diphenylacetylene derivatives that were substituted with an electron-donating group, which included a sterically hindered substrate. The situation was somewhat different with substrates that contained an electron-withdrawing group. In these cases (see Table 3, Entries 3–9), despite almost full conversion, the 1,2-diketones were isolated in moderate to good yields. These results can be rationalized by mechanistic considerations (see below). However, the lower reactivity of alkynes with electron-withdrawing substituents is a general problem that is observed in the oxidation of alkynes.[5,11,14d,16] Likewise, aliphatic alkynes usually display lower reactivity to lead to modest yields.

Table 3. Scope of the reaction.[a]

Entry	Alkyne	Product	Conv. [%][b]/ Yield [%][c]
1	 **3**	 **13**	>98/83
2	 **4**	 **14**	>98/71
3	 **5**	 **15**	96/63
4	 **6**	 **16**	96/61
5	 **7**	 **17**	80/42 77/44[d]
6	 **8**	 **18**	98/79
7	 **9**	 **19**	>98/53
8	 **10**	 **20**	90/83
9	 **11**	 **21**	70/64
10	 **12**	 **22**	66/33 (90/28)[d]

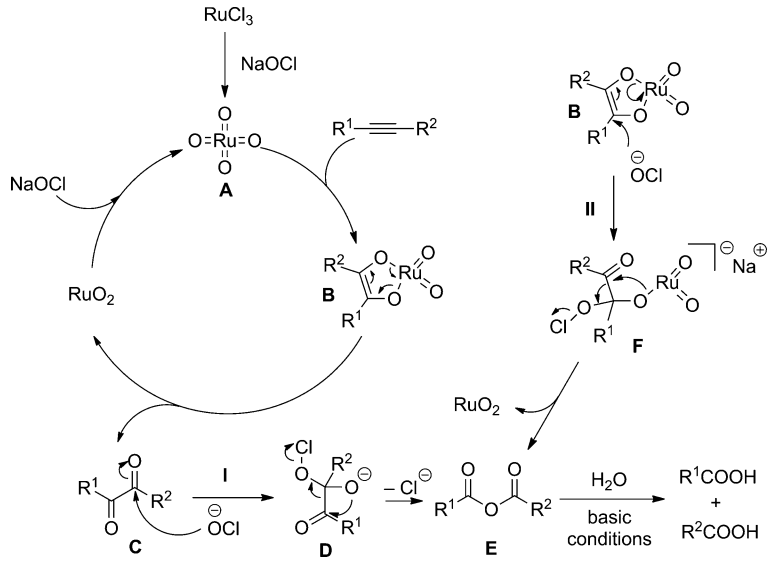
[a] Alkyne (0.5 mmol), $RuCl_3 \cdot 3H_2O$ (0.5 mol-%), NaOCl (3 equiv.), DEC (5 mL), room temp., 4 h. [b] Monitored by GC. [c] Isolated yield. [d] 8 h.

On the basis of the mechanism for the oxidation of alkenes, it is generally accepted that the RuO_4 oxidation of alkynes to 1,2-diketones involves a [3+2] cycloaddition.[13b] This hypothesis was confirmed in 2000 by Che et al. who presented the first evidence for a [3+2] cycloaddition in the oxidation of an alkyne by using a *cis*-dioxoruthenium(VI) complex.[24] In 2004, Yang et al. proposed a mechanism for the oxidation of alkynes to acids, in which the generated 1,2-diketone undergoes a Baeyer–Villiger-type oxidation by using peroxymonosulfate to give an acid anhydride, which upon hydrolysis leads to a carboxylic acid (see Scheme 3).[25]



Scheme 3. Suggested mechanism for the formation of carboxylic acids from diketones.

On the basis of these investigations, a tentative mechanism for the $RuCl_3 \cdot xH_2O$/NaOCl oxidation of alkynes is proposed (see Scheme 4). A [3+2] cycloaddition between the in situ generated RuO_4 and the alkyne generates metallacycle **B**, which undergoes a rapid electrocyclic fragmentation to give the desired 1,2-diketone **C** and RuO_2. Similar to Yang's mechanism (see Scheme 3), the cleavage of the diketone by using NaOCl proceeds through a nucleophilic addition of the hypochlorite ion to the carbonyl functional group to afford intermediate **D**. A Baeyer–Villiger-type rearrangement further leads to acid anhydride **E** and subsequently to the corresponding carboxylic acid. However, a test showed that benzil (**2**) was indeed converted into benzoic acid upon reaction with NaOCl under basic conditions with or without RuO_4.[26,27] These reactions were, however, very slow and could not account for the total formation of benzoic acid. Hence, other pathway(s) were considered, such as pathway **II**. Here, ruthenacycle **B** undergoes a Baeyer–Villiger-type rearrangement followed by the addition of NaOCl to afford **F** and subsequently furnish anhydride **E**. Both mechanisms **I** and **II** are in agreement with the experimental results, as the nucleophilic addition of NaOCl to a carbonyl or alkenyl group should be facilitated by an electron-withdrawing substituent on the aromatic ring (R^1 in Scheme 4) and, hence, lead to larger amounts of benzoic acid derivatives.



Scheme 4. Proposed mechanism for 1,2-diketone formation.

Conclusions

We have demonstrated that the ruthenium-catalyzed oxidation of alkynes to 1,2-diketones could be performed under environmentally friendly experimental conditions. In particular, the use of NaOCl as a unique oxidant along with the low catalyst loading of inexpensive $RuCl_3 \cdot xH_2O$ enabled the room-temperature synthesis of a variety of 1,2-diketones in diethyl carbonate. As encountered in most transition-metal-catalyzed oxidations of alkynes, the reaction performed particularly well when diarylalkynes with electron-rich substituents were employed, but performance dropped when electron-poor or aliphatic alkynes were employed. Despite this limitation, we believe that this protocol exhibits both a favorable balance between cost and environmental impact as well as good yields. Given the strengthening of regulations with regard to the use of toxic reagents and waste treatments, this protocol appears an interesting alternative to the widespread oxidation process that employs $NaIO_4$ in carbon tetrachloride.

Experimental Section

General Methods: All reactions were conducted under argon and by using standard Schlenk tube techniques, unless otherwise mentioned. DMC and DEC were distilled and stored over molecular sieves (4 Å) prior to use. NEt_3 was degassed. Organic reagents were obtained from commercial sources and used as received. $RuCl_3 \cdot xH_2O$ was purchased from Umicore Precious Metals. NMR spectroscopic data were recorded with a Bruker 400 MHz spectrometer, unless otherwise noted. The data are reported in ppm relative to the residual solvent $CHCl_3$ for ^1H NMR (δ = 7.26 ppm) and $CDCl_3$ for ^{13}C NMR (δ = 77.0 ppm). Coupling constants are reported in Hz. A GC-2014 Shimadzu gas chromatograph (Equity-5, 30 m × 0.25 mm) was used to monitor the reactions. LRMS were recorded with a GC–MS Shimadzu QP2010S apparatus. The products were purified by chromatography on a silica gel column using mixtures of petroleum ether and ethyl acetate as the eluent.

General Procedure A. Preparation of Internal Alkynes through Sonogashira Coupling Reaction: A mixture of phenylacetylene (561.3 mg, 5.5 mmol, 1.1 equiv.), a halobenzene derivative (5 mmol, 1.0 equiv.), $PdCl_2(PPh_3)_2$ (35.1 mg, 1 mol-%), and PPh_3 (26.23 mg, 2 mol-%) in NEt_3 (20 mL) was stirred at room temperature under argon for 5 min. CuI (9.5 mg, 1 mol-%) was added, the reaction vessel was sealed, and the mixture stirred at 60 °C overnight. The reaction mixture was filtered, and the filtrate was washed with Et_2O. The combined organic layers were washed with saturated NH_4Cl solution, HCl (1 N), NaOH (1 N), and brine and then dried with $MgSO_4$. After filtration, the solvent was removed in vacuo. The residue was purified by silica gel chromatography to afford the pure alkynes.

General Procedure B. Oxidation of Alkynes: A dry Schlenk tube was loaded with DEC (5 mL), hexadecane (gas chromatography standard, 20 μL) and the substrate (0.5 mmol). $RuCl_3 \cdot 3H_2O$ (0.5 mol-% in solution) and NaOCl (13 wt.-% solution, 3 equiv.) were subsequently added. The mixture was stirred at 25 °C (regulated oil-bath temperature) and monitored by gas chromatography. The reaction was quenched by the addition of a saturated aqueous solution of Na_2SO_3, and the resulting mixture was extracted with ethyl acetate (4 × 10 mL). The combined organic layers were dried with Na_2SO_4 and then concentrated, and the residue was purified by chromatography on a silica gel column (mixture of ethyl acetate and petroleum ether).

Procedure for the Oxidation of Benzil (2): In the first experiment, a dry Schlenk tube was loaded with DEC (5 mL), hexadecane (gas chromatography standard, 20 μL), and **2** (0.5 mmol). Then, NaOCl (13 wt.-% solution, 3 equiv.) was added. The mixture was stirred at 25 °C (regulated oil.bath temperature) for 4 h. The reaction was quenched by the addition of a saturated aqueous solution of Na_2SO_3, and the resulting mixture was extracted with ethyl acetate (4 × 10 mL). The combined organic layers were dried with Na_2SO_4. Conversions were below 6%. The aqueous phase was acidified to pH = 4 by the addition of HCl (1 N) and then extracted with EtOAc. No benzoic acid was detected in this organic phase. A second experiment was carried out by combining $RuCl_3 \cdot 3H_2O$ (0.5 mol-%) and NaOCl (3 equiv.) in DEC (5 mL) at room temp. for 2 h. Compound **2** (1 equiv.) was then added, and the reaction mixture was stirred at room temp. for 2 h. Again, conversions

were below 5%, and only trace amounts of benzoic acid were detected.

Characterization Data

1-Methoxy-4-(phenylethynyl)benzene (3): Compound **3** was prepared according to general procedure A to give a yellow solid (88% yield). NMR spectroscopic data are consistent with reported data.[28] ^{1}H NMR (400 MHz, $CDCl_3$): δ = 7.51 (dd, J = 8.0, 2.0 Hz, 2 H), 7.47 (d, J = 8.4 Hz, 2 H), 7.35–7.30 (m. 3 H), 6.88 (d, J = 8.8 Hz, 2 H), 3.83 (s, 3 H) ppm. ^{13}C NMR (101 MHz, $CDCl_3$): δ = 159.6, 133.0, 131.4, 128.3, 127.9, 123.6, 115.4, 114.0, 89.4, 88.1, 55.3 ppm. LRMS: calcd. for $C_{15}H_{12}O$ $[M]^{+\cdot}$ 208; found 208.

1-Methoxy-2-(phenylethynyl)benzene (4): Compound **4** was prepared according to general procedure A to give a yellow oil (70% yield). NMR spectroscopic data are consistent with reported data.[28] ^{1}H NMR (400 MHz, $CDCl_3$): δ = 7.58 (d, J = 6.8 Hz, 2 H), 7.50 (dd, J = 7.6, 1.2 Hz, 1 H), 7.40–7.25 (m, 4 H), 6.96–6.90 (m, 2 H), 3.92 (s, 3 H) ppm. ^{13}C NMR (101 MHz, $CDCl_3$): δ = 159.9, 133.5, 131.6, 129.7, 128.2, 128.0, 123.5, 120.4, 112.4, 110.7, 93.4, 85.7, 55.8 ppm. LRMS: calcd. for $C_{15}H_{12}O$ $[M]^{+\cdot}$ 208; found 208.

Ethyl 4-(Phenylethynyl)benzoate (5): Compound **5** was prepared according to general procedure A to give a yellow solid (90% yield). NMR spectroscopic data are consistent with reported data.[28] ^{1}H NMR (400 MHz, $CDCl_3$): δ = 8.03 (d, J = 8.3 Hz, 2 H), 7.59 (d, J = 8.3 Hz, 2 H), 7.56–7.54 (m, 2 H), 7.41–7.31 (m, 3 H), 4.39 (q, J = 7.1 Hz, 2 H), 1.41 (t, J = 7.1 Hz, 3 H) ppm. ^{13}C NMR (101 MHz, $CDCl_3$): δ = 166.1, 131.7, 131.5, 129.9, 129.4, 128.7, 128.4, 127.8, 122.7, 92.2, 88.7, 61.1, 14.3 ppm. LRMS: calcd. for $C_{17}H_{14}O_2$ $[M]^{+\cdot}$ 250; found 250.

4-(Phenylethynyl)benzonitrile (6): Compound **6** was prepared according to general procedure A to give a white solid (83% yield). NMR spectroscopic data are consistent with reported data.[28] ^{1}H NMR (400 MHz, $CDCl_3$): δ = 7.64 (d, J = 8.5 Hz, 2 H), 7.61 (d, J = 8.5 Hz, 2 H), 7.58–7.51 (m, 2 H), 7.39–7.36 (m, 3 H) ppm. ^{13}C NMR (101 MHz, $CDCl_3$): δ = 132.1, 132.0, 131.8, 129.1, 128.5, 128.2, 122.2, 118.5, 111.5, 93.8, 87.7 ppm. LRMS: calcd. for $C_{15}H_9N$ $[M]^{+\cdot}$ 203; found 203.

2-(Phenylethynyl)benzonitrile (7): Compound **7** was prepared according to general procedure A to give a yellow oil (82% yield). NMR spectroscopic data are consistent with reported data.[28] ^{1}H NMR (400 MHz, $CDCl_3$): δ = 7.69–7.54 (m, 5 H), 7.47–7.32 (m, 4 H) ppm. ^{13}C NMR (101 MHz, $CDCl_3$): δ = 132.6, 132.3, 132.1, 132.0, 129.2, 128.4, 128.2, 127.2, 122.0, 117.5, 115.3, 96.0, 85.6 ppm. LRMS: calcd. for $C_{15}H_9N$ $[M]^{+\cdot}$ 203; found 203.

1-Chloro-4-(phenylethenyl)benzene (8): Compound **8** was prepared according to general procedure A to give a white solid (81% yield). NMR spectroscopic data are consistent with reported data.[28] ^{1}H NMR (400 MHz, $CDCl_3$): δ = 7.55–7.50 (m, 2 H), 7.46 (d, J = 8.5 Hz, 2 H), 7.37–7.31 (m, 5 H) ppm. ^{13}C NMR (101 MHz, $CDCl_3$): δ = 134.2, 132.8, 131.6, 128.7, 128.5, 128.4, 122.9, 121.8, 90.3, 88.2 ppm. LRMS: calcd. for $C_{14}H_9{}^{35}Cl$ $[M]^+$ 212; found 212; calcd. for $C_{14}H_9{}^{37}Cl$ $[M]^{+\cdot}$ 214; found 214 ($C_{14}H_9{}^{35}Cl/C_{14}H_9{}^{37}Cl$: 2.8).

1-Nitro-4-(phenylethynyl)benzene (9): Compound **9** was prepared according to general procedure A to give a yellow solid (85% yield). NMR spectroscopic data are consistent with reported data.[28] ^{1}H NMR (400 MHz, $CDCl_3$): δ = 8.21 (d, J = 8.8 Hz, 2 H), 7.66 (d, J = 8.8 Hz, 2 H), 7.58–7.55 (m, 2 H), 7.45–7.35 (m, 3 H) ppm. ^{13}C NMR (101 MHz, $CDCl_3$): δ = 147.0, 132.2, 131.8, 130.3, 129.3, 128.5, 123.6, 122.1, 94.7, 87.5 ppm. LRMS: calcd. for $C_{14}H_9NO_2$ $[M]^{+\cdot}$ 223; found 223.

1-[4-(2-Phenylethynyl)phenyl]ethanone (10): Compound **10** was prepared according to general procedure A to give a white solid (95% yield). NMR spectroscopic data are consistent with reported data.[7] ^{1}H NMR (400 MHz, $CDCl_3$): δ = 7.94 (d, J = 8.3 Hz, 2 H), 7.61 (d, J = 8.3 Hz, 2 H), 7.58–7.53 (m, 2 H), 7.40–7.35 (m, 3 H), 2.62 (s, 3 H) ppm. ^{13}C NMR (101 MHz, $CDCl_3$): δ = 197.2, 136.2, 131.7, 131.6, 128.8, 128.4, 128.3, 128.2, 122.7, 92.7, 88.6, 26.6 ppm. LRMS: calcd. for $C_{16}H_{12}O$ $[M]^{+\cdot}$ 220; found 220.

[4-(2-Phenylethynyl)phenyl] Acetate (11): Compound **11** was prepared according to general procedure A to give a white solid (89% yield). NMR spectroscopic data are consistent with reported data.[28] ^{1}H NMR (400 MHz, $CDCl_3$): δ = 7.56–7.52 (m, 4 H), 7.37–7.32 (m, 3 H), 7.10 (d, J = 8.4 Hz, 2 H), 2.31 (s, 3 H) ppm. ^{13}C NMR (101 MHz, $CDCl_3$): δ = 169.1, 150.5, 132.7, 131.6, 128.3, 128.3, 123.1, 121.7, 121.0, 89.4, 88.5, 21.1 ppm. LRMS: calcd. for $C_{16}H_{12}O_2$ $[M]^{+\cdot}$ 236; found 236.

Hex-1-yn-1-ylbenzene (12): Compound **12** was prepared according to general procedure A to give a light yellow oil (81% yield). NMR spectroscopic data are consistent with reported data.[28] ^{1}H NMR (400 MHz, $CDCl_3$): δ = 7.43 (d, J = 6.1 Hz, 2 H), 7.32–7.22 (m, 3 H), 2.44 (t, J = 6.9 Hz, 2 H), 1.68–1.60 (m, 2 H), 1.58–1.45 (m, 2 H), 0.99 (t, J = 7.1 Hz, 3 H) ppm. ^{13}C NMR (101 MHz, $CDCl_3$): δ = 131.5, 128.1, 127.4, 124.1, 90.4, 80.5, 30.8, 22.0, 19.1, 13.6 ppm. LRMS: calcd. for $C_{12}H_{14}$ $[M]^{+\cdot}$ 158; found 158.

1,2-Diphenylethane-1,2-dione (2): Compound **2** was prepared according to general procedure B to give a yellow solid (82% yield). NMR spectroscopic data are consistent with reported data.[5a,10b,15] ^{1}H NMR (400 MHz, $CDCl_3$): δ = 7.98 (d, J = 7.3 Hz, 4 H), 7.67 (t, J = 7.4 Hz, 2 H), 7.52 (m, 4 H) ppm. ^{13}C NMR (101 MHz, $CDCl_3$): δ = 194.7, 135.0, 133.2, 130.0, 129.2 ppm. LRMS: calcd. for $C_{14}H_{10}O_2$ $[M]^{+\cdot}$ 210; found 210.

1-(4-Methoxyphenyl)-2-phenylethane-1,2-dione (13): Compound **13** was prepared according to general procedure B to give a yellow oil (83% yield). NMR spectroscopic data are consistent with reported data.[15] ^{1}H NMR (400 MHz, $CDCl_3$): δ = 7.96 (m, 4 H), 7.63 (m, 1 H), 7.50 (m, 2 H), 6.98 (d, J = 8.1 Hz, 2 H), 3.88 (s, 3 H) ppm. ^{13}C NMR (101 MHz, $CDCl_3$): δ = 194.8, 193.2, 165.0, 134.7, 133.3, 132.4, 129.9, 129.9, 126.2, 114.4, 55.7 ppm. LRMS: calcd. for $C_{15}H_{12}O_3$ $[M]^{+\cdot}$ 240; found 240.

1-(2-Methoxyphenyl)-2-phenylethane-1,2-dione (14): Compound **14** was prepared according to general procedure B to give a yellow solid (71% yield). NMR spectroscopic data are consistent with reported data.[5a] ^{1}H NMR (400 MHz, $CDCl_3$): δ = 8.02 (dd, J = 7.6, 2.1 Hz, 1 H), 7.91 (d, J = 7.6 Hz, 2 H), 7.60–7.58 (m, 2 H), 7.52–7.45 (m, 2 H), 7.15–7.10 (m, 1 H), 6.93 (d, J = 8.4 Hz, 1 H), 3.56 (s, 3 H) ppm. ^{13}C NMR (101 MHz, $CDCl_3$): δ = 194.8, 193.5, 160.4, 136.5, 133.7, 132.9, 130.4, 129.2, 128.6, 123.8, 121.5, 112.3, 55.6 ppm. LRMS: calcd. for $C_{15}H_{12}O_3$ $[M]^{+\cdot}$ 240; found 240.

Ethyl 4-(2-Oxo-2-phenylacetyl)benzoate (15): Compound **15** was prepared according to general procedure B to give a yellow solid (63% yield). NMR spectroscopic data are consistent with reported data.[5a] ^{1}H NMR (400 MHz, $CDCl_3$): δ = 8.10 (d, J = 8.4 Hz, 2 H), 8.03 (d, J = 8.4 Hz, 2 H), 7.97 (dd, J = 7.3, 1.6 Hz, 2 H), 7.68 (m, 1 H), 7.53 (m, 2 H), 4.11 (q, J = 7.1 Hz, 2 H), 1.41 (t, J = 7.1 Hz, 3 H) ppm. ^{13}C NMR (101 MHz, $CDCl_3$): δ = 193.8, 193.7, 165.4, 136.0, 135.7, 135.1, 132.7, 130.0, 129.9, 129.7, 129.1, 61.6, 14.2 ppm. LRMS: calcd. for $C_{17}H_{14}O_4$ $[M]^{+\cdot}$ 282; found 282.

4-(2-Oxo-2-phenylacetyl)benzonitrile (16): Compound **16** was prepared according to general procedure B to give a yellow solid (61% yield). NMR spectroscopic data are consistent with reported data.[16] ^{1}H NMR (400 MHz, $CDCl_3$): δ = 8.08 (d, J = 8.5 Hz, 2

H), 7.987 (dd, J = 7.3, 1.6 Hz, 2 H), 7.81 (d, J = 8.5 Hz, 2 H), 7.70 (m, 1 H), 7.54 (m, 2 H) ppm. ^{13}C NMR (101 MHz, $CDCl_3$): δ = 193.0, 192.4, 135.9, 135.4, 132.7, 132.4, 130.2, 130.0, 129.2, 117.9, 117.5 ppm. LRMS: calcd. for $C_{15}H_9NO_2$ $[M]^{+\cdot}$ 235; found 235.

2-(2-Oxo-2-phenylacetyl)benzonitrile (17): Compound **17** was prepared according to general procedure B to give a yellow solid (42% yield). NMR spectroscopic data are consistent with reported data.[5a] ^{1}H NMR (400 MHz, $CDCl_3$): δ = 8.03 (d, J = 8.0 Hz, 2 H), 7.94–7.88 (m, 2 H), 7.80–7.60 (m, 3 H), 7.55 (m, 2 H) ppm. ^{13}C NMR (101 MHz, $CDCl_3$): δ = 192.1, 191.2, 135.6, 135.3, 135.1, 134.0, 132.7, 132.5, 132.3, 130.2, 129.2, 117.0, 112.0 ppm. LRMS: calcd. for $C_{15}H_9NO_2$ $[M]^{+\cdot}$ 235; found 235.

1-(4-Chlorophenyl)-2-phenylethane-1,2-dione (18): Compound **18** was prepared according to general procedure B to give a yellow solid (79% yield). NMR spectroscopic data are consistent with reported data.[16] ^{1}H NMR (400 MHz, $CDCl_3$): δ = 7.98–7.92 (m, 4 H), 7.67 (m, 1 H), 7.65–7.44 (m, 2 H) ppm. ^{13}C NMR (101 MHz, $CDCl_3$): δ = 193.9, 193.1, 141.6, 135.0, 132.8, 131.3, 131.2, 129.9, 129.4, 129.1 ppm. LRMS: calcd. for $C_{14}H_9{}^{35}ClO_2$ $[M]^+$ 244; found 244; calcd. for $C_{14}H_9{}^{37}ClO_2$ $[M]^{+\cdot}$ 246; found 246 ($C_{14}H_9{}^{35}ClO_2$/$C_{14}H_9{}^{37}ClO_2$: 3.0).

1-(4-Nitrophenyl)-2-phenylethane-1,2-dione (19): Compound **19** was prepared according to general procedure B to give a yellow solid (53% yield). NMR spectroscopic data are consistent with reported data.[16] ^{1}H NMR (400 MHz, $CDCl_3$): δ = 8.36 (d, J = 8.8 Hz, 2 H), 8.17 (d, J = 8.8 Hz, 2 H), 7.99 (d, J = 7.3 Hz, 2 H), 7.71 (m, 1 H), 7.55 (m, 2 H) ppm. ^{13}C NMR (101 MHz, $CDCl_3$): δ = 192.8, 192.0, 151.2, 137.3, 135.4, 132.4, 130.9, 130.0, 129.2, 124.1 ppm. LRMS: calcd. for $C_{14}H_9NO_4$ $[M]^{+\cdot}$ 255; found 255.

1-(4-Acetylphenyl)-2-phenylethane-1,2-dione (20): Compound **20** was prepared according to general procedure B to give a yellow solid (83% yield). NMR spectroscopic data are consistent with reported data.[7] ^{1}H NMR (400 MHz, $CDCl_3$): δ = 8.07 (m, 4 H), 7.98 (d, J = 7.2 Hz, 2 H), 7.69 (t, J = 7.4 Hz, 1 H), 7.53 (dd, J = 7.4, J = 7.4 Hz, 2 H), 2.66 (s, 3 H) ppm. ^{13}C NMR (101 MHz, $CDCl_3$): δ = 197.2, 193.7, 193.6, 141.3, 136.0, 135.1, 132.7, 130.1, 130.0, 129.1, 128.7, 26.9 ppm. LRMS: calcd. for $C_{16}H_{12}O_3$ $[M]^{+\cdot}$ 252; found 252.

4-(2-Oxo-2-phenylacetyl)phenyl Acetate (21): Compound **21** was prepared according to general procedure B to give a yellow solid (64% yield). NMR spectroscopic data are consistent with reported data.[29] ^{1}H NMR (400 MHz, $CDCl_3$): δ = 8.02 (d, J = 8.4 Hz, 2 H), 7.96 (d, J = 7.2 Hz, 2 H), 7.66 (t, J = 7.6 Hz, 1 H), 7.52 (m, 2 H), 7.28–7.23 (m, 2 H), 2.33 (s, 3 H) ppm. ^{13}C NMR (101 MHz, $CDCl_3$): δ = 194.2, 193.1, 168.5, 155.7, 134.9, 132.8, 131.6, 130.5, 129.9, 129.0, 122.3, 21.1 ppm. LRMS: calcd. for $C_{16}H_{12}O_4$ $[M]^{+\cdot}$ 268; found 268.

1-Phenylhexane-1,2-dione (22): Compound **22** was prepared according to general procedure B to give a yellow oil (33% yield). NMR spectroscopic data are consistent with reported data.[5a] ^{1}H NMR (400 MHz, $CDCl_3$): δ = 7.97 (d, J = 7.8 Hz, 2 H), 7.62 (m 1 H), 7.50–7.45 (m, 2 H), 2.87 (t, J = 7.4 Hz, 2 H), 1.68 (m, 2 H), 1.39 (m, 2 H), 0.94 (t, J = 7.3 Hz, 3 H) ppm. ^{13}C NMR (101 MHz, $CDCl_3$): δ = 203.5, 192.6, 134.5, 132.0, 130.1, 128.8, 38.5, 24.9, 22.3, 13.8 ppm. LRMS: calcd. for $C_{12}H_{14}O_2$ $[M]^{+\cdot}$ 190; found 190.

Supporting Information (see footnote on the first page of this article): ^{1}H and ^{13}C NMR spectra.

Acknowledgments

The authors are grateful to the Centre National de la Recherche Scientifique (CNRS) and the Ministère de l'Enseignement Supérieur et de la Recherche for their support. We thank the Fondation Rennes 1 for a grant to Y. M. The authors also thank the ADEME (Agence de l'Environnement et de la Maîtrise de l'Energie) and the Région Bretagne for a Ph.D. grant to A. D.

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Received: April 25, 2014
Published Online: July 7, 2014

