ChemPubSoc Europe

DOI: 10.1002/ejoc.201701684

EurJOC European Journal of Organic Chemistry

Full Paper

Microwave-Promoted Synthesis

A One-Pot Synthesis of Pyranocoumarins Through Microwave-Promoted Propargyl Claisen Rearrangement/Wittig Olefination

Bernd Schmidt*[a] and Christiane Schultze[a]

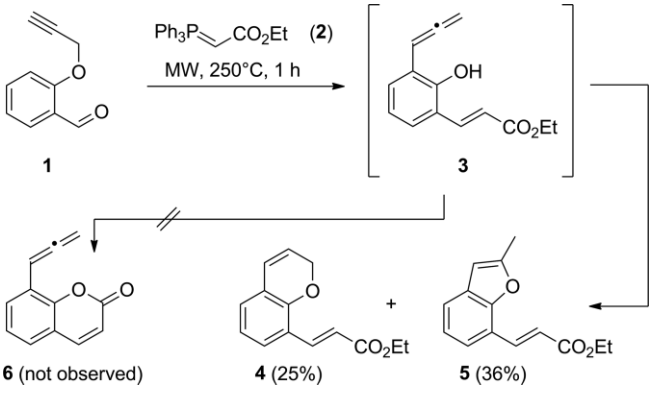
Abstract: The reaction between propargyl ethers of hydroxybenzaldehydes and the ylide ethyl (triphenylphosphoranylidene)acetate was carried out under microwave irradiation to regioselectively afford angular pyranocoumarins. The chromene and coumarin heterocyclic scaffolds were simultaneously formed in the same synthetic step without changing the reaction conditions. The natural products seselin, braylin, and dipetalolactone were among the products synthesized by this method.

Introduction

Microwave irradiation as an alternative energy supply for organic reactions was first reported in the 1980s with the use of the domestic microwave oven.[1] Since then, the number of reports of organic transformations carried out under microwave irradiation — now exclusively performed in dedicated microwave reactors — has increased dramatically to more than 1000 per year. Compared with conventional heating, microwave irradiation has the potential to reduce reaction times by heating mixtures in closed systems at temperatures greater than the boiling point of the solvent (superheating), and shorter times may result in fewer side products. Thus, microwave irradiation may be the chosen method if reactions that use conventional heating are excessively slow.[2]

One-pot processes and tandem reactions[3,4] often achieve their high selectivity by the successive addition of reagents or catalysts in due course.[5] Such reaction protocols are, however, not practical in a microwave reactor under closed conditions, as the addition of catalysts, reagents, or solvents over the course of a synthesis implies that microwave irradiation is interrupted and the reaction vessel is cooled and opened. Alternatively, special pumps can be used to inject reagents into sealed systems without interrupting the microwave irradiation or the internal pressure. Unfortunately, microwave-assisted reactions that are conducted in an open vessel do not provide the positive effects normally expected of microwave heating, as superheating the reaction mixture is not possible[6] and nonthermal microwave effects are no longer believed to play a substantial role in these transformations.[7] For these reasons, microwave-promoted one-pot and tandem reactions are more conveniently performed if the reaction conditions tolerate the presence of all reagents and catalysts at the outset. Recent examples include a Suzuki coupling/nitro reduction sequence[8] and a tandem imination/cycloisomerization reaction for the synthesis of 3-benzylisoquinolines.[9] In contrast, the carbonyl alkynylation/Sonogashira coupling/cyclization sequence for the synthesis of indoles — although synthetically attractive — requires the interruption of the microwave irradiation and addition of further reagents and catalysts.[10]

Over the past few years, we have contributed to the field of microwave-promoted tandem reactions with the development of a Claisen rearrangement/oxa-Michael cyclization reaction sequence for the synthesis of substituted chromones and chroman-4-ones.[11] Various 8-allyl- and prenyl-substituted coumarins have been obtained by us[12] and others[13] through a tandem sequence that involves a Claisen rearrangement of allyl phenyl ethers, a Wittig olefination, *E*/*Z* isomerization, and cyclization reactions. During a latter study, we also investigated an example of a tandem propargyl Claisen rearrangement/Wittig olefination reaction sequence (Scheme 1). Propargyl ether **1** was converted into a mixture of cinnamates **4** and **5** when irradiated in the presence of stable ylide **2**. The formation of **5** as the major product is remarkable, because the primary products of thermal propargyl Claisen rearrangements, that is, the *ortho*-



Scheme 1. Previous investigation of a propargyl Claisen rearrangement/Wittig olefination sequence by our group (MW = microwave)..[12]

[a] *Institut für Chemie, Universität Potsdam, Karl-Liebknecht-Strasse 24-25, 14476 Potsdam-Golm, Germany*
E-mail: bernd.schmidt@uni-potsdam.de
http://www.chem.uni-potsdam.de/groups/schmidt/

Supporting information and ORCID(s) from the author(s) for this article are available on the WWW under https://doi.org/10.1002/ejoc.201701684.

allenyl phenols, normally cyclize selectively to give chromenes.[14,15] Chromenes have also been obtained from propargyl ethers under microwave irradiation[16] and in the presence of gold catalysts.[17] The alternative 5-*endo* cyclization pathway has only been reported in unusual cases (e.g., in the presence of Ag salts[18] or fluoride bases[19]). Notably, no coumarins such as **6** or its isomers were detected in our case, which suggests that the cyclization proceeding through the allenyl substituent is much faster than *E*/*Z* isomerization and lactonization.

In general, coumarins are widespread secondary plant metabolites.[20] In plants, they act as fungal pathogen inhibitors, insect repellants, growth regulators, and UV light absorbers.[21] In mammals, numerous bio- and pharmacological activities, such as anti-inflammatory,[22] anticoagulant, antibacterial, antiviral, antifungal, anticancer,[23] and neuroprotective[24] properties, have been reported for natural and synthetic coumarins.[25] A classification scheme based on structural scaffolds has also been proposed.[25] Pyranocoumarins, in which a pyran ring (most commonly a 2,2-dimethyl-substituted pyran) is annulated to the benzene ring of a coumarin, is an important class of this scheme. Other classes include simple coumarins (that have aliphatic or hydroxy groups on the benzene ring), furanocoumarins, and coumarins with substituents on the pyrone ring. The pyranocoumarins are further subdivided into linear [e.g., xanthyletin (**7**)] and angular representatives [e.g., seselin (**8**),[26] braylin (**9**),[27] dipetalolactone (**10**),[28] Figure 1].

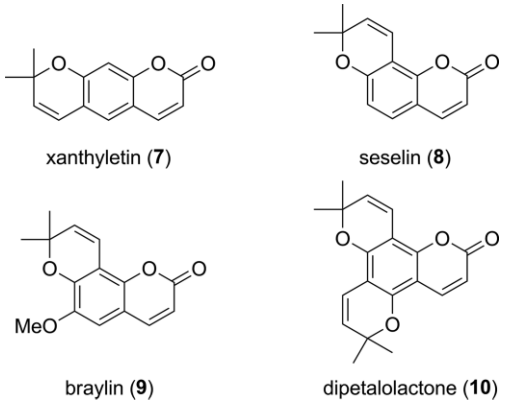


Figure 1. Representative examples of linear and angular pyranocoumarins.

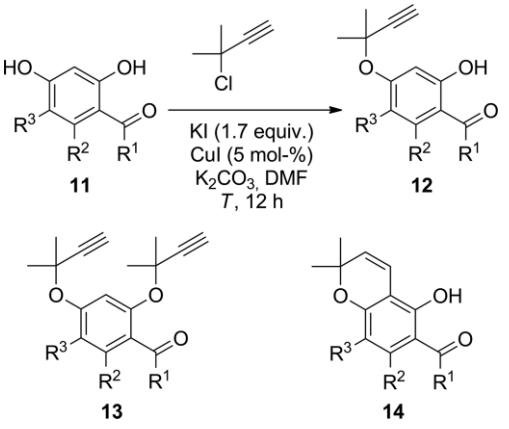
Recent syntheses of pyranocoumarins, inter alia seselin (**8**), involve catalyst-free multicomponent[29] or two-step condensation reactions[28] that start from phloroglucinol, ring-closing metathesis reactions at preformed coumarin scaffolds,[30] cobalt-catalyzed cyclizative carbonylations of vinylphenols,[31] cyclizative Wittig olefinations of 6-formyl chromenes,[32] or oxidative selenium-mediated cyclizations of prenylated hydroxycoumarins.[33] Most syntheses of seselin and structurally related angular pyranocoumarins are prepared from preformed coumarins, either by thermal propargyl Claisen rearrangements of the corresponding coumarin 2,2-dimethylpropargyl ethers[34,35] or by acid-catalyzed condensations of hydroxycoumarins and acetals of senecialdehyde.[36] Microwave conditions have been used only in a limited number of pyranocoumarin syntheses. In these cases, either a propargyl Claisen rearrangement of a preformed coumarin[37] or an intermolecular cyclizative condensation of a hydroxycoumarin and a C3 building block were investigated under microwave irradiation.[38]

In continuation of our investigations into the microwave-promoted synthesis of 8-prenyl coumarins,[12] we have pursued a related synthetic approach to pyranocoumarins that relies on the combination of a propargyl Claisen rearrangement and intermolecular Wittig olefination reaction. We are aware of one report by Mali et al. that describes such a one-pot sequence under thermal conditions. These authors report that heating monopropargyl dihydroxybenzaldehydes in the presence of ylide **2** at 180–190 °C for prolonged periods of time (3 to 10 h) yielded angular pyranocoumarins, such as seselin (**8**) in 55 % yield.[39,40] The objective herein is to identify and evaluate suitable microwave conditions for a one-pot propargyl Claisen rearrangement/Wittig-olefination/cyclization reaction sequence and determine whether the high selectivity of the rearrangement step towards angular pyranocoumarins is maintained in a closed vessel under superheating microwave conditions. Some reported observations in the literature regarding the syntheses of microwave-promoted pyranocoumarin under these conditions point to the predominant formation of linear byproducts.[38,41]

Results and Discussion

The results for the preparation of the 1,1-dimethylpropargyl aryl ethers **12** are summarized in Table 1. We used an adaptation of a procedure that was previously published by Godrey et al.[42]

Table 1. Synthesis of aryl propargyl ethers **12**.

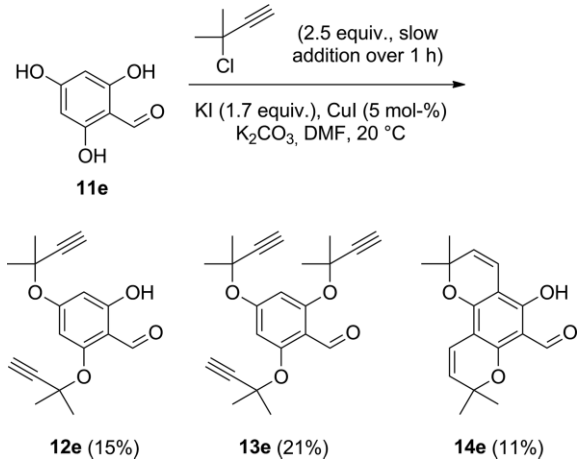


Entry	**11**	R^1	R^2	R^3	*T* [°C]	**12**	Yield [%]
1[a]	**11a**	CH_3	H	H	65	**12a**	29
2	**11a**	CH_3	H	H	20	**12a**	83
3	**11b**	H	H	H	20	**12b**	93
4	**11c**	Ph	H	H	20	**12c**	80
5[b]	**11d**	H	H	OCH_3	20	**12d**	<5
6[c]	**11d**	H	H	OCH_3	0	**12d**	14
7[d]	**11d**	H	H	OCH_3	0	**12d**	41

[a] Compound **14a** (17 %) was also formed as a product. [b] Compounds **13d** (36 %) and **14d** (10 %) were formed as additional products. [c] Compound **13d** (58 %) was formed as well. [d] Dimethylpropargyl chloride was slowly added over 1 h. Compound **13d** (35 %) was also produced.

and Mann and co-workers.[43] These authors reported that 1,1-dialkylpropargyl ethers were only obtained in synthetically useful yields if catalytic amounts of CuI salts were present. The Cu-catalyzed propargylation of phenols, which presumably proceeds through a cross-coupling mechanism,[42] was later used by Winssinger and co-workers in the synthesis of propargyl ether **12b**[16] and by Stratakis and co-workers for the preparation of starting materials for Au-catalyzed cycloisomerization reactions.[17]

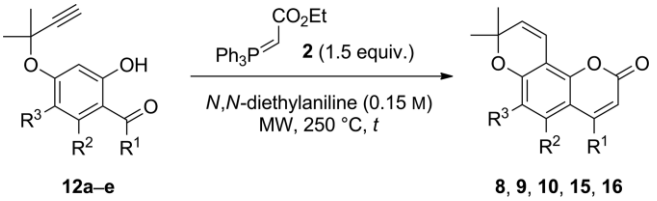
Under the original conditions by Mann and co-workers, the desired product **12a** was obtained in only 29 % yield along with considerable amounts of chromene **14a**, a product that resulted from a propargyl Claisen rearrangement (Table 1, Entry 1). The formation of this rearrangement product was fully suppressed, and the yield of **12a** increased to 83 % by lowering the reaction temperature to 20 °C (Table 1, Entry 2). These modified conditions were then applied to **11b** and **11c**, which resulted in the regioselective formation of monopropargyl ethers **12b** and **12c**, respectively, in good yields (Table 1, Entries 3 and 4). Unfortunately, the more electron-rich methoxy-substituted phenol **11d** did not undergo a reaction at ambient temperature to give the desired **12d** but only gave chromene **14d** and double propargylated product **13d** (Table 1, Entry 5). Lowering the reaction temperature to 0 °C completely suppressed the propargyl Claisen rearrangement, but the isolated yield of **12d** was still unsatisfactory (Table 1, Entry 6). The slow addition of the alkylating agent over 1 h, however, led to an increased yield of **12d** along with the formation of dipropargyl ether **13d** (Table 1, Entry 7). The synthesis of dipetalolactone precursor **12e** was troublesome because of the occurrence of a double propargyl Claisen rearrangement to give pyranochromene **14e** and threefold propargylation to provide **13e**. The separation of the three products was possible and allowed us to isolate sufficient quantities of **12e** to investigate the envisaged microwave-promoted one-pot conversion into the dipetalolactone (Scheme 2).



Scheme 2. Synthesis of dipetalolactone precursors (DMF = *N*,*N*-dimethylformamide).

The microwave-promoted one-pot sequence to give the pyranocoumarins was first investigated by starting from precursor **12a**. In the presence of 1.5 equiv. of ylide **2** and *N*,*N*-diethylaniline in a closed vessel at 250 °C under microwave irradiation, compound **12a** cleanly afforded pyranocoumarin **15**. After 10 min of reaction time, the starting material was fully consumed, and product **15** was isolated in 71 % yield (Table 2, Entry 1). Longer reaction times of 30 min (Table 2, Entry 2) and 1 h (Table 2, Entry 3) gave comparable yields, which verify the stability of the pyranocoumarin at the reaction temperature. Next, we examined whether microwave irradiation was indeed better than conventional heating. To this end, a solution of **12a** was heated to the same reaction temperature in a silicon oil bath for 1 h and 12 h, respectively. After 1 h, TLC analysis indicated virtually no conversion and the presence of unreacted starting material (Table 2, Entry 4). After 12 h, some formation of product **15** was observed, but substantial amounts of starting material were still present. Upon workup, compound **15** was isolated in a low yield of 28 % (Table 2, Entry 5). We were confident that our preferred reaction temperature of 250 °C could not be substantially lowered, because both our research group[12] and that of Pospíšil[13] recently found that *E*/*Z* isomerization of the intermediate cinnamates, a prerequesite for the cyclization into coumarin, does not efficiently proceed at temperatures lower than 200 °C. There is literature precedent for the conversion of preformed cinnamates into coumarins through an *E*/*Z* isomerization/cyclization sequence at temperatures below 100 °C, but this method requires the presence of air-sensitive trialkylphosphines as catalysts.[44] Nevertheless, we submitted **12a** under otherwise identical conditions to microwave irradiation at 200 °C for 1 h (Table 2, Entry 6). This resulted in complete consumption of the starting material but, not surprisingly, with very poor selectivity, as a complex mixture of

Table 2. Microwave-promoted one-pot propargyl Claisen rearrangement/Wittig olefination/cyclization reaction sequence.



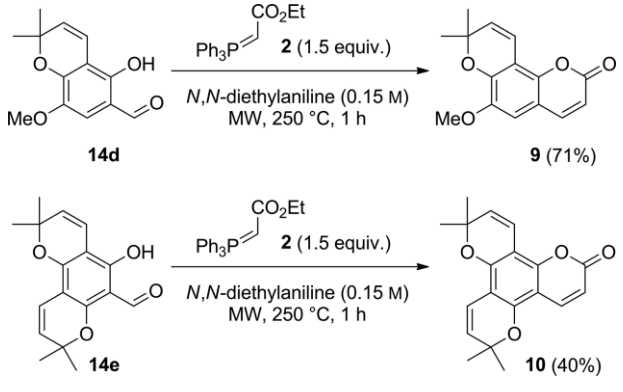
Entry	12	Product	R^1	R^2	R^3	*t* [min]	% Yield[a]
1	**12a**	**15**	CH_3	H	H	10	71
2	**12a**	**15**	CH_3	H	H	30	73
3	**12a**	**15**	CH_3	H	H	60	78
4[b]	**12a**	**15**	CH_3	H	H	60	–[c]
5[b]	**12a**	**15**	CH_3	H	H	720	28[d]
6[e]	**12a**	**15**	CH_3	H	H	60	–[f]
7	**12b**	**8**	H	H	H	10	66
8	**12b**	**8**	H	H	H	60	67
9	**12c**	**16**	Ph	H	H	10	54
10	**12c**	**16**	Ph	H	H	60	56
11	**12d**	**9**	H	H	OCH_3	10	75
12	**12d**	**9**	H	H	OCH_3	60	74
13	**12e**	**10**	H	$OCMe_2CH{=}CH$		10	45
14	**12e**	**10**	H	$OCMe_2CH{=}CH$		60	43

[a] Yields of isolated products are reported. Unless otherwise stated, full conversion was observed by TLC analysis. [b] Reaction mixture was heated to 250 °C with conventional heating (oil bath). [c] No conversion was observed. [d] Incomplete conversion (by TLC analysis) was observed. [e] Reaction was carried out under microwave irradiation at 200 °C. [f] Complex mixture of products resulted.

products was observed. We assume that the high reaction temperature of 250 °C ensures the rapid conversion into the stable pyranocoumarin **15** (see Table 2, Entry 3 and the discussion referring to this) through a defined order of steps, whereas at lower temperatures intermediates are formed that are prone to undefined side reactions.

We next applied the optimized conditions from Table 2, Entry 1 (i.e., 250 °C, 10 min of reaction time) to precursors **12b**–**12e**, and for a comparison, we also employed the conditions from Table 2, Entry 3 (250 °C, 60 min of reaction time). As a result, four other pyranocoumarins, including the natural products seselin (**8**, Table 2, Entries 7 and 8), braylin (**9**, Table 2, Entries 11 and 12), and dipetalolactone (**10**, Table 2, Entries 13 and 14) were formed. The latter product was obtained from **12e** proceeding through a double propargyl Claisen rearrangement/Wittig olefination/cyclization sequence. We also demonstrated that 4-aryl pyranocoumarins are also accessible through this sequence by the formation of product **16** (Table 2, Entries 9 and 10). Such phenyl coumarins represent another important class of naturally occurring coumarins. Although 4-aryl substituents and pyranoannulated systems are not found concurrently in natural products, 4-arylpyranocoumarin hybrids have been synthesized and biologically evaluated.[45–47] For all of the products listed in Table 2, Entries 7–14, full conversion into the corresponding pyranocoumarin was observed after 10 min. Irradiation for 1 h did not result in any notable decomposition of the products, which were obtained in yields similar to those resulting after an irradiation time of 10 min.

The isolation of chromenes **14** as side products during the Cu-catalyzed propargylation (Table 1 and Scheme 2) provided an opportunity to investigate the Wittig olefination and cyclization steps independently from the propargyl Claisen rearrangement (Scheme 3). To this end, compounds **14d** and **14e** were treated with the Wittig reagent under the standard microwave conditions as shown in Table 2, Entry 3. Interestingly, braylin (**9**) and dipetalolactone (**10**) were isolated by the two-step sequence in yields very similar to those obtained from the three-step sequence (Table 2, Entries 11–14). This observation suggests that the propargyl Claisen rearrangement proceeds with high selectivity and conversion, but that either the Wittig olefination or cyclization, which follow, is the rate-limiting step.



Scheme 3. Microwave-promoted Wittig olefination/cyclization sequence from preformed chromenes.

Conclusions

In summary, we described a microwave-promoted one-pot synthesis for angular pyranocoumarins by starting from propargyl ethers. The sequence proceeds through a single or double propargyl Claisen rearrangement, a Wittig olefination, an *E*/*Z* isomerization, and eventually a cyclization to give the coumarin scaffold. The utility of this synthetic method was demonstrated for the seselin, braylin, and dipetalolactone natural products.

Experimental Section

General Methods: All experiments were conducted in dry reaction vessels under dry nitrogen. Solvents were purified by standard procedures. The ^{1}H NMR spectroscopic data were obtained at 300 MHz in $CDCl_3$ with $CHCl_3$ (δ = 7.26 ppm) as an internal standard. Coupling constants are reported in Hz. The ^{13}C NMR spectroscopic data were recorded at 75 MHz in $CDCl_3$ with $CDCl_3$ (δ = 77.0 ppm) as an internal standard. IR spectra were recorded as ATR-FTIR (ATR = attenuated total reflectance) spectra. Wavenumbers ($\tilde{\nu}$) are reported in cm^{-1}. The intensities of the bands are defined as strong (s), medium (m), or weak (w). Low and high resolution mass spectral data were obtained by EI/TOF or ESI-TOF analysis. Microwave reactions were carried out in an Anton-Paar-monowave-300 reactor (monowave, maximum power 850 W, temperature control by IR sensor, vial volume: 20 mL). Starting material **11d** was synthesized according to a reported procedure.[48]

General Procedure for the Microwave-Promoted One-Pot Reaction Sequence: The appropriate propargyl ether **12** (1.00 mmol) was dissolved in *N*,*N*-diethylaniline (10 mL) in a vessel that was suited for microwave irradiation. Ylide **2** (522 mg, 1.50 mmol) was added, and the vessel was sealed. The reaction mixture was irradiated at 250 °C for 10 min in the dedicated microwave reactor. After cooling to ambient temperature, the mixture was diluted with ethyl acetate (50 mL), and the resulting mixture was washed with HCl (2 M aqueous solution, 3 × 30 mL). The organic layer was separated, dried with $MgSO_4$, and filtered. The filtrate was concentrated, and the crude residue was purified by column chromatography on silica gel [hexanes/methyl *tert*-butyl ether (MTBE) mixtures of increasing polarity].

4,8,8-Trimethyl-2*H*,8*H*-pyrano[2,3-*f*]chromen-2-one (15):[46] By following the general procedure, **12a** (218 mg, 1.00 mmol) provided **15** (172 mg, 0.71 mmol, 71 %) as a colorless solid; m.p. 119–121 °C. ^{1}H NMR (300 MHz, $CDCl_3$): δ = 7.33 (d, J = 8.7 Hz, 1 H), 6.88 (d, J = 10.1 Hz, 1 H), 6.73 (d, J = 8.7 Hz, 1 H), 6.10 (q, J = 1.1 Hz, 1 H), 5.71 (d, J = 10.1 Hz, 1 H), 2.36 (d, J = 1.1 Hz, 3 H), 1.46 (s, 6 H) ppm. ^{13}C NMR (75 MHz, $CDCl_3$): δ = 161.2, 156.2, 153.0, 149.6, 130.8, 124.6, 115.5, 113.7, 113.2, 111.7, 109.4, 77.6, 28.2, 18.9 ppm. IR (ATR): $\tilde{\nu}$ = 2975 (w), 1723 (s), 1624 (m), 1589 (s), 1435 (m), 1384 (s), 1373 (s), 1288 (s), 1212 (m), 1171 (s), 1112 (s), 1072 (s) cm^{-1}. HRMS (EI): calcd. for $C_{15}H_{14}O_3$ $[M]^+$ 242.0943; found 242.0949.

Seselin (8):[31] By following the general procedure, **12b** (204 mg, 1.00 mmol) provided **8** (151 mg, 0.66 mmol, 66 %) as a yellowish oil. ^{1}H NMR (300 MHz, $CDCl_3$): δ = 7.58 (d, J = 9.5 Hz, 1 H), 7.18 (d, J = 8.4 Hz, 1 H), 6.85 (d, J = 10.1 Hz, 1 H), 6.69 (d, J = 8.5 Hz, 1 H), 6.20 (d, J = 9.5 Hz, 1 H), 5.71 (d, J = 10.1 Hz, 1 H), 1.45 (s, 6 H) ppm. ^{13}C NMR (75 MHz, $CDCl_3$): δ = 161.1, 156.4, 150.2, 144.0, 130.9, 127.9, 115.1, 113.6, 112.7, 112.7, 109.4, 77.7, 28.2 ppm. IR (ATR): $\tilde{\nu}$ = 2975 (w), 2930 (w), 1720 (s), 1636 (m), 1593 (s), 1484 (m), 1403 (m), 1290 (m), 1258 (m), 1153 (m), 1109 (s), 1073 (s), 1007 (s) cm^{-1}. HRMS (EI): calcd. for $C_{14}H_{12}O_3$ $[M]^+$ 228.0786; found 228.0789.

8,8-Dimethyl-4-phenyl-2*H*,8*H*-pyrano[2,3-*f*]chromene-2-one (16):[46] By following the general procedure, **12c** (280 mg, 1.00 mmol) provided **16** (164 mg, 0.54 mmol, 54 %) as an orange oil. ^{1}H NMR (300 MHz, $CDCl_3$): δ = 7.53–7.47 (3 H), 7.46–7.39 (2 H), 7.21 (d, *J* = 8.8 Hz, 1 H), 6.96 (d, *J* = 10.1 Hz, 1 H), 6.67 (d, *J* = 8.8 Hz, 1 H), 6.19 (s, 1 H), 5.74 (d, *J* = 10.1 Hz, 1 H), 1.48 (s, 6 H) ppm. ^{13}C NMR (75 MHz, $CDCl_3$): δ = 161.2, 156.4, 156.4, 150.3, 135.8, 130.8, 129.6, 128.9, 128.5, 127.2, 115.5, 113.3, 112.7, 111.6, 109.7, 77.7, 28.3 ppm. IR (ATR): $\tilde{\nu}$ = 3060 (w), 2974 (w), 1727 (s), 1614 (m), 1586 (s), 1445 (m), 1372 (s), 1289 (s), 1210 (m), 1154 (m), 1113 (s), 1081 (s) cm^{-1}. HRMS (EI): calcd. for $C_{20}H_{16}O_3$ $[M]^+$ 304.1099; found 304.1092.

Braylin (9):[46] By following the general procedure, **12d** (234 mg, 1.00 mmol) provided **9** (194 mg, 0.75 mmol, 75 %). Alternatively, **14d** (234 mg, 1.00 mmol) also afforded **9** (183 mg, 0.71 mmol, 71 %) as an orange solid, m.p. 139–141 °C. ^{1}H NMR (300 MHz, $CDCl_3$): δ = 7.57 (d, *J* = 9.5 Hz, 1 H), 6.87 (d, *J* = 10.0 Hz, 1 H), 6.76 (s, 1 H), 6.24 (d, *J* = 9.4 Hz, 1 H), 5.74 (d, *J* = 10.1 Hz, 1 H), 3.88 (s, 3 H), 1.51 (s, 6 H) ppm. ^{13}C NMR (75 MHz, $CDCl_3$): δ = 161.3, 146.1, 145.8, 145.1, 143.8, 131.0, 115.3, 113.3, 111.6, 110.4, 108.8, 78.1, 56.7, 28.1 ppm. IR (ATR): $\tilde{\nu}$ = 2972 (w), 2925 (w), 1713 (s), 1599 (m), 1566 (s), 1463 (m), 1480 (m), 1408 (s), 1292 (s), 1147 (s), 1128 (s), 1078 (m), 1015 (s) cm^{-1}. HRMS (EI): calcd. for $C_{15}H_{14}O_4$ $[M]^+$ 258.0892; 258.0906.

Dipetalolactone (10):[28] By following the general procedure, **12e** (286 mg, 1.00 mmol) provided **10** (140 mg, 0.45 mmol, 45 %). Alternatively, **14e** (234 mg, 1.00 mmol) also afforded **10** (124 mg, 0.40 mmol, 40 %) as a yellowish oil. ^{1}H NMR (300 MHz, $CDCl_3$): δ = 7.93 (d, *J* = 9.6 Hz, 1 H), 6.79 (d, *J* = 10.0 Hz, 1 H), 6.62 (d, *J* = 10.0 Hz, 1 H), 6.11 (d, *J* = 9.6 Hz, 1 H), 5.58 (d, *J* = 10.1 Hz, 1 H), 5.54 (d, *J* = 9.5 Hz, 1 H), 1.46 (s, 6 H) ppm. ^{13}C NMR (75 MHz, $CDCl_3$): δ = 161.4, 152.1, 150.3, 138.9, 127.8, 127.7, 116.1, 115.4, 110.8, 106.1, 103.3, 102.4, 78.2, 78.1, 77.4, 28.4, 28.2 ppm. IR (ATR): $\tilde{\nu}$ = 2975 (w), 1731 (s), 1640 (m), 1592 (s), 1442 (m), 1364 (m), 1134 (s), 1018 (m) cm^{-1}. HRMS (EI): calcd. for $C_{19}H_{18}O_4$ $[M]^+$ 310.1205; found 310.1209.

Acknowledgments

We thank Evonik for the generous donations of solvents.

Keywords: Domino reactions · Alkynes · Arenes · Oxygen heterocycles · Microwave chemistry · Rearrangement

[1] R. Gedye, F. Smith, K. Westaway, H. Ali, L. Baldisera, L. Laberge, J. Rousell, *Tetrahedron Lett.* **1986**, *27*, 279–282.
[2] C. O. Kappe, *Chem. Soc. Rev.* **2008**, *37*, 1127–1139.
[3] P. T. Parvatkar, P. S. Torney, S. G. Tilve, *Curr. Org. Synth.* **2013**, *10*, 288–317.
[4] L. M. Ambrosini, T. H. Lambert, *ChemCatChem* **2010**, *2*, 1373–1380.
[5] D. E. Fogg, E. N. dos Santos, *Coord. Chem. Rev.* **2004**, *248*, 2365–2379.
[6] A. Stadler, C. O. Kappe, *J. Chem. Soc. Perkin Trans. 2* **2000**, 1363–1368.
[7] J. M. Kremsner, A. Stadler, *A Chemist's Guide to Microwave Synthesis*, 2nd ed., Anton Paar GmbH, Graz, **2016**.
[8] S. Rohilla, P. Pant, N. Jain, *RSC Adv.* **2015**, *5*, 31311–31317.
[9] M. Dell'Acqua, V. Pirovano, G. Confalonieri, A. Arcadi, E. Rossi, G. Abbiati, *Org. Biomol. Chem.* **2014**, *12*, 8019–8030.
[10] F. Capitta, L. De Luca, A. Porcheddu, *RSC Adv.* **2014**, *4*, 59297–59301.
[11] B. Schmidt, M. Riemer, U. Schilde, *Eur. J. Org. Chem.* **2015**,7602–7611.
[12] B. Schmidt, M. Riemer, *Synthesis* **2016**, *48*, 141–149.
[13] D. Konrádová, H. Kozubíková, K. Doležal, J. Pospíšil, *Eur. J. Org. Chem.* **2017**, 5204–5213.
[14] M. Harfenist, E. Thom, *J. Org. Chem.* **1972**, *37*, 841–848.
[15] D.-J. Chang, H. An, K.-s. Kim, H. H. Kim, J. Jung, J. M. Lee, N.-J. Kim, Y. T. Han, H. Yun, S. Lee, G. Lee, S. Lee, J. S. Lee, J.-H. Cha, J.-H. Park, J. W. Park, S.-C. Lee, S. G. Kim, J. H. Kim, H.-Y. Lee, K.-W. Kim, Y.-G. Suh, *J. Med. Chem.* **2012**, *55*, 10863–10884.
[16] J. Garcia, S. Barluenga, K. Beebe, L. Neckers, N. Winssinger, *Chem. Eur. J.* **2010**, *16*, 9767–9771.
[17] I. N. Lykakis, C. Efe, C. Gryparis, M. Stratakis, *Eur. J. Org. Chem.* **2011**, 2334–2338.
[18] U. Koch-Pomeranz, H.-J. Hansen, H. Schmid, *Helv. Chim. Acta* **1973**, *56*, 2981–3004.
[19] H. Ishii, T. Ishikawa, S. Takeda, S. Ueki, M. Suzuki, *Chem. Pharm. Bull.* **1992**, *40*, 1148–1153.
[20] R. O'Kennedy, R. D. Thornes (Eds.), *Coumarins - Biology, Applications, and Mode of Action*, Wiley, Chichester, **1997**.
[21] see ref.[20], pp. 1–22.
[22] G. Kirsch, A. Abdelwahab, P. Chaimbault, *Molecules* **2016**, *21*, 1322.
[23] J. Lü, J. Zhang, L. Li, C. Jiang, C. Xing, *Curr. Pharmacol. Rep.* **2015**, *1*, 373–381.
[24] K. Sowndhararajan, S. Kim, *Sci. Pharm.* **2017**, *85*, 21.
[25] K. N. Venugopala, V. Rashmi, B. Odhav, *Biomed. Res. Int.* **2013**, Article ID 963248.
[26] R. Purcaro, K. K. Schrader, C. Burandt, M. DellaGreca, K. M. Meepagala, *J. Agric. Food Chem.* **2009**, *57*, 10632–10635.
[27] W. Li, J.-S. Zhang, J.-L. Huang, M.-H. Jiang, Y.-K. Xu, A. Ahmed, S. Yin, G.-H. Tang, *RSC Adv.* **2017**, *7*, 31061–31068.
[28] E. Melliou, P. Magiatis, S. Mitaku, A.-L. Skaltsounis, E. Chinou, I. Chinou, *J. Nat. Prod.* **2005**, *68*, 78–82.
[29] J.-L. Cao, S.-L. Shen, P. Yang, J. Qu, *Org. Lett.* **2013**, *15*, 3856–3859.
[30] S. K. Chattopadhyay, P. Mondal, D. Ghosh, *Synthesis* **2014**, *46*, 3331–3340.
[31] X.-G. Liu, S.-S. Zhang, C.-Y. Jiang, J.-Q. Wu, Q. Li, H. Wang, *Org. Lett.* **2015**, *17*, 5404–5407.
[32] Y. R. Lee, W. K. Lee, S. K. Noh, W. S. Lyoo, *Synthesis* **2006**, 853–859.
[33] K. C. Nicolaou, J. A. Pfefferkorn, A. J. Roecker, G. Q. Cao, S. Barluenga, H. J. Mitchell, *J. Am. Chem. Soc.* **2000**, *122*, 9939–9953.
[34] Y. Selim, N. Ouf, M. Sakran, *Molecules* **2013**, *18*, 11485–11495.
[35] J. Reisch, A. A. W. Voerste, *J. Chem. Soc. Perkin Trans. 1* **1994**, 3251–3256.
[36] E. A. Domínguez-Mendoza, J. Cornejo-Garrido, E. Burgueño-Tapia, C. Ordaz-Pichardo, *Bioorg. Med. Chem. Lett.* **2016**, *26*, 4086–4091.
[37] H. Ding, H. Sun, H. Xu, *Huaxue Gongye Yu Gongcheng Jishu* **2010**, *31*, 12–15; CAS155:243600.
[38] T. Zhou, Q. Shi, K. H. Lee, *Tetrahedron Lett.* **2010**, *51*, 4382–4386.
[39] R. S. Mali, N. A. Pandhare, M. D. Sindkhedkar, *Tetrahedron Lett.* **1995**, *36*, 7109–7110.
[40] R. S. Mali, P. P. Joshi, *Synth. Commun.* **2001**, *31*, 2753–2760.
[41] K. Subburaj, R. Katoch, M. G. Murugesh, G. K. Trivedi, *Tetrahedron* **1997**, *53*, 12621–12628.
[42] J. D. Godfrey, R. H. Mueller, T. C. Sedergran, N. Soundararajan, V. J. Colandrea, *Tetrahedron Lett.* **1994**, *35*, 6405–6408.
[43] D. Bell, M. R. Davies, G. R. Geen, I. S. Mann, *Synthesis* **1995**, 707–712.
[44] F. Boeck, M. Blazejak, M. R. Anneser, L. Hintermann, *Beilstein J. Org. Chem.* **2012**, *8*, 1630–1636.
[45] Z.-Y. Yang, Y. Xia, P. Xia, L. M. Cosentino, K.-H. Lee, *Bioorg. Med. Chem. Lett.* **1998**, *8*, 1483–1486.
[46] L. Xie, Y. Takeuchi, L. M. Cosentino, K.-H. Lee, *J. Med. Chem.* **1999**, *42*, 2662–2672.
[47] W.-w. Mao, T.-t. Wang, H.-p. Zeng, Z.-y. Wang, J.-p. Chen, J.-g. Shen, *Bioorg. Med. Chem. Lett.* **2009**, *19*, 4570–4573.
[48] S. Cananzi, L. Merlini, R. Artali, G. L. Beretta, N. Zaffaroni, S. Dallavalle, *Bioorg. Med. Chem.* **2011**, *19*, 4971–4984.

Received: December 4, 2017