Photocycloaddition of 4-(Alk-1-ynyl)-Substituted Coumarins and Thiocoumarins to 2,3-Dimethylbuta-1,3-diene

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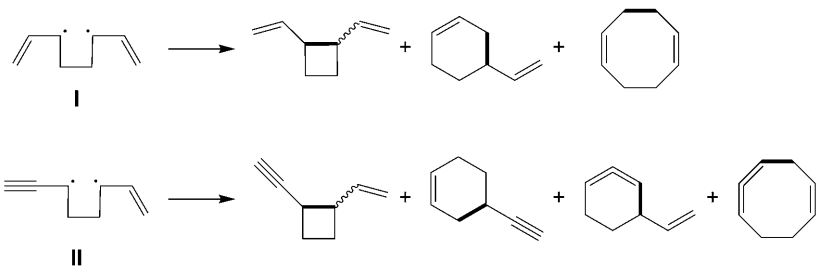
On irradiation (350 nm) in the presence of 2,3-dimethylbuta-1,3-diene (**8**), 4-(alk-1-ynyl)coumarins **1** afford mixtures of cyclobuta- and cycloocta-annulated products **9** and **10**, respectively. In contrast, the corresponding thiocoumarins **2** react with the same diene chemoselectively to give cyclohexa-annulated products **11**.

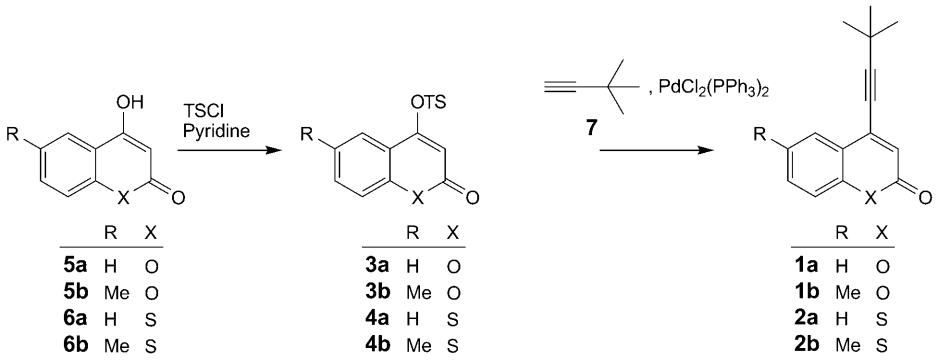
Introduction. – The thermal isomerization of 1,2-divinylcyclobutanes to either of their diastereoisomers, to vinylcyclohexenes, or to cycloocta-1,5-dienes has been intensively studied, and hypothetical octa-1,7-diene-3,6-diyl radicals (**I**) proposed as common intermediates for the three possible cyclization modes [1][2]. In contrast, the much less [3][4] investigated oct-1-en-7-yne-3,6-diyl biradicals (**II**) can formally undergo four modes of cyclization, *i.e.*, one 1,4-, two 1,6-, and one 1,8-cyclization, to afford cyclobutanes, 4-alkynylcyclohexenes and 4-vinylcyclohexa-1,2-dienes, and cycloocta-1,2,5-trienes, respectively (*Scheme 1*).

Scheme 1



We have recently observed competitive 1,4- *vs.* 1,8-cyclization of intermediates of type **II** in photocycloadditions of 3-(alk-1-ynyl)cyclohept-2-enones to dienes, and proposed that additional benzylic stabilization of the propargyl radical moiety of the bis-delocalized 1,4-biradical would favor '*end-to-end*', *i.e.*, 1,8-cyclization [5]. We have now extended these studies to alkynyl-substituted coumarins **1** and thiocoumarins **2**, readily available by Pd-mediated coupling of the corresponding 4-tosyloxy (TsO) derivatives **3** and **4** (obtained from the 4-OH precursors **5** and **6**, resp.) with 3,3-dimethylbut-1-yne (**7**) (*Scheme 2*). Here, we report the results of these reactions.

Scheme 2



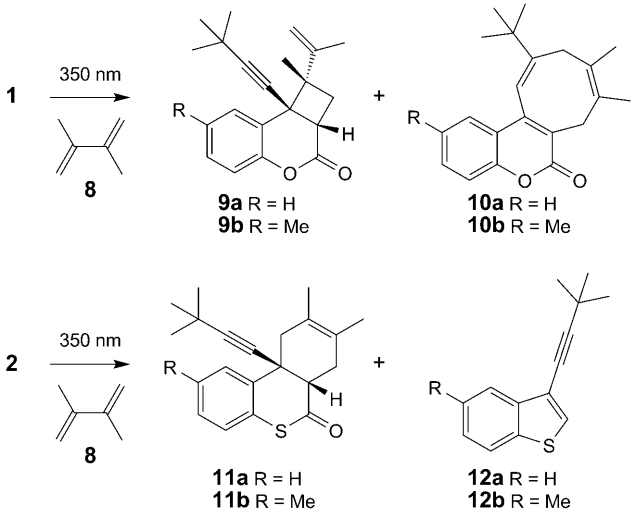
	R	X
5a	H	O
5b	Me	O
6a	H	S
6b	Me	S

	R	X
3a	H	O
3b	Me	O
4a	H	S
4b	Me	S

	R	X
1a	H	O
1b	Me	O
2a	H	S
2b	Me	S

Results. – Irradiation (350 nm) of coumarin (=2*H*-1-benzopyran) **1a** in the presence of a 20-fold molar excess of 2,3-dimethylbuta-1,3-diene (**8**) afforded a 2:1 mixture of products **9a** and **10a**. Similarly, irradiation of coumarin **1b** gave a 2:1 mixture of **9b** and **10b**. In contrast, both thiocoumarins (=2*H*-1-benzothiopyrans) **2a** and **2b** afforded dibenzothiopyrans **11a** and **11b**, respectively, as main products, together with minor amounts of benzothiophenes **12a** and **12b**, respectively, resulting from photodecarbonylation (*Scheme 3*). All products were separated and purified by column chromatography, and fully characterized by 1D- and 2D-NMR spectroscopy.

Scheme 3



Discussion. – The essential point regarding the results presented above is certainly the dissimilar behavior of excited heterocycles **1** and **2** towards diene **8**, as reflected in

the formation of cycloadducts **9** and **10** (from **1**), and **11** (from **2**), respectively. On one hand, the behavior of excited 4-alkynylcoumarins **13** parallels that of 5-alkynylbenzocyclohept-5-en-7-ones [5] in the reaction with **8** affording two products resulting from either 1,4- or 1,8-cyclization of biradical **14**. On the other hand, there appear two differences: *a*) here, the intermediate cyclic allene **15** is not observed; and *b*) again here, the 1,3-H shift originates in the α-position to the CO group. Whereas, for benzocycloheptenones, the cyclooctatriene adduct represented the major (2:1) product, it is now not surprising that the less flexible six-membered lactone ring gives a relatively higher amount (2:1) of cyclobuta-annulated product. Nevertheless, from this point of view, we expected that thiocoumarins **2** would again afford cycloocta-annulated products preferentially due to the – now longer – C–S bonds in the thiolactone ring. Our answer to the question 'why do thiocoumarins **2** behave differently?' is for the moment purely speculative. It is well-known that organic molecules containing (bivalent) S-atoms react with alkyl radicals to afford sulfuranyl radicals, *i.e.*, intermediates involving an expansion of the sulfur valence octet [6][7]. Similarly, intramolecular addition/elimination sequences proceeding *via* sulfuranyl-alkyl biradicals have been proposed in light-induced rearrangements of S-heterocycles [8]. If both benzo adducts **11** and benzothiophenes **12** are formed *via* a common intermediate stemming from excited thiocoumarins **16**, then sufuranyl-alkyl biradicals **17** are indeed highly plausible candidates, as addition to diene **8** would now occur *via* the benzylic radical center with formation of biradical **18**, whereas concomitant decarbonylation would afford benzothiophenes **12**. Finally, the selective 1,6-cyclization of **17** to **11** is thermodynamically controlled, reflecting the higher strain in vinylcyclobutanes as compared to that in cyclohexenes [9] (*Scheme 4*).

Experimental Part

1. *General.* Photolyses were conducted in a *Rayonet RPR-100* photoreactor, equipped with 350-nm lamps, and with solvents of spectrophotometric grade. Column chromatography (CC): silica gel *60* (SiO_2; *Merck*; 230–400 mesh). ^{1}H- and ^{13}C-NMR spectra (including 2D plots): *Bruker WM-500*; at 500.13 and 125.8 MHz, resp.; δ in ppm rel. to Me_4Si as internal standard, *J* in Hz. GC/EI-MS: *Varian MAT-311A* at 70 eV.

2. *Starting Materials.* The syntheses of compounds **1a** and **2a** have been reported in [10]. The 4-hydroxy-substituted heterocycles **5b** and **6b** were synthesized according to [11], and converted into **1b** and **2b**, resp., *via* the 4-TsO derivatives **3b** and **4b**, resp., according to [12].

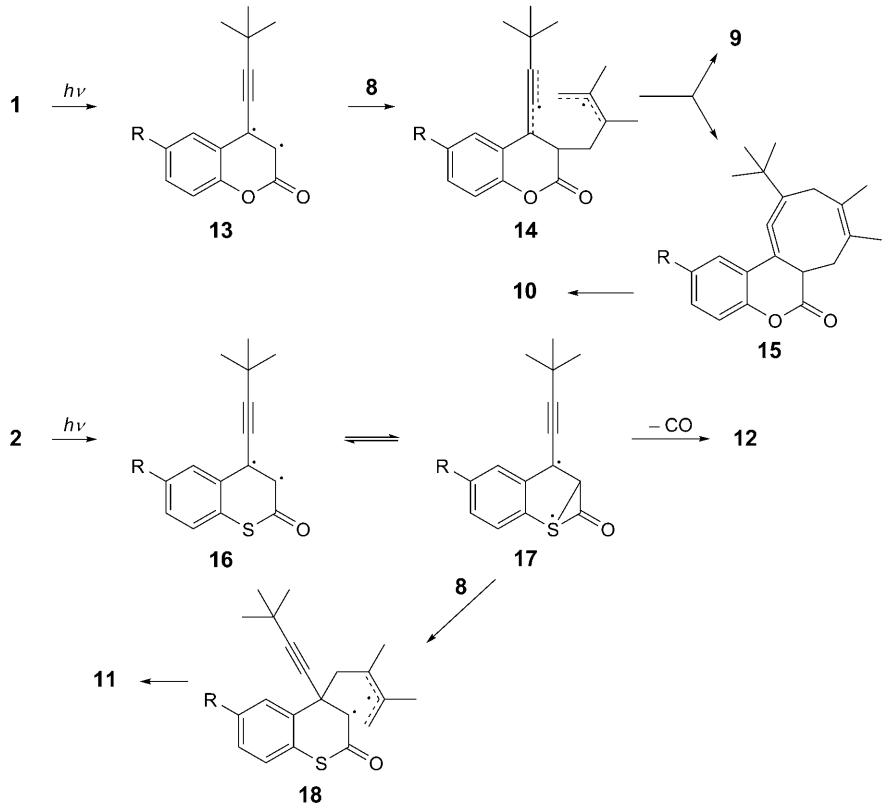
*4-(3,3-Dimethylbut-1-yn-1-yl)-6-methyl-2*H*-1-benzopyran* (**1b**). Light-yellow solid. M.p. 103–105°. ^{1}H-NMR ($CDCl_3$): 7.57 (*s*, 1 H); 7.34 (*d*, *J* = 7.2, 1 H); 7.20 (*d*, *J* = 7.2, 1 H); 6.45 (*s*, 1 H); 2.43 (*s*, 3 H); 1.41 (*s*, 9 H). ^{13}C-NMR ($CDCl_3$): 159.7 (*s*); 149.9 (*s*); 136.7 (*q*); 133.1 (*s*); 131.0 (*d*); 130.2 (*d*); 126.7 (*d*); 126.1 (*s*); 117.3 (*d*); 111.2 (*s*); 74.2 (*s*); 30.5 (*s*); 30.4 (*q*); 21.2 (*q*). MS: 240 (100, M^+).

*4-(3,3-Dimethylbut-1-yn-1-yl)-6-methyl-2*H*-1-benzothiopyran-2-one* (**2b**). Light-yellow solid. M.p. 110–112°. ^{1}H-NMR ($CDCl_3$): 8.00 (*s*, 1 H); 7.33 (*s*, 2 H); 6.72 (*s*, 1 H); 2.46 (*s*, 3 H); 1.41 (*s*, 9 H). ^{13}C-NMR ($CDCl_3$): 184.3 (*s*); 148.3 (*s*); 136.7 (*s*); 133.1 (*s*); 131.0 (*d*); 130.2 (*d*); 126.7 (*d*); 126.1 (*s*); 125.6 (*d*); 111.2 (*s*); 76.2 (*s*); 30.8 (*s*); 30.5 (*q*); 21.4 (*q*). MS: 256 (32, M^+), 213 (100).

3. *Photocycloadditions to 2,3-Dimethylbuta-1,3-diene.* Ar-Degassed solns. of **1** or **2** (1 mmol) and **8** (20 mmol) in benzene (10 ml) were irradiated for 12–14 h up to 80–90% conversion (as monitored by GC). After evaporation of the solvent and excess diene, the residue was subjected to CC.

3.1. *Photocycloaddition of* **1a**. CC (pentane/Et_2O 5:1) afforded first 139 mg (45%) of *(1S,2aS,8bR)-8b-(3,3-dimethylbut-1-yn-1-yl)-1,2,2a,8b-tetrahydro-1-methyl-1-(prop-1-en-2-yl)-3*H*-cyclobuta[c]chromen-3-one* (**9a**; R_f 0.35). Colorless oil. ^{1}H-NMR ($CDCl_3$): 7.11–6.98 (*m*, 4 H); 4.71 (*s*, 1 H); 4.50 (*s*, 1 H);

Scheme 4



3.54 (*dd*, *J* = 9.3, 9.3, 1 H); 2.53 (*dd*, *J* = 9.3, 11.3, 1 H); 2.10 (*dd*, *J* = 9.3, 11.3, 1 H); 1.59 (*s*, 3 H); 1.55 (*s*, 3 H); 1.22 (*s*, 9 H). ^{13}C-NMR ($CDCl_3$): 162.1 (*s*); 150.1 (*s*); 146.2 (*s*); 130.3 (*d*); 128.9 (*d*); 125.5 (*d*); 124.1 (*d*); 121.7 (*s*); 117.0 (*d*); 112.8 (*t*); 94.6 (*s*); 80.3 (*s*); 53.1 (*s*); 43.2 (*s*); 39.1 (*d*); 32.8 (*t*); 30.1 (*s*); 29.8 (*q*); 24.1 (*q*); 20.5 (*q*). EI-MS: 308 (41, M^+); 226 (100).

The second fraction consisted of 77 mg (25%) of *11-(*tert*-butyl)-8,9-dimethyl-6*H*-cycloocta[*c*]chromen-6-one* (**10a**; R_f 0.24). Viscous yellow oil. ^{1}H-NMR ($CDCl_3$): 7.48–7.43 (*m*, 2 H); 7.32 (*d*, *J* = 8.2, 1 H); 6.54 (*s*, 1 H); 3.27 (*s*, 2 H); 2.67 (*s*, 2 H); 1.93 (*s*, 3 H); 1.79 (*s*, 3 H); 1.20 (*s*, 9 H). ^{13}C-NMR ($CDCl_3$): 160.9 (*s*); 152.5 (*s*); 151.0 (*s*); 147.6 (*s*); 129.4 (*d*); 124.8 (*s*); 124.5 (*d*); 122.8 (*d*); 119.4 (*s*); 118.3 (*s*); 130.4 (*s*); 116.7 (*d*); 115.6 (*d*); 36.2 (*t*); 35.3 (*t*); 32.9 (*s*); 28.7 (*q*); 22.3 (*q*); 22.1 (*q*). EI-MS: 308 (11, M^+), 224 (100).

3.2. *Photocycloaddition of* **1b**. CC (pentane/Et_2O/toluene 25 : 2 : 2) afforded first 138 mg (43%) of *(1*S*,2a*S*,8b*R*)-8b-(3,3-dimethylbut-1-yn-1-yl)-1,2,2a,8b-tetrahydro-1,7-dimethyl-1-(prop-1-en-2-yl)-3*H*-cyclobuta[*c*]chromen-3-one* (**9b**; R_f 0.27). Colorless oil. ^{1}H-NMR ($CDCl_3$): 7.05 (*s*, 1 H); 7.02 (*d*, *J* = 8.2, 1 H); 6.68 (*d*, *J* = 8.2, 1 H); 4.71 (*s*, 1 H); 4.50 (*s*, 1 H); 3.51 (*dd*, *J* = 9.3, 9.3, 1 H); 2.52 (*dd*, *J* = 9.3, 11.1, 1 H); 2.29 (*s*, 3 H); 2.08 (*dd*, *J* = 9.3, 11.1, 1 H); 1.58 (*s*, 3 H); 1.54 (*s*, 3 H); 1.23 (*s*, 9 H). ^{13}C-NMR ($CDCl_3$): 165.7 (*s*); 148.1 (*s*); 146.3 (*s*); 133.3 (*s*); 130.3 (*d*); 129.3 (*d*); 121.1 (*s*); 116.5 (*d*); 112.8 (*t*); 94.5 (*s*); 78.9 (*s*); 53.0 (*s*); 45.5 (*s*); 38.9 (*d*); 32.8 (*t*); 30.9 (*q*); 29.6 (*s*); 23.8 (*q*); 20.6 (*q*); 20.1 (*q*). EI-MS: 322 (23, M^+); 240 (100).

The second fraction consisted of 81 mg (25%) of *11-(*tert*-butyl)-3,8,9-trimethyl-6*H*-cycloocta[*c*]-chromen-6-one* (**10b**; R_f 0.11). Viscous yellow oil. ^{1}H-NMR ($CDCl_3$): 7.29–7.19 (*m*, 2 H); 7.21 (*s*, 1 H); 6.52 (*s*, 1 H); 3.26 (*s*, 2 H); 2.66 (*s*, 2 H); 2.40 (*s*, 3 H); 1.93 (*s*, 3 H); 1.78 (*s*, 3 H); 1.21 (*s*, 9 H). ^{13}C-NMR ($CDCl_3$): 162.1 (*s*); 153.5 (*s*); 149.9 (*s*); 148.6 (*s*); 134.5 (*s*); 133.2 (*s*); 131.3 (*d*); 125.5 (*s*); 125.3 (*s*); 124.9 (*d*); 120.2 (*s*); 117.0 (*d*); 116.3 (*d*); 39.7 (*t*); 36.2 (*t*); 31.1 (*s*); 29.5 (*q*); 23.2 (*q*); 22.9 (*q*); 20.6 (*q*). EI-MS: 322 (18, M^+), 238 (100).

3.3. *Photocycloaddition of* **2a**. CC (pentane/Et_2O/toluene 20 : 2 : 1) afforded first 43 mg (20%) of *3-(3,3-dimethylbut-1-yn-1-yl)-1-benzothiophene* (**12a**; R_f 0.7). Colorless oil. ^{1}H-NMR ($CDCl_3$): 7.90 (*d*, *J* = 7.3, 1 H); 7.82 (*d*, *J* = 7.5, 1 H); 7.48 (*s*, 1 H); 7.43 (*dd*, *J* = 7.3, *J* = 7.5, 1 H); 7.37 (*dd*, *J* = 7.3, *J* = 7.5, 1 H); 1.39 (*s*, 9 H). ^{13}C-NMR ($CDCl_3$): 139.3 (*s*); 139.0 (*s*); 128.0 (*d*); 124.9 (*d*); 124.4 (*d*); 122.6 (*d*); 122.4 (*d*); 119.1 (*s*); 101.1 (*s*); 79.1 (*s*); 31.1 (*s*); 28.0 (*q*). EI-MS: 214 (60, M^+), 199 (100).

The second fraction consisted of 120 mg (37%) of *(6a*S*,10a*R*)-10a-(3,3-Dimethylbut-1-yn-1-yl)-6a,7,10,10a-tetrahydro-8,9-dimethyl-6*H*-benzo[*c*][1]benzothiopyran-6-one* (**11a**; R_f 0.5). Yellow oil. ^{1}H-NMR ($CDCl_3$): 7.26–7.20 (*m*, 2 H); 7.17–7.14 (*m*, 2 H); 2.95 (*dd*, *J* = 5.8, 5.8, 1 H); 2.78 (*d*, *J* = 17.3, 1 H); 2.35–2.27 (*m*, 2 H); 2.19 (*d*, *J* = 17.3, 1 H); 1.62 (*s*, 3 H); 1.59 (*s*, 3 H); 1.19 (*s*, 9 H). ^{13}C-NMR ($CDCl_3$): 199.1 (*s*); 135.8 (*s*); 130.4 (*s*); 127.8 (*d*); 127.1 (*d*); 126.5 (*d*); 126.1 (*d*); 124.1 (*s*); 122.6 (*s*); 94.5 (*s*); 80.3 (*s*); 52.9 (*d*); 40.6 (*s*); 40.3 (*t*); 30.9 (*q*); 30.3 (*t*); 27.3 (*s*); 18.9 (*q*); 18.3 (*q*). EI-MS: 324 (40, M^+), 214 (100).

3.4. *Photocycloaddition of* **2b**. CC (pentane/Et_2O/toluene 12 : 2 : 1) afforded first 13 mg (6%) of *3-(3,3-dimethylbut-1-yn-1-yl)-5-methyl-1-benzothiophene* (**12b**; R_f 0.27). Colorless oil. ^{1}H-NMR ($CDCl_3$): 7.70 (*d*, *J* = 8.3, 1 H); 7.65 (*d*, *J* = 8.3, 1 H); 7.54 (*s*, 1 H); 7.32 (*s*, 1 H); 2.51 (*s*, 3 H); 1.40 (*s*, 9 H). ^{13}C-NMR ($CDCl_3$): 139.8 (*s*); 137.6 (*s*); 134.3 (*s*); 133.6 (*s*); 126.3 (*d*); 125.6 (*d*); 122.5 (*d*); 121.8 (*d*); 111.3 (*s*); 86.4 (*s*); 31.2 (*q*); 30.9 (*q*); 20.9 (*q*). EI-MS: 228 (56, M^+), 213 (100).

The second fraction consisted of 125 mg (37%) of *(6a*S*,10a*R*)-10a-(3,3-Dimethylbut-1-yn-1-yl)-6a,7,10,10a-tetrahydro-2,8,9-trimethyl-6*H*-benzo[*c*][1]benzothiopyran-6-one* (**11b**; R_f 0.11). Yellow oil. ^{1}H-NMR ($CDCl_3$): 7.07 (*d*, *J* = 8.0, 1 H); 7.06–7.03 (*m*, 2 H); 2.92 (*dd*, *J* = 5.7, 5.7, 1 H); 2.77 (*d*, *J* = 17.4, 1 H); 2.42–2.32 (*m*, 2 H); 2.36 (*s*, 3 H); 2.15 (*d*, *J* = 17.3, 1 H); 1.62 (*s*, 3 H); 1.60 (*s*, 3 H); 1.20 (*s*, 9 H). ^{13}C-NMR ($CDCl_3$): 199.4 (*s*); 136.8 (*s*); 135.7 (*s*); 130.5 (*s*); 128.3 (*d*); 128.0 (*d*); 126.4 (*d*); 123.9 (*s*); 122.6 (*s*); 92.6 (*s*); 80.5 (*s*); 52.5 (*d*); 40.4 (*s*); 40.3 (*t*); 30.6 (*s*); 29.9 (*t*); 27.4 (*q*); 20.9 (*q*); 18.3 (*q*); 17.6 (*q*). EI-MS: 338 (32, M^+), 228 (100).

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