Cyclotrimerization of alkynes catalyzed by the naphthalene ruthenium complex $[CpRu(C_{10}H_8)]^+$

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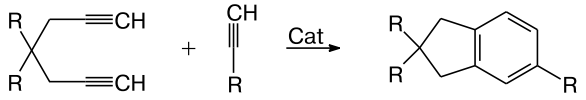
The naphthalene ruthenium complex $[CpRu(C_{10}H_8)]^+$ (in the presence of Cl^- ions) catalyzes the cyclotrimerization of 2,2-dimethyl-5,5-dipropargyl-1,3-dioxane-4,6-dione with alkynes (acetylene, hex-1-yne, hex-3-yne, oct-1-yne, phenylacetylene, trimetylsilylacetylene, octa-1,7-diyne, pent-1-yn-5-ol, methyl propargyl ether, and propargyl acetate) giving tricyclic aromatic compounds in 55—85% yields.

Key words: alkynes, diynes, arenes, cyclotrimerization, ruthenium, homogeneous catalysis.

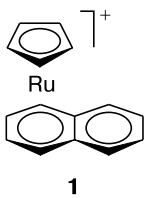
Cyclotrimerization of alkynes is an efficient method for synthesis of aromatic compounds.[1—3] This reaction makes it possible to obtain arenes containing several functional groups in one stage (unlike the classical approach based on the consecutive introduction of substituents into the benzene ring). It should be mentioned, however, that regioselective catalytic cyclotrimerization of three various alkynes remains to be a difficult task.[4] Therefore, the cotrimerization of 1,6-diynes with alkynes is used most frequently (see, *e.g.*, Scheme 1). In particular, this reaction was used for the synthesis of a series of biologically active compounds,[5—9] and complex Cp*Ru(cod)Cl (cod is cycloocta-1,5-diene) turned out to be the most active catalyst.[10—13]

Scheme 1



Cat is catalyst.

We have previously shown that the $[CpRu(C_{10}H_8)]^+$ cation (**1**) readily exchanged naphthalene to other ligands to give ruthenocenes $CpRu(C_5R_5)$ (see Ref. 14), ruthenacarboranes $CpRuC_3B_8H_{11}$ (see Ref. 15) as well as arene and diene complexes $[CpRu(arene)]^+$ (see Refs 16—18) and CpRu(diene)Cl (see Ref. 19). It was also shown that in the presence of various ligands cation **1** catalyzes the anti-Markovnikov hydration of alkynes[20] and Carroll rearrangement.[21] In the present work, we report the first example of using complex **1** as a catalyst of alkyne cyclotrimerization.



1

2,2-Dimethyl-5,5-dipropargyl-1,3-dioxane-4,6-dione (**2**) was chosen as a model substrate for the study of cyclotrimerization.[10] We found that the reaction of compound **2** with hex-1-yne (4 equiv.) in CH_2Cl_2 in the presence of complex **1** (2 mol.%, as salt $[\mathbf{1}]BF_4$) and Cl^- (2 mol.%, in the form of salt $[PhCH_2NEt_3]Cl$) occurred with 100% conversion within 1 h giving indane **3a** in 85% yield (Scheme 2). The by-products of this reaction are dimer **4** (9%) and trimer **5** (4%) of the initial diyne **2**; their formation was not suppressed even in the presence of 4 equiv. of hex-1-yne.*

A similar reaction of diyne **2** with oct-1-yne and phenylacetylene in the presence of cation **1** and anion Cl^- affords arenes **3b,c** in 87 and 76% yields, respectively. Sterically hindered trimethylsilylacetylene reacts with **2** more slowly than hex-1-yne, which decreases the yield of desired arene **3d** to 54% and increases the yield of by-products **4** (27%) and **5** (15%). In the case of cyclotrimerization **2** with internal hex-3-yne, the desired arene **3e** is formed in 24% yield only; the yield of **3e** can be increased to 65% when 10 equiv. of hex-3-yne are used. The reaction of diyne **2** with gaseous acetylene (1 atm) gives compound **3f** (56%).

We studied the influence of some functional groups on the cyclotrimerization. The reaction of compound **2** with pent-1-yn-5-ol smoothly gives arene **3g** (75%). Similar reactions of diyne **2** with methyl propargyl ether and propargyl acetate afford compounds **3h** (63%) and **3i** (69%), respectively.

* When using 1 equiv. of hex-1-yne, the yields of products **3a**, **4**, and **5** are 47, 30, and 16%, respectively.

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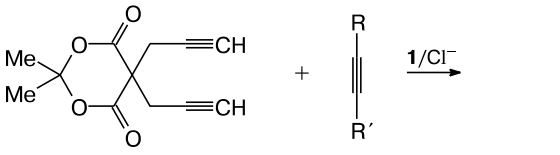
Схема 2



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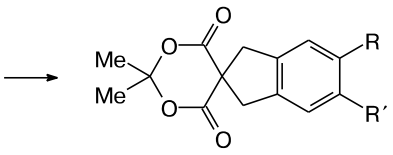
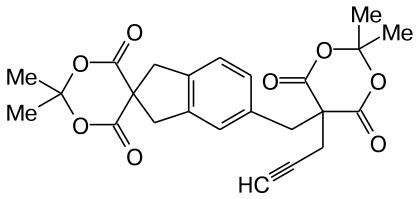


3a—i

3	R	R′	**3**	R	R′
a	C_4H_9	H	**f**	H	H
b	C_6H_{13}	H	**g**	$(CH_2)_3OH$	H
c	Ph	H	**h**	CH_2OMe	H
d	Me_3Si	H	**i**	CH_2OAc	H
e	Et	Et			



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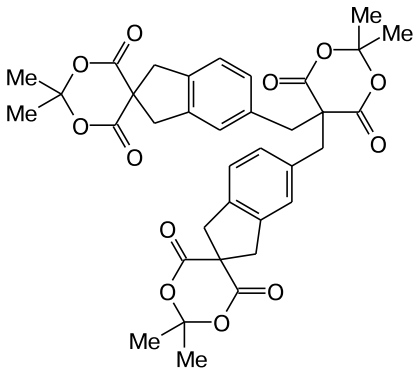
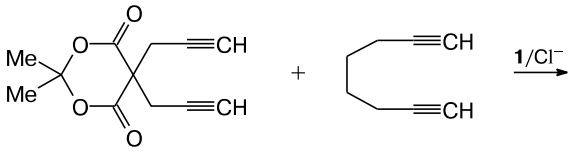


5

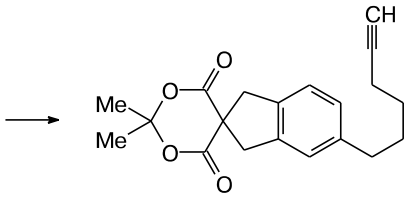
Unfortunately, no desired product is formed in the reaction of **2** with propargyl alcohol; trimers of propargyl alcohol 1,2,4-$C_6H_3(CH_2OH)_3$ and 1,3,5-$C_6H_3(CH_2OH)_3$ were found instead in the reaction mixture. The reaction with *N*,*N*-dimethylpropargylamine and methyl propiolate proceeds similarly. It is most likely that the functional group in the α-position to the triple bond is coordinated with the ruthenium atom changing the direction of the reaction.[22] It should be mentioned that no similar side processes are observed when the Cp*Ru(cod)Cl catalyst containing more donor and sterically hindered ligand Cp* is used.[10]

The reaction of diyne **2** with octa-1,7-diyne selectively yields compound **3j** (80%, Scheme 3), and alternative product **6** is not formed. It should be mentioned that octa-1,7-diyne does not react with hex-1-yne even in the presence of 10 mol.% of catalyst **1**. It is most likely that the cyclotrimerization of octa-1,7-diyne is less favored because the triple bonds are remote from each other.

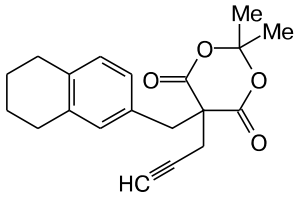
Scheme 3



2



3j



6

It should be mentioned that complex **1** does not react with alkynes in the absence of chloride anion. The role of the Cl^- anion seems to be the formation of catalytically active species [CpRuCl] from cation **1**, and the further interaction of this species with diyne **2** gives a metallocyclopentadiene intermediate.[23,24] Cyclotrimerization also occurs in the presence of other halide and pseudo-halide anions, and the reaction rate decreases in the order $Cl^- > Br^- > I^- > N_3^- > CN^- >> F^-$.

Thus, in the presence of Cl^- anions, complex **1** is an efficient catalyst of alkyne cyclotrimerization. The activity of this catalyst is comparable with that of the widespread catalysts Cp*Ru(cod)Cl (see Ref. 10), $(Ph_3P)_3RhCl$ (see Ref. 25), and $[(cod)IrCl]_2$/dppe (see Ref. 26) and allows one to carry out the reactions without inert atmosphere.

Experimental

Complex [**1**]BF_4 was synthesized according to a published procedure.[27] Solvents were purified by distillation over the corresponding drying agent: CH_2Cl_2 over CaH_2, petroleum ether

over Na, and ethyl acetate over anhydrous K_2CO_3. Silica gel Merck (240—400 mesh) was used for column chromatography. ^{1}H NMR spectra were recorded on a Bruker Avance-400 instrument in $CDCl_3$; chemical shifts are presented in the δ scale relative to Me_4Si. Elemental analysis was carried out at the Laboratory of Microanalysis of the A. N. Nesmeyanov Institute of Organoelement Compounds, Russian Academy of Sciences.

Cotrimerization of diyne 2 with alkynes (general procedure). A solution of diyne **2** (44 mg, 0.2 mmol) in CH_2Cl_2 (1 mL) was added by portions to a solution of [**1**]BF_4 (1.6 mg, 0.004 mmol), $[PhCH_2NEt_3]Cl$ (1 mg, 0.004 mmol), and alkyne (0.8 mmol) in CH_2Cl_2 (1 mL) for 30 min. The mixture was stirred for 1—3 h at room temperature. After the end of the reaction (TLC monitoring), the reaction mixture was concentrated *in vacuo*. The product was isolated by gradient column chromatography using EtOAc—petroleum ether (from 5 : 1 to 1 : 1) as an eluent. The fractions containing the pure product were combined, evaporated, and dried *in vacuo*.

5′-Butyl-2,2-dimethyl-1′,3′-dihydrospiro([1,3]dioxane-5,2′-indene)-4,6-dione (3a). The yield was 52 mg (85%). ^{1}H NMR, δ: 0.91 (t, 3 H, Me, J = 7.6 Hz); 1.35 (m, 2 H, CH_2); 1.56 (m, 2 H, CH_2); 1.76 (s, 6 H, Me); 2.57 (t, 2 H, CH_2, J = 7.6 Hz); 3.66 (s, 2 H, CH_2); 3.67 (s, 2 H, CH_2); 7.01—7.08 (m, 3 H, CH). Found (%): C, 71.60; H, 7.38. $C_{18}H_{22}O_4$. Calculated (%): C, 71.50; H, 7.33.

5′-Hexyl-2,2-dimethyl-1′,3′-dihydrospiro([1,3]dioxane-5,2′-indene)-4,6-dione (3b). The yield was 57 mg (87%). ^{1}H NMR, δ: 0.87 (t, 3 H, Me, J = 7.6 Hz); 1.29 (m, 6 H, CH_2); 1.57 (m, 2 H, CH_2); 1.81 (s, 6 H, Me); 2.57 (t, 2 H, CH_2, J = 7.6 Hz); 3.68 (s, 2 H, CH_2); 3.69 (s, 2 H, CH_2); 7.01—7.08 (m, 3 H, CH). Found (%): C, 72.64; H, 7.94. $C_{20}H_{26}O_4$. Calculated (%): C, 72.20; H, 7.93.

2,2-Dimethyl-5′-phenyl-1′,3′-dihydrospiro([1,3]dioxane-5,2′-indene)-4,6-dione (3c). The yield was 48 mg (76%). ^{1}H NMR, δ: 1.83 (s, 6 H, Me); 3.76 (s, 2 H, CH_2); 3.78 (s, 2 H, CH_2); 7.28—7.48 (m, 6 H, CH); 7.54 (d, 2 H, CH, J = 7.2 Hz). Found (%): C, 74.45; H, 5.48. $C_{20}H_{18}O_4$. Calculated (%): C, 74.52; H, 5.63.

2,2-Dimethyl-5′-trimethylsilyl-1′,3′-dihydrospiro([1,3]-dioxane-5,2′-indene)-4,6-dione (3d). The yield was 34 mg (54%). ^{1}H NMR, δ: 0.24 (s, 9 H, Me); 1.82 (s, 6 H, Me); 3.72 (s, 2 H, CH_2); 3.73 (s, 2 H, CH_2); 7.20 (d, 1 H, CH, J = 7.6 Hz); 7.37 (m, 2 H, CH). Found (%): C, 64.49; H, 6.85. $C_{17}H_{22}O_4Si$. Calculated (%): C, 64.12; H, 6.96.

5′,6′-Diethyl-2,2-dimethyl-1′,3′-dihydrospiro([1,3]dioxane-5,2′-indene)-4,6-dione (3e) was synthesized similarly using 10 equiv. of hex-3-yne. The yield was 39 mg (65%). ^{1}H NMR, δ: 1.19 (t, 6 H, Me, J = 7.6 Hz); 1.81 (s, 6 H, Me); 2.62 (q, 4 H, CH_2, J = 7.6 Hz); 3.67 (s, 4 H, CH_2); 7.00 (s, 2 H, CH). Found (%): C, 71.13; H, 7.31. $C_{18}H_{22}O_4$. Calculated (%): C, 71.50; H, 7.33.

2,2-Dimethyl-1′,3′-dihydrospiro([1,3]dioxane-5,2′-indene)-4,6-dione (3f). The yield was 27 mg (54%). ^{1}H NMR, δ: 1.82 (s, 6 H, Me); 3.73 (s, 4 H, CH_2); 7.22 (m, 4 H, CH). Found (%): C, 68.26; H, 5.77. $C_{14}H_{14}O_4$. Calculated (%): C, 68.28; H, 5.73.

5′-(3-Hydroxypropyl)-2,2-dimethyl-1′,3′-dihydrospiro([1,3]-dioxane-5,2′-indene)-4,6-dione (3g). The yield was 46 mg (75%). ^{1}H NMR, δ: 1.81 (s, 6 H, Me); 1.85 (m, 2 H, CH_2); 2.16 (s, 1 H, OH); 2.68 (t, 2 H, CH_2, J = 8.0); 3.68 (m, 2 H, CH_2); 3.69 (s, 4 H, CH_2); 7.04 (s, 1 H, CH); 7.07 (d, 1 H, CH, J = 7.6 Hz); 7.10 (d, 1 H, CH, J = 7.6 Hz). Found (%): C, 67.06; H, 6.71. $C_{17}H_{20}O_5$. Calculated (%): C, 67.09; H, 6.62.

2,2-Dimethyl-5′-(methoxymethyl)-1′,3′-dihydrospiro([1,3]-dioxane-5,2′-indene)-4,6-dione (3h). The yield was 37 mg (63%). ^{1}H NMR, δ: 1.81 (s, 6 H, Me); 3.37 (s, 3 H, Me); 3.71 (s, 4 H, CH_2); 4.43 (s, 2 H, CH_2); 7.19 (m, 3 H, CH). Found (%): C, 66.44; H, 6.19. $C_{16}H_{18}O_5$. Calculated (%): C, 66.19; H, 6.25.

5′-(Acetoxymethyl)-2,2-dimethyl-1′,3′-dihydrospiro([1,3]-dioxane-5,2′-indene)-4,6-dione (3i). The yield was 44 mg (69%). ^{1}H NMR, δ: 1.79 (s, 6 H, Me); 2.08 (s, 3 H, Me); 3.70 (s, 2 H, CH_2); 3.71 (s, 2 H, CH_2); 5.07 (s, 2 H, CH_2); 7.21 (m, 3 H, CH). Found (%): C, 64.25; H, 5.48. $C_{17}H_{18}O_6$. Calculated (%): C, 64.14; H, 5.70.

5′-(Hex-5-ynyl)-2,2-dimethyl-1′,3′-dihydrospiro([1,3]-dioxane-5,2′-indene)-4,6-dione (3j). The yield was 52 mg (80%). ^{1}H NMR, δ: 1.56 (m, 4 H, CH_2); 1.71 (m, 2 H, CH_2); 1.81 (s, 6 H, Me); 1.93 (s, 1 H, CH); 2.60 (m, 2 H, CH_2); 3.67 (s, 2 H, CH_2); 4.68 (s, 2 H, CH_2); 7.02 (s, 1 H, CH); 7.04 (d, 1 H, CH, J = 8.0 Hz); 7.09 (d, 1 H, CH, J = 8.0 Hz). Found (%): C, 74.16; H, 7.00. $C_{20}H_{22}O_4$. Calculated (%): C, 73.60; H, 6.79.

Compounds **4** and **5** were identified by the ^{1}H NMR spectra resembling the published ones.[26]

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