Photochemical Cycloaromatization of Non-Benzenoid Enediynes**

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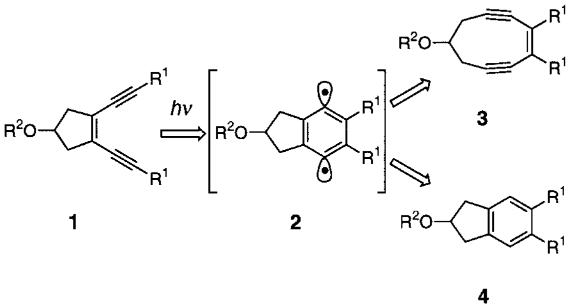
Dedicated to Professor Satoru Masamune on the occasion of his 70th birthday

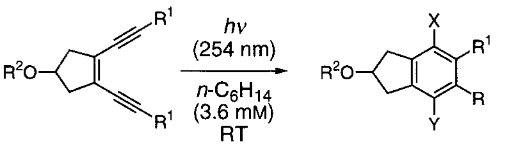
The Bergman reaction, the thermal cycloaromatization of hexa-1,5-diyn-3-enes to afford benzenoid compounds, is well-known.[1, 2] Some photochemical examples have been reported; however, these are restricted to arene-fused enediynes.[3–5] A photo-Bergman reaction of aliphatic enediynes could play an important role in 1,4-didehydrobenzene (*p*-benzyne) chemistry because it could be carried out at low temperature and thus allow characterization of reactive intermediates.[6] We describe herein the successful photo-cycloaromatization of several aliphatic enediynes.

Based on our previous studies on the synthesis of nine-membered cyclic enediynes,[7] we first examined the photoreaction of 1,2-diethynylcyclopentene derivatives **1**. The photochemical formation of **3** was expected through the 1,4-didehydrobenzene intermediate **2** (Scheme 1). A degassed solution of **1a** ($R^1 = H$)[8] in hexane was irradiated in a quartz flask at room temperature with a low-pressure mercury lamp (4 × 20 W) for 6 h. The enediyne **1a** disappeared completely, but the aromatic product **4a** was obtained only in very low yield (3 %) and no nine-membered enediyne **3** ($R^1 = H$) was detected (Table 1). Neither **1b**[8] nor **1c**[8] possessing the bulky substituents trimethylsilyl (TMS) and phenyl, respectively, at the alkyne termini yielded any indane derivatives under the same reaction conditions; the reactants were recovered almost quantitatively. However, photolysis of the dipropynyl derivative **1d** ($R^1 = Me$)[8] gave **4d** in high yield (71 %; 80 % yield by GC analysis).[9] Photoreduction products such as dienynes, which are formed in the case of benzenoid enediynes,[4b] were not detected. The photo-cycloaromatization took place in a variety of solvents (but not in MeOH): *n*-hexane/1,4-cyclohexadiene (20/1; **4d**: 41 %), cyclohexane (**4d**: 52 %), THF (**4d**: 35 %), CH_3CN (**4d**: 21 %, **5**: 8 %), *i*PrOH (**4d**: 20 %), CH_2Cl_2 (**4d**: trace, **6**: 20 %).



Scheme 1. Plausible course of the photo-Bergman reaction. $R^2 = TBS =$ *tert*-butyldimethylsilyl.

Table 1. Photoreaction of 1,2-diethynylcyclopentene derivatives **1a – 1d** in hexane.



1a - d
R^2 = TBS

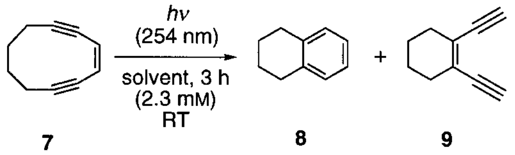
4a - d (X = Y = H)
5 (R = Me, X = H, Y = CH_2CN)
6 (R = Me, X = H, Y = $CHCl_2$)

Substrate	Reaction time [h]	Yield [%]
1a: $R^1 = H$	6	**4a**: 3
1b: $R^1 = TMS$	18	**4b**: 0
1c: $R^1 = Ph$	18	**4c**: 0
1d: $R^1 = Me$	18	**4d**: 71

Photolysis of **1d** was then carried out in $[D_8]$THF (99.5 atom% D). The deuterated product $[D_2]$**4d** (X = Y = D) ($[D_2]$: 88 %, $[D_1]$: 12 %, $[D_0]$: 0 %) was obtained in 14 % yield. These results strongly suggest that the photocyclization of **1d** proceeds through the 4,7-didehydroindane diradical intermediate **2** ($R^1 = Me$). Irradiation of **1d** under a high-pressure mercury lamp (400 W, Riko UVL-400HA, pyrex) in hexane did not cause any reaction, not even in the presence of triplet photosensitizers (toluene, acetophenone, benzophenone, anthraphenone, or naphthalene). Thus, neither pyrex-filtered light nor the triplet energy of these sensitizers is effective for the photo-cycloaromatization of **1d**.

We then irradiated the strained, ten-membered cyclic enediyne **7**[8, 10] with a low-pressure mercury lamp (4 × 20 W) at room temperature for 3 h. Tetrahydronaphthalene (**8**) was obtained, and an appreciable amount of 1,2-diethynylcyclohexene (**9**)[11] was formed in all solvents except *i*PrOH (Table 2). Compound **9** underwent photolysis under the same reaction conditions, and it was consumed completely upon photolysis in *i*PrOH for 3 h to give **8** in 3 % yield. Photolysis of **7** in $[D_8]$*i*PrOH was stopped after 30 % conversion (5 min), and the products were analyzed by 500-MHz ^1H NMR

Table 2. Photolysis of cyclodeca-1,5-diyn-3-ene (**7**).



Solvent	Yield of **8** [%][a]	Yield of **9** [%][a]
hexane[b]	29	6
cyclohexane	26	20
CH_3CN	12	24
*i*PrOH	3	–[c]

[a] By GC analysis. [b] Irradiated for 5 h. [c] Not detected.

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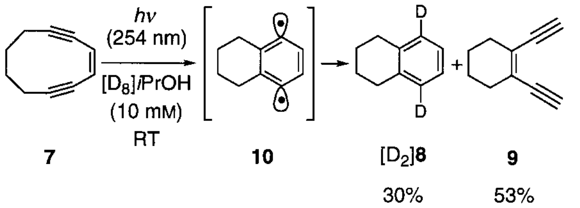
spectroscopy (Scheme 2). The yields of $[D_2]$**8** and **9** were 30 and 53 %, respectively, based on recovered **7**. The formation of **9** in over 50 % yield is highly remarkable because enediyne **9** should arise from the retro-Bergman reaction of the hypothetical diradical intermediate **10**, and because **9** has never been isolated in the thermal reaction of **7**.[10, 12]



Scheme 2. Photolysis of **7** in $[D_8]$*i*PrOH for 5 min (30 % conversion).

We have established a highly effective photo-Bergman reaction of the aliphatic, ten-membered cyclic enediyne **7**. The photoreaction of **7** also showed remarkable formation of **9**, which should be a retro-Bergman product from **10**. Thus, **7** appears to be ideal for flash photolysis and for the characterization of the 1,4-didehydrobenzene diradical intermediate **10**. A mechanistic study along this line will be reported in due course.

Experimental Section

Photolysis of **1d**: A solution of **1d** (50.0 mg, 0.182 mmol) in hexane (50 mL) was irradiated in a quartz flask (30 mm (inner diameter) × 230 mm) with four GL-20 low-pressure mercury lamps (National Electric Co. Ltd.) at room temperature under an argon atmosphere for 18 h. The solution was concentrated and purified by flash column chromatography on silica gel (eluent: hexane containing 0–1 % of ethyl acetate). The solid residue **4d** was recrystallized from hexane; yield: 35.8 mg (0.129 mmol, 71 %).

GC analysis of the photoreaction products of **7** was carried out with 1,3,5-trimethylbenzene as an internal standard.

^{1}H NMR analysis of the photoreaction of **7**: A 5.0 mM solution of **7** in $[D_8]$*i*PrOH (99 + atom % D) in a quartz NMR tube (5 mm inner diameter) was placed in a quartz jacket filled with methanol and irradiated for 5 min with four GL-20 low-pressure mercury lamps (National Electric Co. Ltd.) at 25 °C under an argon atmosphere. The ^{1}H NMR spectra were taken directly for the reaction mixture on a Varian INOVA-500 instrument. The yields of **8** and **9** and the amount of recovered **7** were determined using the residual protons of $[D_8]$*i*PrOH as an internal standard.

1d: Pale yellow crystals; m.p. 39.5–40 °C (*n*-hexane); ^{1}H NMR (200 MHz, $CDCl_3$): $\delta = 0.04$ (6H, s), 0.87 (9H, s), 2.05 (6H, s), 2.38–2.45 (2H, m), 2.67–2.79 (2H, m), 4.37–4.51 (1H, m); ^{13}C NMR (125 MHz, $CDCl_3$): $\delta = -4.82$ (CH_3), 4.84 (CH_3), 18.08 (C), 25.81 (CH_3), 46.58 (CH_2), 71.05 (CH), 76.28 (C), 91.98 (C), 126.05 (C); IR (neat): $\tilde{\nu} = 2958$, 2932, 2860, 2224, 1473, 1437,1363, 1257, 1216, 1195, 1104, 1069, 1007 cm^{-1}; MS (EI, 70 eV): *m*/*z* (%): 276 (1.1) $[M^+ + 2H]$, 275 (3.9) $[M^+ + H]$ 274 (16) $[M^+]$, 217 (100), 143 (8.9); elemental analysis calcd for $C_{17}H_{26}OSi$: C 74.39, H 9.55; found: C 74.60, H 9.67; HR-MS (EI, 70 eV) calcd for $C_{17}H_{26}OSi$ $[M^+]$: 274.1753, found 274.1752.

4d: Pale yellow amorphous solid; ^{1}H NMR (500 MHz, $CDCl_3$): $\delta = 0.09$ (6H, s), 0.90 (9H, s), 2.22 (6H, s), 2.81 (2H, dd, ^3J(H,H) = 15.5, 6.0 Hz), 3.06 (2H, dd, ^3J(H,H) = 15.5, 6.5 Hz), 4.63 (1H, quint, ^3J(H,H) = 6.2 Hz), 6.96 (2H, s); ^{13}C NMR (125 MHz, $CDCl_3$): $\delta = -4.73$ (CH_3), 18.25 (C), 19.73 (CH_3), 25.93 (CH_3), 42.21 (CH_2), 74.17 (CH), 125.70 (CH), 134.49 (C), 138.55 (C); IR (neat): $\tilde{\nu} = 3010$, 2960, 2860, 1497, 1464, 1379, 1255, 1199, 1104, 1069 cm^{-1}; MS (EI, 70 eV): *m*/*z* (%): 276 (2.0) $[M^+]$, 261 $[M^+ - Me]$ (3.5), 219 (100) $[M^+ - tBu]$, 145 (14); HR-MS (EI, 70 eV) calcd for $C_{17}H_{28}OSi$ $[M^+]$: 276.1909, found: 276.1901; calcd for $C_{17}H_{28}OSi$ $[M^+ - Me]$: 261.1675, found: 261.1678; calcd for $C_{17}H_{28}OSi$ $[M^+ - tBu]$: 219.1205, found: 219.1238.

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[8] UV spectra of enediynes. **1a** (*n*-hexane): λ_{max} (lg ε) = 270 (4.05), 259 (4.16), 250 nm (sh, 4.05); **1b** (*n*-hexane): λ_{max} (lg ε) = 294 (4.23), 280 nm (4.15); **1c** (*n*-hexane): λ_{max} (lg ε) = 350 (sh, 4.11), 328 (4.32), 260 (4.40), 225 nm (4.31); **1d** (*n*-hexane): λ_{max} (lg ε) = 275 (4.15), 263 nm (4.22); **7** (CH_3CN): λ_{max} (lg ε) = 281 (3.76), 270 (sh, 3.83), 267 (3.84), 258 nm (sh, 3.75).

[9] Turro and co-worker independently found that the photolysis of 1,2-bis(1-pentynyl)cyclopentene as well as of 1,2-bis(1-phenylacetylenyl)-cyclopentene yielded the indane derivatives; see citation [39] in reference [4b].

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[12] We confirmed that the thermal reaction of **7** proceeded smoothly at 57 °C and did not give even trace amounts of **9**. The enediyne **9** did not undergo cycloaromatization at the same temperature; this reaction did not occur at an appreciable rate until at least 100 °C.