Thermal Rearrangements, XXII[1]

The Propargyl-Cope Rearrangement of *meso*- and *d,l*-3,4-Dimethyl-1,5-hexadiyne-3,4-diol

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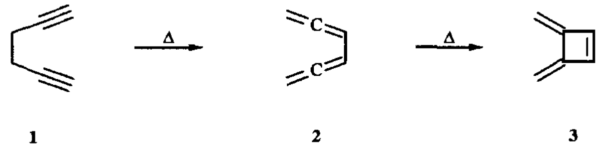
The thermal behavior of *meso*- and *d,l*-3,4-dimethyl-1,5-hexadiyne-3,4-diol (*meso*- and *d,l*-**4**) has been studied at 400°C in the gas phase. In a tandem reaction the diols isomerize via the bisallenes **5** first to *cis*- and *trans*-3,4-diacetylcyclobutene (*cis*- and *trans*-**8**) which have been detected as intermediates by ^{13}C-NMR spectroscopy as well as catalytic hydrogenation to 1,2-diacetylcyclobutane (**9**). Subsequently, **8** stabilizes itself by ring opening to (*E,Z*)- and (*E,E*)-3,5-octadien-2,7-dione [(*E,Z*)- and (*E,E*)-**6**]. As a side reaction retro-ene cleavage of **4** to 2-butynone (**10**) and methyl vinyl ketone (**12**) is observed. By pyrolysis of the pure diastereomers **4** it is shown that the retro-ene process is more pronounced in the *d,l* than in the *meso* series.

In 1963 Huntsman and Wristers[2] first described that 1,5-hexadiyne (**1**, bipropargyl) on heating above 250°C smoothly and quantitatively cyclizes to 3,4-bis(methylene)-cyclobutene (**3**); the Arrhenius parameters, determined in the 210–300°C temperature range (E_a = 34.4 kcal/mol, $\Delta S^{\neq} = -9$ cal K^{-1} mol^{-1}), were indicative of a concerted process[3]. Subsequent work showed that the cycloisomerization actually begins with a [3.3]-sigmatropic process which converts **1** into 1,2,4,5-hexatetraene (**2**, biallenyl) which subsequently electrocyclically closes to **3**[4].

Scheme 1. Propargyl-Cope rearrangement of 1,5-hexadiyne (**1**)



Although the basic reaction mechanism of this "propargyl-Cope-type" isomerization[5] hence appears to be established; the reaction is, in fact, more complicated. Even at the temperatures employed by the original workers **3** is not the only product formed, both fulvene and benzene being produced in small amounts. At higher temperatures (400–600°C) these latter C_6H_6 isomers become the main products as was shown by Jones et al.[6]. Depending on the pyrolysis temperature, either **3** or fulvene can thus be made the main product, making the process a viable and simple method for the preparation of either hydrocarbon (isolated yields of fulvene 30%). Further insights into the details of this part of the C_6H_6 energy surface were obtained by Bergman and Henry who followed the isomerization process by means of a deuterium tracer[7]. Still, as we show in a forthcoming publication[8] the high-temperature behavior of **1**–**3** is far from being totally understood, a fact underlined by the continuing interest of theoreticians in these processes[9].

But it is not only the mechanistic aspect of the propargyl-Cope rearrangement which deserves a second look. Preparatively as well the **1** → **3** cyclization has only been exploited to a very limited extent, the work of Criegee on the use of bismethylenecyclobutenes as starting materials for cyclobutadiene-metal complexes being a notable exception[10]. In principle, though, propargyl-Cope processes could be synthetically as valuable as the Cope rearrangement (of 1,5-hexadienes) itself. To test this proposal one would have to study simple, functionalized 1,5-hexadiynes, not hydrocarbons, and then proceed to more complex structures and applications. One of the few thermal isomerizations of functionalized bipropargyls has been described by Chuche and Manisse[11], and it involves the title compound 3,4-dimethyl-1,5-hexadiyne-3,4-diol (**4**)[12].

When **4** is heated to 350°C the only products formed are 3,5-octadien-2,7-dione (**6**), 2-butynone (**10**) and methyl vi-

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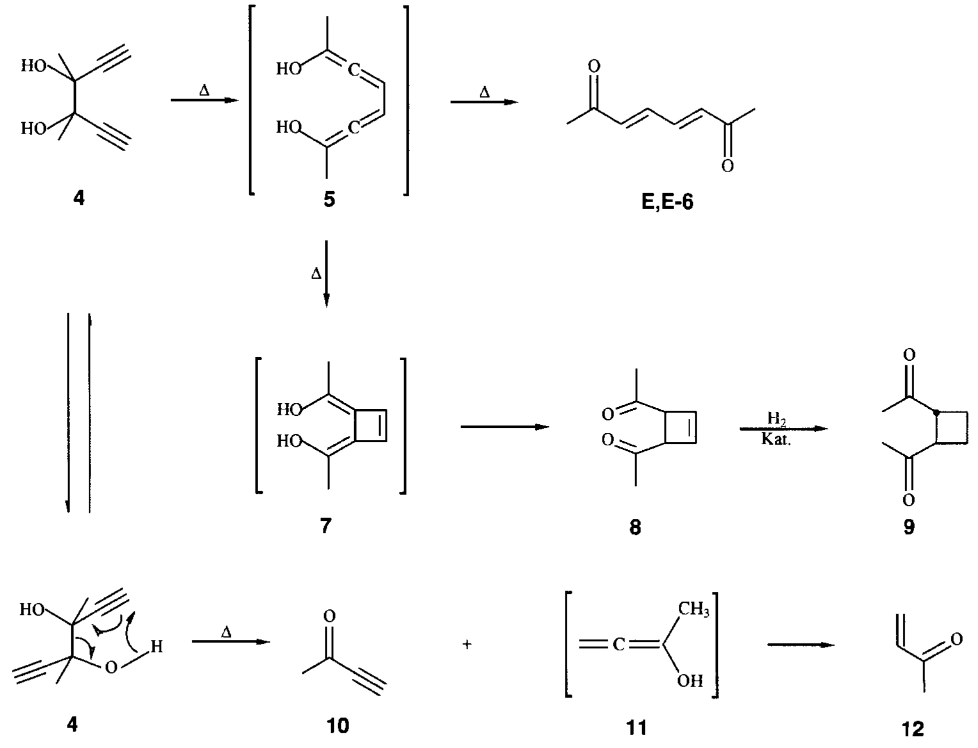
Scheme 2. Thermal isomerization of 3,4-dimethyl-1,5-hexadiyne-3,4-diol (**4**); overall reaction mechanism



nyl ketone (**12**). The latter two compounds are obviously the result of a retro-ene fragmentation (involving the allenol **11** as an intermediate) whereas the former is presumably the bis(ketonization) product of the initial Cope product, 2,3,5,6-octatetraen-2,7-diol (**5**), a bis(enol). The (*E*,*E*) configuration of **6**[13] which is based on NMR and IR evidence[10] has been questioned[13], and indeed it would have been more satisfactory had the spectral data of 3,4-diacetylcyclobutene (**8**) been available as well, the expected product if the course outlined in Scheme 2 had been taken in this instance as well [proceeding via the cyclic bis(enol) **7** in this case]. Since bis(trimethylsilyl) derivatives of **7** have been obtained by thermal rearrangement of the bis(trimethylsilyl) derivative of **4**[14] it is indeed surprising why **8** should be entirely missing in the case of **4**. The isomerization of this diol is furthermore complicated by the fact that it exists in two diasteromeric forms, *meso*- and *d,l*-**4**. Since we considered it necessary to clarify these ambiguities in order to make the propargyl-Cope reaction of synthetic significance, we have prepared the diastereomers of **4** in pure form and have pyrolyzed them both as a mixture and separately.

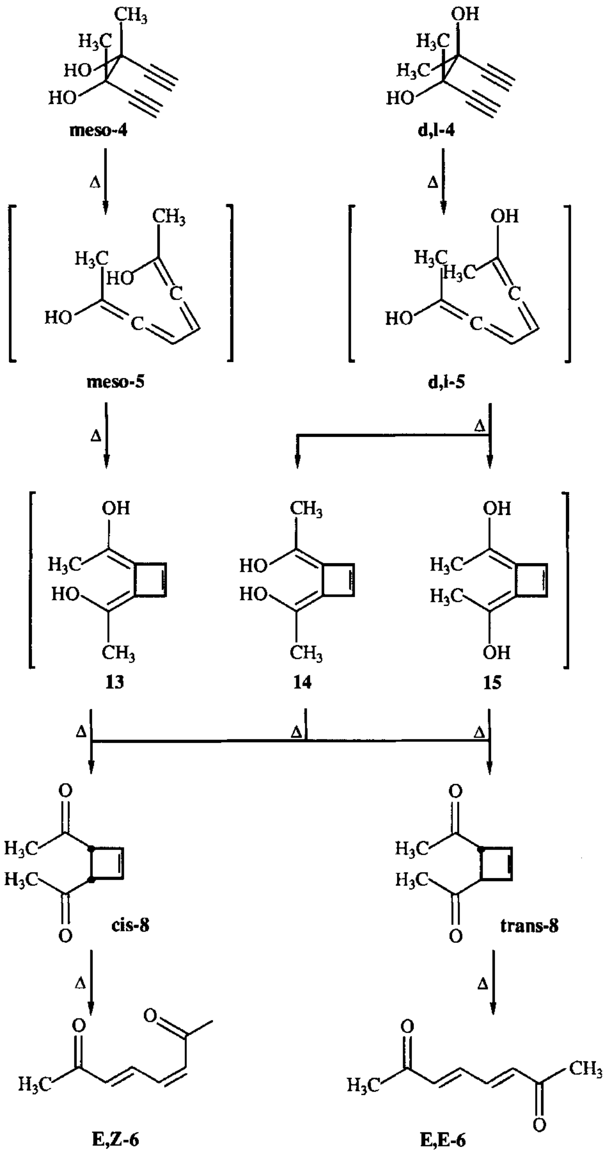
Results and Discussion

The Thermal Isomerization of *meso*- and *d,l*-4 to (*E,Z*)- and (*E,E*)-6

The mixture of *meso*- and *d,l*-**4** employed in this study was obtained by treating biacetyl with an excess of sodium acetylide in liquid ammonia according to a published procedure[15]; according to GC analysis the *meso*/*d,l* ratio is 58:42. Small samples of the analytically pure diastereomers may be isolated by preparative gas chromatography (SE-30, 80°C), whereas for larger amounts their separation by addition/crystallization as described by Schmid and co-workers is to be preferred[16]. The Swiss workers also established the configuration of the two diols, *meso*-**4** being a crystalline solid, its *d,l* form an oil at room temperature[16].

When the *meso*/*d,l* mixture **4** is pyrolyzed at 400°C in the gas phase a pyrolysate is produced which according to ^{13}C-NMR analysis contains besides small amounts of the starting materials and the retro-ene cleavage products **10** and **12** two novel products in a 3:1 ratio which are isomers of **4**. Separating these latter compounds by preparative gas chromatography, we quickly noted by spectral comparison that the new products underwent a chemical transformation in the gas chromatograph whose injection block and detector system were kept at 240°C with a column (SE 30) temperature of 130°C. According to all spectral data (see Experimental) the GC-purified compounds possess the structures of (*E,Z*)- and (*E,E*)-3,5-octadien-2,7-dione [(*E,Z*)- and (*E,E*)-**6**]. Their characteristic signals were absent in the ^{13}C-NMR spectrum of the original pyrolysate. This spectrum however, contained pairs of singlets (in the already mentioned product ratio) at $\delta = 23.1$ and 24.7 (CH_3), 56.2 and 57.4 (CH), 137.1 and 137.6 ($-CH=$) as well as 205.9 and 206.6 ($C=O$), absorptions which are in accordance with *cis*- and *trans*-3,4-diacetylcyclobutene (*cis*- and *trans*-**8**)[17] as the primary isomerization products of **4**. Chemically, the occurrence of a cyclobutene intermediate in the overall isomerization was proven by subjecting a "fresh" pyrolysis mixture to catalytic hydrogenation over platinum followed by gas-chromatographic separation. Among other (unidentified) hydrogenation products *trans*-1,2-diacetylcyclo-

Scheme 3. Thermal isomerization of 3,4-dimethyl-1,5-hexadiyne-3,4-diol (**4**); detailed reaction mechanism



butane (**9**) was isolated as shown by comparing its spectral data with those of an authentic sample prepared by us previously from *trans*-1,2-diethinylcyclobutane by hydration[18]. Since the *cis* isomer of **9** could not be isolated we assume that the major isomer in the cyclobutene series is also *trans*-configurated (*trans*-**8**).

Having detected **8** as a reactive intermediate, we have established the mechanistic picture shown in Scheme 3 for the **4** → **6** interconversion.

The reaction cascade begins with a [3.3]-sigmatropic shift which converts *meso*-**4** into the *meso*-bisallene **5** and *d,l*-**4** into the diastereomeric bisallene *d,l*-**5**. In principle, product formation can take place at this point already, since the dienediones **6** could be produced from the allenols **5** by 1,3-hydrogen shifts (enol-to-ketone interconversions). Although this isomerization may occur catalytically, e.g. on the surface of the pyrolysis system (which had not been deactivated in our pyrolyses), we think it is unlikely to take place in the gas phase since its activation energy should be much higher than that for the ring closure to a bis(methylene)cyclobutene intermediate. As we have pointed out previously[19] the position of the thermal equilibrium between a butadiene and its cyclobutene isomer, which is normally completely on the side of the open-chain structure because of the strain present in the cycloisomer, may be shifted by replacing the double bonds of the diene by allene groupings. With one such allene unit (i.e. in the case of a vinylallene system) the cyclic form just becomes competitive, and with two, as in the case of **5**, the equilibrium is shifted completely towards the cyclic structure.

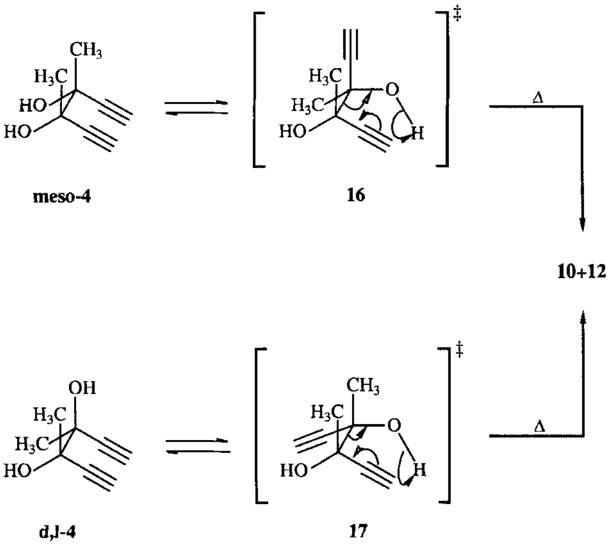
From *meso*- and *d,l*-**5** three stereoisomeric 1,2-bis(methylene)cyclobutene derivatives, **13**–**15**, may be formed. If these ring closures take place by conrotatory electrocyclization *meso*-**5** is converted into **13** exlusively, whereas *d,l*-**5** isomerizes either to the (*Z,Z*) isomer **14** or the (*E,E*) derivative **15**. The ensuing ketonization converts **13**–**15** to the first detectable intermediates, *cis*- and *trans*-**8**. Again, this process is assumed to be slow if it occurs uncatalyzed in the gas phase. If any of the bis(methylene)cyclobutenes prefers to isomerize to either *cis*- or *trans*-**8** is an open question. In principle, both cyclobutenes are accessible from all three isomers **13**–**15**.

In the fourth and ultimate step of the sequence *cis*- and *trans*-**8** open to (*E,Z*)- and (*E,E*)-**6**, respectively. If these processes take place stereospecifically (i.e. in a conrotatory manner) the first two isomers of each pair are correlated, as are the second. Since, however, geometric isomerization may well occur under the reaction conditions not too much significance should be attached to the (*E,Z*)-/(*E,E*)-**6** ratios. That the previous authors[11,14] could not isolate any (*E,Z*)-**6** in their pyrolysis experiments may be regarded as a hint that this equilibration step is actually taking place.

The retro-Ene Cleavage of *meso*- and *d,l*-4 to 10 and 12

Although the retro-ene fragmentation process was not of major concern in the present study – after all, both **10** and especially **12** are available by much simpler reactions – it was thought worth while studying the details of this side reaction, especially since both diastereomers were available in pure form. To this end, the two diols were pyrolyzed at 400°C under conditions which provide the cyclobutene intermediates **8** only in concentrations below the detection limit of ^{1}H-NMR spectroscopy. This is the case when the diols are passed comparatively slowly through the pyrolysis oven allowing sufficient time for the cyclobutene **8** to undergo ring opening to isomers of **6**. According to ^{1}H-NMR analysis *meso*-**4** yielded a pyrolysate containing 24% of the starting material, 19% each of (*E,Z*)- and (*E,E*)-**6**, and both 19% of 2-butynone (**10**) and methyl vinyl ketone (**12**). From *d,l*-**4** the same compounds are formed in 24, 13, 13, 25, and 25% yield, respectively. Thus, although the two diols do not show any dramatic difference in their pyrolysis behavior there is a clear increase in retro-ene decomposition for the *d,l* diastereomer. This process can occur only if the hydroxy and the ethinyl function are oriented in one plane as shown in **16** for the *meso* compound[13]. When *d,l*-**4** fulfills this condition (reactive conformation **17**) both hydroxy groups are in juxtaposition to triple bonds causing a statistical advantage for the retro-ene reaction in this case as compared to *meso*-**4**/**16**.

Scheme 4. Retro-ene fragmentation of *meso*- and *d,l*-**4**



Considering the ease with the readily available bis(ethynyl)diol **4** is converted into the unsaturated ketones **8** the propargyl-Cope isomerization of appropriately functionalized 1,5-hexadiynes (including cyclic ones) clearly deserves the increased attention of the synthetic chemist.

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Experimental

IR (film): Perkin-Elmer 157 and Nicolet 320 FT/IR. – UV: Beckman UV 5230. – MS: MAT 8430. – ^{1}H NMR: Varian T60 (60 MHz) and Bruker AM-400 (400.13 MHz) in deuteriochloroform with TMS as internal standard. – ^{13}C NMR: Bruker AM-400 (100.60 MHz) in deuteriochloroform which also served as internal standard ($\delta^{13}C = 77.05$). Spin multiplicities were determined by the DEPT 135 technique. – Analytical GC: DANI 3800, 30 m quartz capillary column SE 54. – Preparative GC: Shimadzu GC 8A, 6-m column, 20% SE-30.

Pyrolysis of meso- and d,l-3,4-Dimethyl-1,5-hexadiyne-3,4-diol (*meso*- and *d,l*-**4**): The pyrolysis reactions were carried out by passing the diol mixture through a quartz tube (*i.d.* = 3 cm, *l* = 80 cm) which had been placed into a Heraeus tubular furnace. The tube was connected through a series of cold traps (–196°C) to a high-vacuum system which maintained a pressure of 10^{-3} Torr. After warming to room temp. and weighing, the contents of the traps was analyzed by NMR spectroscopy and analytical gas chromatography. In a typical experiment 1.0 g (7.2 mmol) of a *meso*-/*d,l*-**4** mixture was pyrolyzed at 400°C (pyrolysis time: several min). Amount of material condensed in the cold traps: 0.7 g (70%). Composition (^{1}H-NMR analysis): **10** (10%), **12** (10%), *meso*-/*d,l*-**4** (30%), *trans*-**8** (35%), *cis*-**8** (15%); ^{13}C-NMR data of *trans*- and *cis*-**8**: Main section. When this mixture was separated by preparative GC (130°C, 6 m SE-54) the isomers **8** were converted into (*E,Z*)- and (*E,E*)-**6**. The same result may be obtained by increasing the contact time (30 min). Since the spectroscopic data of the isomers **6** reported in the literature are incomplete[11,14,20] they are given in this paper in full. – *(3E,5Z)-Octadien-2,7-dione:* Yellow oil. – IR (film): $\tilde{\nu}$ = 3075 cm^{-1} (w), 3005 (m), 1690 (vs), 1670 (vs), 1640 (s), 1610 (s), 1575 (vs), 1515 (s), 1360 (vs), 1180 (vs), 1020 (s), 1005 (s), 975 (s), 860 (m). – ^{1}H NMR: δ = 8.22 (ddd, *J* = 16.0, 11.2 and 1.0 Hz, 4-H), 6.51 (td, *J* = 11.2, 11.2 and >0.6 Hz, 5-H), 6.34 (d, *J* = 11.2 Hz, 6-H), 6.26 (d, *J* = 16.0 Hz, 3-H), 2.37 (s, 1-H), 2.31 (s, 8-H). – ^{13}C NMR: δ = 199.28, 198.65 (2 × C=O), 139.66, 138.45, 138.13, 131.03 (4 × =CH), 31.77, 26.65 (2 × CH_3). – UV (acetonitrile): λ_{max} (lg ε) = 205 nm (3.66), 274 (4.32). – MS (70 eV): *m/z* (%) = 139 (6), 138 (39) [M^+], 123 (6), 96 (8), 95 (100), 69 (6), 67 (18), 51 (10), 43 (88), 41 (17). – *(3E,5E)-Octadien-2,7-dione:* Colorless needles, m.p. 125°C[20]. – IR (KBr): $\tilde{\nu}$ = 3052 cm^{-1} (m), 3026 (w), 3001 (w), 1664 (vs), 1629 (s), 1592 (s), 1254 (vs), 1201 (s). – ^{1}H NMR: δ = 7.16 and 6.47 (two complex AA'XX' multiplets, $J_{34} = J_{56} = 15.6$, $J_{45} = 11.2$, $J_{35} = J_{46} = -0.8$, $J_{36} = +0.7$ Hz), 2.34 (s, 1 and 8-H). – ^{13}C NMR: δ = 197.64 (C=O), 139.64 and 136.80 (2 × =CH), 27.86 (CH_3). – The UV spectrum is reported in ref.[20].

Catalytic Hydrogenation of the Pyrolysis Mixture: 1.0 g of a freshly prepared pyrolysis mixture was dissolved in 20 ml of ethyl acetate, then 0.5 g of a Pd/C catalyst (0.5% Pd) was added to the solution, and the resulting suspension was stirred at room temp. under hydrogen for 18 h. After filtration, *trans*-1,2-diacetylcyclobutane (*trans*-**9**) was isolated from the product mixture by preparative GC (6 m SE 54, 120°C). Although *trans*-**9** is a known compound[18] its spectral data have not been published in the primary literature. – IR (film): $\tilde{\nu}$ = 2990 cm^{-1} (w), 2950 (w), 1780 (vs), 1360 (m), 1180 (m). – ^{1}H NMR: δ = 3.54–3.47 (m, 2H, 1-, 2-H), 2.13–2.06 (m, 4H, 3-, 4-H_2), 2.11 (s, 6H, 2 CH_3). – ^{13}C NMR: δ = 208.0 (C=O), 46.8 (CH), 27.3 (CH_3), 20.8 (CH_2).

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