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Origin of the Regiochemistry in the Photochemical Cycloaddition Reaction of 2-Cyclopentenone with Allene: Trapping of Triplet 1,4-Biradical Intermediates with Hydrogen Selenide[1]

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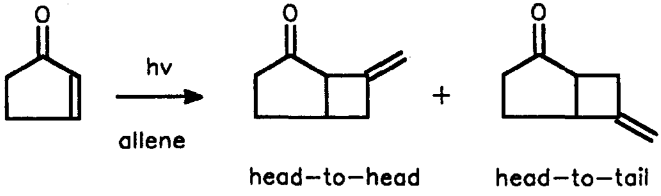
Abstract: *The photochemical cycloaddition reaction between 2-cyclopentenone and allene in toluene at -78°C yields cyclobutane adducts with head-to-head and head-to-tail regiochemistry in a ratio of 88:12. In the presence of high concentrations of hydrogen selenide the three 1,4-biradical intermediates involved in the photocycloaddition reaction are quantitatively trapped in the ratio 68:29:3. The dominant biradical intermediate is derived from bonding of the enone 2-position to one of the allene terminal carbons and is the precursor of the minor, head-to-tail cycloadduct; in the absence of hydrogen selenide this biradical therefore preferentially reverts to ground state starting materials. The biradical formed in least amount is derived from bonding of the enone 3-position to one of the terminal carbons of the allene, while the third biradical is derived from bonding of the enone 2-position to the central carbon of allene; both of these biradicals close to yield the head-to-head cycloadduct regiosomer.*

The photochemical cycloaddition of allene to 2-cyclopentenone yields cyclobutane adducts with preferential head-to-head regiochemistry (Scheme 1).[2] This is in contrast to the preferential head-to-tail orientation of addition to cyclic enones observed with the majority of mono-substituted alkenes.[3] The allene reaction therefore offers a method of control of regiochemistry for synthetic applications of the photocycloaddition reaction of cyclic enones with alkenes.[4]

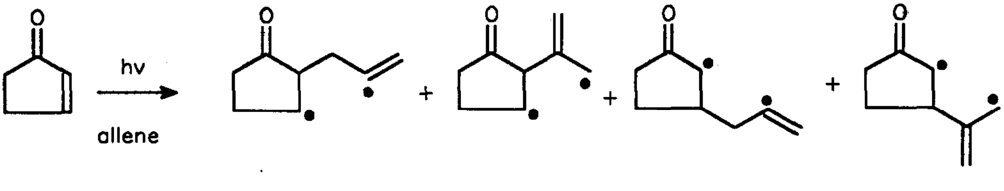
SCHEME 1



The origin of the regioselectivity and the mechanism of the allene photocycloaddition reaction with cyclic enones have been the subject of some debate. By analogy with the corresponding reaction with simple alkenes it is generally assumed that the addition occurs from the enone triplet excited state and proceeds via triplet 1,4-biradical intermediates formed by bonding of an allene carbon to either the 2-position or the 3-position of the enone. The structures of the biradicals that could, in principle, be intermediates are shown in Scheme 2. Biradicals 1 and 4 are the possible precursors of the head-to-tail cycloadduct, while biradicals

2 and 3 are the possible precursors of the head-to-head cycloadduct. Each of these biradical intermediates could be formed at different rates, and hence to different extents. In addition, following spin inversion each could proceed to products or revert to ground state starting materials with different efficiency. Thus, the overall reaction regiochemistry could depend either on the relative rates of formation of the biradicals 1-4, or on the relative efficiencies with which they close to product in competition with dissociation to the ground state precursors. Possibly both of these factors could be important in determining the reaction regiochemistry.

SCHEME 2



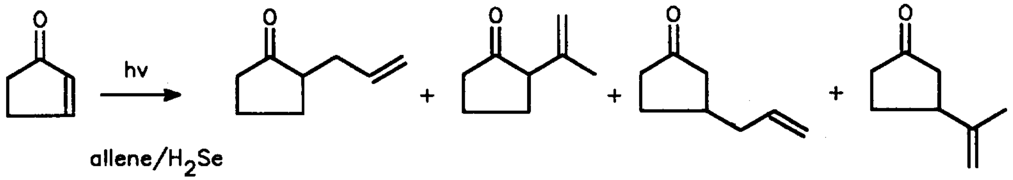
1 2 3 4

In order to explain the stereochemical outcome of the photocycloaddition reaction between cyclohexenones and allene Wiesner proposed[9] some years ago that in the enone excited state the β-carbon (i.e. the carbon in the 3-position) becomes pyramidal while the α-carbon (i.e. that in the 2-position) remains trigonal; product formation then proceeds by interaction of the allene π-system with the exposed sp^3 lobe of the pyramidalized carbon. Since the head-to-head cycloadduct predominates, this proposal implies that biradical 3 must be formed faster than biradical 4, and that biradicals 1 and 2 are not important intermediates. Elsewhere the possibility has been discussed[10,11,12] that the reaction might also proceed by attack of the enone excited state at the central carbon of the allene, to produce biradicals 2 and 4, rather than attack at one of the terminal carbons to give biradicals 1 and 3. However, it has been pointed out[10,11] that a variety of radicals show a high to moderate preference for attack at the terminal carbons of allene and that this therefore may also be the case for attack by the triplet excited state of a cyclic enone; if this were so then the head-to-head and head-to-tail cycloadducts would tend to be derived from biradicals 3 and 1, respectively.

It has recently been shown that the biradicals involved as intermediates in the photocycloaddition of a variety of alkenes to cyclopentenones[8,13] and to *N*-acylindoles[8,14] can be trapped quantitatively by hydrogen selenide, which acts as a fast hydrogen atom donor for reduction of the radical centres. Application of this technique to the photocycloaddition reaction of 2-cyclopentenone with allene could reveal how much of each of the biradicals 1-4 are formed and hence reveal the origin of the regioselectivity of the reaction. Accordingly, we have examined the photoaddition of allene to 2-cyclopentenone in toluene at -78°C in the presence and absence of varying concentrations of hydrogen selenide (TOXIC[15]).[16] In the absence of hydrogen selenide the head-to-head and head-to-tail cyclobutane adducts shown in Scheme 1 were obtained as the only products in a ratio of 88:12. In the presence of sufficient amounts[16] of hydrogen selenide the formation of cycloadducts was completely suppressed and instead compounds 5-7 were obtained as the only photochemical products. Compounds 5-7 were formed in the ratio 68:29:3 and are presumed to arise from reduction of biradicals 1-3, respectively; none of the product of trapping of biradical 4, i.e. compound 8, was detected. The formation of compounds 5 and 7, and the absence of 8, was confirmed by g.c. and g.c.-m.s. comparison with authentic samples prepared by unambiguous routes.[17] The identification of compound 6 was confirmed by conversion (by ozonolysis) to 2-acetylcyclopentanone and comparison with an authentic sample, and by rearrangement to 2-isopropylidenecyclopentanone.

The relative yields of **5**-**8** are a direct measure of the relative amounts of the biradicals **1**-**4** formed in the photocycloaddition of allene to cyclopentenone, and of their relative rates of formation by interaction of the enone excited state with allene. Therefore the relative yields of **5**-**8** indicate that the initial bond formed between the enone triplet excited state and the allene is overwhelmingly to the 2-position of the enone. This is in contrast to the situation found for photocycloaddition of simple, non-cumulated alkenes to cyclopentenone where little selectivity between the 2- and 3-positions is seen in the initial step leading to biradical formation.[8,13] The preferential formation of product **5** over **6** indicates that attack of the enone triplet on an allene terminal carbon to give biradical **1** is faster than attack at the central carbon to give biradical **2**. This is consistent with the preference seen for the attack of many radicals on allene.[10,11] This preference is somewhat surprising given that **2** possesses an allyl radical and might be expected to be more stable than **1**, which possesses a vinyl radical. However, it has been calculated[18] that addition of radicals to the central carbon of allene is a higher activation energy process than addition to one of the terminal carbons. It is interesting to note that the ratio of **5**:**6** is close to the statistical product ratio expected if attack of the enone triplet excited state at the central and the terminal carbons of allene were to occur at the same rate.

SCHEME 3



5 (68%) **6** (29%) **7** (3%) **8** (0%)

The total yield of **2** and **3**, which are the precursors of the major, head-to-head adduct is lower than that of **1**, which is the precursor of the minor, head-to-tail adduct. This implies that following spin inversion **1** preferentially reverts to ground state starting materials while **2** and **3** are more prone to close to product. Therefore, as is also the case for the addition of mono-substituted alkenes to cyclopentenone,[8,13] the regiochemistry of the photocycloaddition with allene is determined by the fates of the intermediate biradicals and not by their relative rates of formation.

The use of lower concentrations of hydrogen selenide resulted in incomplete suppression of photoadduct formation. For example, when the hydrogen selenide concentration was *circa* 2 M the ratio of the total amount of cycloadducts formed to the total amount of trapped product was 30:70; in addition, the ratio of head-to-head to head-to-tail cycloadduct was 60:40 (compared with 88:12 in the absence of hydrogen selenide) and the trapped product ratio **5**:**6**:**7**:**8** was 0:70:30:0. This suggests that biradicals **2** and **3** may have similar lifetimes which are considerably longer than that of **1**.

We are currently attempting to trap the biradical intermediates in the photocycloaddition reaction of 2-cyclohexenone and 2-cyclopentenone with alkyl-substituted allenes, and of 2-cyclohexenone with allene itself in order to determine the effect of structure on the selectivity of biradical formation and also to correlate this with the regiochemistry of the cycloaddition reaction.

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3. Alkenes with a single alkyl substituent show a weak preference for the formation of head-to-tail products when irradiated with 2-cyclopentenones or 2-cyclohexenones; however, a polar, electron donating substituent on the alkene generally favours the formation of the head-to-tail product strongly (for examples see reference 4). For many years it has been assumed, based on a very few examples, that alkenes possessing an electron withdrawing substituent yield the head-to-head regiosomer preferentially; however several recent reports indicate that cyano or carboalkoxy substituted alkenes can yield the head-to-tail regioisomer as the major product (see references 5-8).
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15. HYDROGEN SELENIDE IS AN EXTREMELY TOXIC GAS AND SHOULD BE HANDLED WITH UTMOST CAUTION.
16. Hydrogen selenide gas was prepared by addition of water to a known weight of powdered aluminum selenide under an atmosphere of nitrogen. The hydrogen selenide gas evolved was condensed directly into a toluene solution (7 ml) containing 2-cyclopentenone (0.1 M) and allene (1.0 M) and maintained at -78°C. The concentration of the hydrogen selenide was estimated and controlled by adjusting the weight of aluminum selenide used and was varied from *circa* 0.1 M to 12 M. The aluminum selenide was prepared by magnesium flare induced fusion of powdered aluminum and selenium according to the method described by F. Feher in *Handbook of Inorganic Chemistry*, G. Bauer (ed.), Academic Press, New York, 1963, Vol. 1, p 418. The toluene solutions were irradiated at -78°C using Pyrex and water filtered light from a medium pressure mercury lamp.
17. Compound **5** was prepared using the method of N.B. Lorette, and W.L. Howard, *J. Org. Chem.*, **1961**, *26*, 3112; *ibid.*, **1960**, *25*, 521. Compound **7** was prepared by the method of W.C. Agosta, and S. Wolff, *Tetrahedron Letters*, **1979**, *31*, 2845. Compound **8** was prepared by conjugate addition of the appropriate alkenyl Grignard reagent to cyclopentenone.
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