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Ene Reaction of Arylallyl Alkenes with C_{60}. A Mechanistic Approach

Nikos Chronakis and Michael Orfanopoulos*

Department of Chemistry, University of Crete, Iraklion 71409, Crete, Greece

orfanop@chemistry.uch.gr

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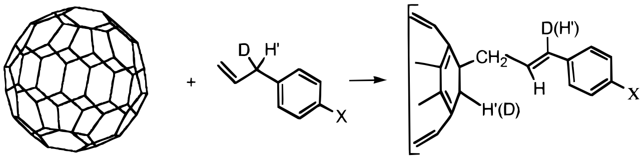
ABSTRACT



The ene reaction of arylallyl alkenes with C_{60} occurs either by a concerted mechanism or by the reversible formation of a charged or a dipolar intermediate, followed by the C–H(D) breakage in a rate-limiting step.

The isolation of C_{60} in large quantities[1] triggered a large number of investigations, over the past 10 years, on its chemical reactivity and physical properties. Several research groups have reported the preparation and isolation of well characterized [4 + 2],[2] [3 + 2],[3,4] and [2 + 2][5−8] monoadducts of C_{60}. However, the ene functionalization of C_{60} has received less attention and, to our knowledge, only three reports describe the isolation and characterization of ene monoadducts. For example, Wu and Komatsu reported[9] independently the first examples of ene addition of 1-heptene, 4-propenylanisole, and 3,5-di-*tert*-butyl-4-(trimethylsiloxy)-allylbenzene to C_{60}. Later, Miles and co-workers[10] reported an additional example of the ene reaction of C_{60} with 3-methylene-2,3-dihydrofuran.

Our previous mechanistic studies of the ene reaction of several enophiles with alkenes,[11] as well as the recent reports of [2 + 2] cycloadditions[8] of aryl alkenes and dienes to C_{60}, prompted us to investigate for the first time the mechanism

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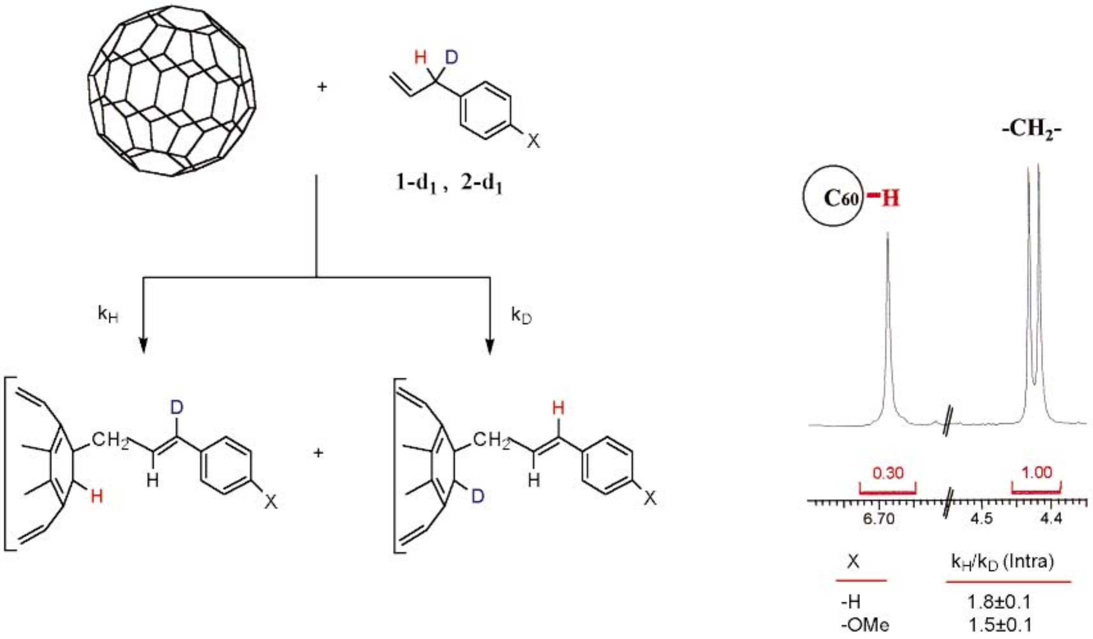
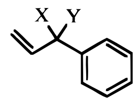
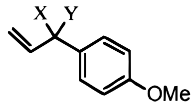


Figure 1. Intramolecular isotope effects in the ene reaction of **1-d$_1$** and **2-d$_1$** with C_{60}.

of C_{60}-ene functionalization. For this purpose we have studied and report here both intramolecular (product) and intermolecular (kinetic) isotope effects of the ene reaction of C_{60} with arylallyl alkenes.

It is well established that isotope effect measurements are a powerful tool for distinguishing between concerted and stepwise reaction pathways.[11,12] To determine the intramolecular isotope effect, a mixture of C_{60} and a 100-fold excess of 3-phenyl-1-propene-3-d$_1$, **1-d$_1$**,[13] were dissolved in deoxygenated toluene and heated at 200 °C in a thick glass tube equipped with a rotaflo valve and magnetic stirrer. The reaction was interrupted at various conversions and analyzed by HPLC equipped with a Separon C_{18} reversed phase column.





1-d$_0$ X= H, Y= H
1-d$_1$ X= H, Y= D
1-d$_2$ X= D, Y= D

2-d$_0$ X= H, Y= H
2-d$_1$ X= H, Y= D
2-d$_2$ X= D, Y= D

A 24% yield of the ene monoadduct was obtained after 40 h, based on the recovered C_{60}. The adduct was purified by flash column chromatography (toluene/hexane 2/1) and characterized by ^{1}H NMR and FAB-MS [*m*/*z* (M + 1) 840.92].

A substantial intramolecular (product) isotope effect $k_H/k_D = 1.80$ (average) was measured by careful integration of the methylenic hydrogen absorptions at 4.46 ppm and the hydrogen on the fullerene carbon at 6.69 ppm, Figure 1.

The intermolecular (kinetic) isotope effect k_H/k_D was obtained from the equimolar competition of **1-d$_0$** vs **1-d$_2$**[13] with C_{60}. The experimental conditions were similar to those described previously for the intramolecular competition. Again, a substantial kinetic isotope effect (average $k_H/k_D = 2.0$) was found. The results are shown in Table 1. These effects (substantial intra- and intermolecular isotope effects) are comparable to previously reported isotope effects for other ene reactions which were interpreted as supporting a concerted reaction mechanism.[12] It should be noted that the determination of the primary isotope effects was possible only from the integration of the methylenic absorption at 4.46 ppm and the C_{60}−H absorption at 6.69 ppm (Figure

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[13] Alkenes **1-d$_1$**, **1-d$_2$**, **2-d$_1$**, and **2-d$_2$** were prepared as follows: reduction of benzaldehyde with $LiAlD_4$ followed by chlorination with thionyl chloride gave the corresponding benzyl chloride-*d*$_1$. The Grignard reagent of benzyl chloride-*d*$_1$ coupled with vinyl bromide in the presence of $NiCl_2/Ph_3P$[14] catalyst, to give **1-d$_1$**, in 70% yield. MS [*m*/*z* 118 (M − 1, 100)]. Reduction of methyl benzoate with $LiAlD_4$ gave benzyl chloride-*d*$_2$, and then following the procedure described for the preparation of **1-d$_1$**, **1-d$_2$** was prepared in reasonable yield. MS [*m*/*z* 119 (M − 1, 100)]. NBS monobromination of methyl *p*-methoxyphenylacetate followed by $LiAlD_4$ reduction gave 2-(*p*-methoxyphenyl)ethanol-*1,1,2-d*$_3$ which was then converted to the corresponding bromide by using $Ph_3P{\cdot}Br_2$ as the brominating reagent. Reaction of 2-(*p*-methoxyphenyl)ethyl-*1,1,2-d*$_3$ bromide with Ph_3P gave the corresponding Wittig salt. The α-deuterium atoms of this salt were exchanged for hydrogens by treating the Wittig salt with $NaOH/CH_3OH$.[15] The ylide of the previously prepared Wittig salt was coupled with paraformaldehyde to afford **2-d$_1$**. MS [*m*/*z* 149 (M^+, 100)]. Treatment of the *p*-methoxyphenylacetic acid with NaOH in D_2O at 160 °C, and after repeating this process twice gave *p*-methoxyphenylacetic acid-*d*$_2$, **2-d$_2$** , with more than 96% deuterium atom incorporation. Esterification of the above deuterated acid followed by $LiAlH_4$ reduction afforded 2-(*p*-methoxyphenyl)ethanol-*d*$_2$, **2-d$_2$**, and then, following the procedure described for the preparation of **2-d$_1$** (delete the step of D exchange), **2-d$_2$** was prepared. MS [*m*/*z* 150 (M^+, 100)].

Table 1. Isotope Effects for the Ene Reaction of 3-Phenyl-1-propene and 3-(*p*-Methoxyphenyl)-1-propene with C_{60}

reaction type	substrate	solvent	*t*, h	convn,[a] %	*T*, °C	k_H/k_D[b]
intramol.	**1-d$_1$**	toluene	40	24	200	1.8 ± 0.1
intermol.	**1-d$_0$/1-d$_2$**	toluene	40	21	200	2.0 ± 0.1
intramol.	**2-d$_1$**	DCB[c]	3	24	180	1.5 ± 0.1[d]
intermol.	**2-d$_0$/2-d$_2$**	DCB[c]	3	25	180	1.8 ± 0.1[d]

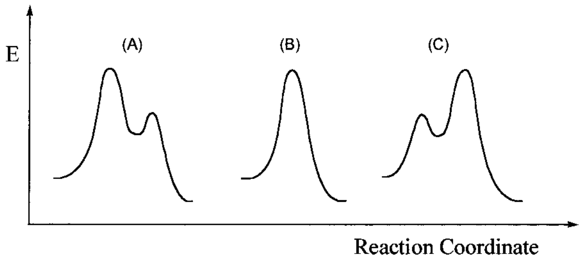
[a] Based on recovered C_{60}. [b] Determined by ^{1}H NMR integration of the methylenic and C_{60}-H protons. [c] 1,2-Dichlorobenzene. [d] Determined as previously[b] and by ^{1}H NMR integration of the vinylic and aromatic protons.

1). It was difficult to measure the isotope effect from the integration of the vinylic hydrogen absorption (between 7.26 and 7.05 ppm) of the ene adducts, because the phenyl hydrogens of traces of toluene, which was the solvent used in the reaction, absorb in the same chemical shift region. Several attempts to remove completely toluene from the ene adduct were unsuccessful. A crystalline form of C_{60} in which a number of toluene molecules are occluded is probably formed.[16]

To confirm both the intra- and the intermolecular isotope effect values found with the 3-phenyl-1-propene system, the 3-(*p*-methoxyphenyl)-1-propene-3-d_1, **2-d$_1$**, and its dideuterated analogue 3-(*p*-methoxyphenyl)-1-propene-3,3-d_2, **2-d$_2$**, were prepared[13] and studied. In this case, the ene reactions of **2-d$_1$** and **2-d$_0$/2-d$_0$** with C_{60}, in separate experiments (intra- and intermolecular competition correspondingly), were run in 1,2-dichlorobenzene, DCB, using molar ratios similar to those described previously. DCB dissolves C_{60} better than toluene.[17] The presence of the heteroatom oxygen in these substrates (**2-d$_1$**, **2-d$_0$**, and **2-d$_2$**) makes the separation and purification of the C_{60} derivatives much easier. Moreover, unlike toluene, DCB is completely removed from the reaction mixture at the end of the reaction. The ene adducts were characterized both by ^{1}H NMR chemical shifts and by FAB-MS. The isolated ene monoadduct was stable under the reaction conditions for several hours. The results are summarized in Table 1. The measured intramolecular (product) isotope effect k_H/k_D was 1.5 and the intermolecular k_H/k_D was 1.8, values which are similar to those obtained from the ene reaction of C_{60} with **1-d$_1$** and **1-d$_0$/1-d$_2$** ($k_H/k_D = 1.8$ and 2.0 respectively). In this case, the determination of the isotope effects was possible by integration of the appropriate signals in two independent hydrogen absorption regions, namely, by the integration of the vinylic vs the phenylic hydrogens, as well as of the methylenic vs C_{60}-H of the ene adducts. Both integrations gave, within experimental error, the same isotope effects. Thus, these results confirm the measured values of primary isotope effects of the **1-d$_1$** and **1-d$_0$/1-d$_2$** system with C_{60}. Furthermore, these results indicate that under the reaction conditions and purification processes no H/D exchange of C_{60}-H occurs, although the hydrogens on the C_{60} carbon (C_{60}-H) are weakly acidic.[18]

The similar and substantial product and kinetic isotope effects exclude a mechanism where the formation of an intermediate is a rate-determining step, case A in Scheme 1.

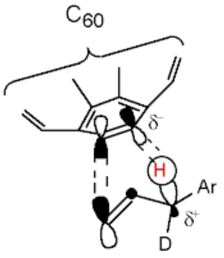
Scheme 1. Possible Mechanism of the ene Reaction of C_{60} and Aryl Alkenes.



Had this been the case, no C−H(D) bond breaking would have occurred at the transition state and only a very small intermolecular kinetic isotope effect, if any, would have been expected. The presense of substantial and equal kinetic and product isotope effects in the inter- and intramolecular competitions (Table 1) supports a concerted one-step reaction, i.e., case B in Scheme 1, with both C−H bond breaking and C−C bond making having occurred in the transition state. This is consonant with previous findings in a variety of other concerted ene reactions.[12] However, the reversible formation of a charge transfer or a dipolar intermediate preceding the rate-determining step, case C in Scheme 1, cannot be excluded.

The relatively small primary isotope effects, k_H/k_D about 2, measured in these studies may be attributed either to a bent transition state, i.e., nonlinear transfer of the hydrogen between the two carbons, or to a linear but early transition state in which the C−H bond breaking is not extensively developed. It is interesting also to note that the reaction rate increases by a factor of 20 in going from the nonpolar solvent toluene to the more polar DCB.[19] Furthermore, the ene

Scheme 2. Unsymmetrical and Partially Charged Transition State of the Ene Reaction of C_{60} and Arylallyl Alkenes.



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reaction of 3-(*p*-methoxyphenyl)-1-propene, **2-d$_0$**, is three times faster than that of the corresponding nonsubstituted allylbenzene, **1-d$_0$**. These results indicate an ene transition state with a partial dipolar character. A suprafacial orbital presentation of an unsymmetrical and partially charged transition state is shown below, Scheme 2.

In conclusion, the ene reaction of arylallyl alkenes with C_{60} occurs either by a concerted mechanism or by the reversible formation of a charged or a dipolar intermediate that is followed by the rate-determining breaking of the C−H(D) bond.

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Supporting Information Available: GC MS and ^{1}H NMR spectra for **1-d$_1$**, **1-d$_2$**, **2-d$_1$**, and **2-d$_2$**; high-resolution FAB-MS and ^{1}H NMR spectra for adducts C_{60} with **1-d$_1$**, **1-d$_0$/1-d$_2$**, **2-d$_1$**, and **2-d$_0$/2-d$_2$**; kinetic data. This material is available free of charge via the Internet at http://pubs.acs.org.

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