Mechanism of the [2 + 2] Photocycloaddition of Fullerene C_{60} with Styrenes

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Stereochemical studies on [2 + 2] photoaddition of *cis*-/*trans*-4-propenylanisole (*cis*-**1** and *trans*-**1**) and *cis*-1-(*p*-methoxyphenyl)ethylene-2-d_1 (*cis*-**3**-d_1) to C_{60} exhibit stereospecificity in favor of the *trans*-**2** cycloadduct in the former case and nonstereoselectivity in the latter. The observed stereoselectivity in favor of the *cis*-**6**-d_3 [2 + 2] diastereomer by 12% in the case of the photochemical addition of (*E*)-1-(*p*-methoxyphenyl)-2-methyl-prop-1-ene-*3,3,3*-d_3 (*trans*-**5**-d_3) to C_{60} is attributed to a steric kinetic isotope effect ($k_H/k_D = 0.78$). The loss of stereochemistry in the cyclobutane ring excludes a concerted addition and is consistent with a stepwise mechanism. Intermolecular secondary kinetic isotope effects of the [2 + 2] photocycloaddition of **3**-d_0 vs **3**-d_1, and **3**-d_6 as well as **5**-d_0 vs **5**-d_1, and **5**-d_6 to C_{60} were also measured. The intermolecular competition due to deuterium substitution of both vinylic hydrogens at the β-carbon of **3** exhibits a substantial inverse α-secondary isotope effect $k_H/k_D = 0.83$ (per deuterium). Substitution with deuterium at both vinylic methyl groups of **5** yields a small inverse $k_H/k_D = 0.94$. These results are consistent with the formation of an open intermediate in the rate-determining step.

Introduction

Since the discovery of C_{60}[1] (buckminsterfullerene) and its preparation in large quantities,[2] a large variety of thermal and photochemical cycloadditions[3] have been studied. C_{60} behaves like an electron-deficient alkene, with double bonds located at the junctions of two hexagons (6−6 bonds),[4] rather than like an aromatic compound. It is an electronegative molecule, which can be easily reduced.[5] This is reflected theoretically by the molecular orbital diagram[6] of C_{60} (low-lying triply degenerate LUMOs), as well as experimentally by the reversible one-electron reductions up to a hexaanion.[7] The relief of strain in the C_{60} cage (highly pyramidalized sp^2 carbon atoms)[8] is the primary driving force for addition reactions. As a result of these properties, C_{60} undergoes exothermic, electrophilic cycloadditions on the 6−6 double bond. Due to the stability of the cycloadducts, further side-chain chemistry can be applied which is suitable for preparation of useful and interesting fullerene derivatives.

[2 + 2] cycloadditions to C_{60} are relatively uncommon. The thermal [2 + 2] cycloaddition of benzyne to C_{60} was the first reported example.[9] Foote and co-workers reported a possible charge-transfer mechanism for the photochemical [2 + 2] cycloaddition of electron-rich ynamines[10] to $^3C_{60}$. The triplet excited state of C_{60} ($^3C_{60}$) is formed with a quantum yield near unity and has a reduction potential close to 0.98 V.[11] Thus $^3C_{60}$ is more electrophilic than the ground state. They also reported the thermal [2 + 2] cycloaddition of tetraalkoxyethylenes[10c] (a very efficient π-electron donor) to C_{60} and C_{70}.

Schuster and co-workers have reported a photochemical [2 + 2] cycloaddition of cyclic enones[12] and cyclic 1,3-diones[13] to C_{60}. These photocycloadditions cannot be achieved by irradiation at 532 nm wavelength where C_{60}

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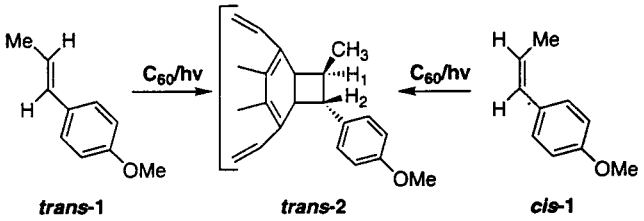
Scheme 1. Stereospecific Photochemical [2 + 2] Cycloaddition of *trans*-1 and *cis*-1 to C_{60}



is the only light absorbing component,[12a] while product yields were improved either by decreasing the concentration of C_{60} or by increasing the concentration of enone. These results indicate that $^3C_{60}$ does not undergo addition to the ground-state enone. It was proposed that the addition of enones to C_{60} proceeds by a stepwise addition of the enone triplet excited state to the ground state of the fullerene, via an intermediate triplet 1,4-biradical, as occurs in the [2 + 2] photoadditions of enones to alkenes.[14] The regio- and stereoselectivity of the [2 + 2] photocycloaddition of acyclic enones to C_{60} was also recently reported.[15]

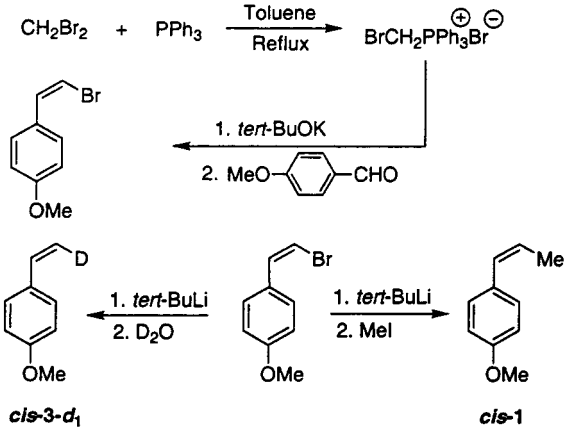
We also reported[16] the photochemical [2 + 2] cycloaddition of alkyl substituted 1,3-butadienes to C_{60}. These substrates are less electron rich than the previously reported unsaturated substrates that undergo [2 + 2] addition to $^3C_{60}$. Stereochemical and secondary kinetic isotope effects studies showed that electron transfer from the dienes to $^3C_{60}$ was the likely first step of the reaction, followed by rapid collapse of the initial open intermediate to the [2 + 2] adducts.

In this paper, we report the stereochemistry and the secondary isotope effects of [2 + 2] photocycloaddition between arylalkenes and C_{60}. These results shed light on the mechanism of [2 + 2] photocycloadditions of arylalkenes to C_{60}.

Results

A mixture of C_{60} and a 200-fold excess of *trans*-4-propenylanisole (*trans*-**1**) did not react when heated for 10 h at reflux in deoxygenated toluene. However, upon 30 min of irradiation at $\lambda > 500$ nm with a 300 W xenon lamp, a reaction product was detected by HPLC on a Separon C_{18} reversed-phase column. This stable adduct, at ambient conditions (no traces of decomposition products were detected by ^{1}H NMR and HPLC after standing for several days), was isolated by flash column chromatography on SiO_2 (2:1 toluene:hexane) and was characterized by ^{1}H NMR to be the [2 + 2] cycloaddition product (*trans*-**2**)[17] (Scheme 1). The ^{1}H NMR spectrum of *trans*-**2** exhibits a doublet at 2.01 ppm ($-CH_3$), a singlet at 3.64 ppm ($-OCH_3$), a multiplet at 4.63 ppm (H_1), a doublet at 4.98 ppm (H_2), and two doublets at 6.85 and 7.69 ppm corresponding to the aromatic hydrogens (Scheme 1). The photocycloaddition is stereospecific, affording uniquely one of the two possible diastereomeric [2 + 2] adducts. If a mixture of diastereomeric adducts had been formed, more ^{1}H resonances should have been observed. Furthermore, the coupling constant between H_1 and H_2 ($J = 8.8$ Hz) is typical for a trans disubstituted cyclobutane ring. Thus the trans stereochemistry of the double bond is maintained in the [2 + 2] adduct *trans*-**2**. A small degree of isomerization of the recovered *trans*-4-propenylanisole to the cis analogue (~2%) was detected by gas chromatography.

Scheme 2. Stereoselective Preparation of *cis*-1 and *cis*-3-d_1



To further examine the stereochemistry of this reaction, the opposite isomer *cis*-4-propenylanisole (*cis*-**1**) was prepared in 96% isomerical purity (Scheme 2). The synthesis of *cis*-**1** was carried out from *cis*-1-bromo-2-(*p*-methoxyphenyl)ethylene via a Wittig reaction of *p*-methoxybenzaldehyde with bromomethylenetriphenylphosphorane[18] followed by transmetalation with *tert*-butyllithium and MeI addition.

Cycloaddition of *cis*-**1** to C_{60}, under identical photochemical conditions to those of *trans*-**1** and C_{60}, afforded exclusively the same *trans*-**2** cycloadduct (Scheme 1). The structure of this adduct was confirmed by matching the ^{1}H NMR spectra of [2 + 2] adducts produced by the photochemical addition of *trans*-**1** and *cis*-**1** to C_{60}. An unexpected complete reversion of the double bond stereochemistry of *cis*-**1** in the [2 + 2] adduct *trans*-**2** was observed. After 30 min of irradiation, a small amount of isomerization of the recovered *cis*-4-propenylanisole to the trans analogue (~3%) was detected by gas chromatography. Additional irradiation did not increase the yield of *trans*-**2** (40% based on recovered C_{60}), but rather resulted in isomerization of the starting alkene. Photochemical cycloreversion of the isolated *trans*-**2** adduct afforded 90% *trans*-4-propenylanisole, 10% *cis*-4-propenylanisole, and C_{60}. Similar photocycloreversion products from C_{60} and tetraalkoxyethylenes [2 + 2] adducts have been reported earlier.[10c]

In an effort to rationalize effectively the stereospecificity of [2 + 2] photocycloaddition of *cis*-/*trans*-4-propenylanisole to C_{60} (complete retention of stereochemistry in case of *trans*-**1** and complete reversion in case of *cis*-**1**), *cis*-1-(*p*-methoxyphenyl)ethylene-*2*-d_1, *cis*-**3**-d_1, was prepared in greater than 96% isomerical purity according

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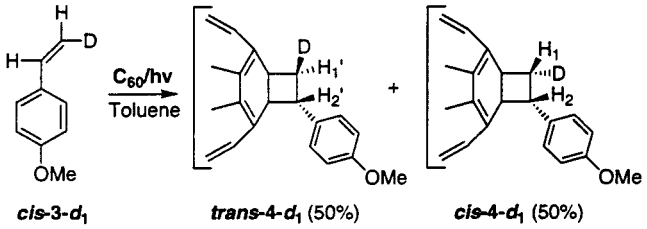
Scheme 3. Nonstereoselective Photochemical [2 + 2] Cycloaddition of *cis*-3-d_1 to C_{60}

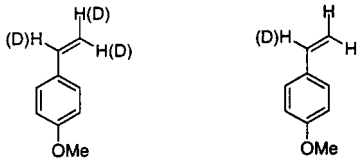


cis-3-d_1 *trans*-4-d_1 (50%) *cis*-4-d_1 (50%)

to the former synthetic pocedure,[18] using D_2O instead of MeI in the last step (Scheme 2).

Irradiation of a mixture of C_{60} and a 200-fold excess of *cis*-3-d_1 in deoxygenated toluene at $\lambda > 500$ nm afforded [2 + 2] adducts *cis*-**4**-d_1 and *trans*-**4**-d_1 (Scheme 3), within 30 min, in 30% yield based on recovered C_{60}. The [2 + 2] diastereomers were purified by flash column chromatography (2:1 toluene:hexane) and were characterized by ^{1}H NMR and FAB-MS [*m*/*z* 856 (M + 1, 8), 720 (M − 135, 100)]. Two doublets of equal intensity corresponding to the resonances of H_1 and H_1' were observed in the ^{1}H NMR spectrum at 4.25 and 4.30 ppm, respectively ($J_{H_1H_2} = 10.4$ Hz, $J_{H_1'H_2'} = 8.3$ Hz, Scheme 3). Thus, the photochemical [2 + 2] addition of *cis*-**3**-d_1 to C_{60} is not stereoselective.[19] Interruption of the reaction after 30 min and ^{1}H NMR analysis of the unreacted alkene revealed the formation of 10% of *trans*-**3**-d_1 (6% isomerization of *cis*-**3**-d_1, taking into account the 96% isomerical purity of the reactant alkene). *trans*-**3**-d_1 and *cis*-**3**-d_1 are expected to be equally reactive with C_{60}. Furthermore, irradiation at $\lambda > 500$ nm of the isolated [2 + 2] adducts afforded complete cycloreversion to C_{60} and equimolar amounts of *trans*-**3**-d_1 and *cis*-**3**-d_1.

To obtain information on the extent of bond formation and bond breaking in the transition state, we measured the intermolecular secondary isotope effects of this [2 + 2] photocycloaddition reaction. For this purpose, we prepared 1-(*p*-methoxyphenyl)ethylene-*1*-d_1, (**3**-d_1), and 1-(*p*-methoxyphenyl)ethylene-*1,2,2*-d_3, (**3**-d_3). Compound **3**-d_1 was prepared by reduction of *p*-methoxyacetophenone with $LiAlD_4$, followed by dehydration. Compound **3**-d_3 was prepared by addition of CD_3MgI to *p*-methoxybenzaldehyde followed by Jones oxidation, $LiAlD_4$ reduction, and dehydration.



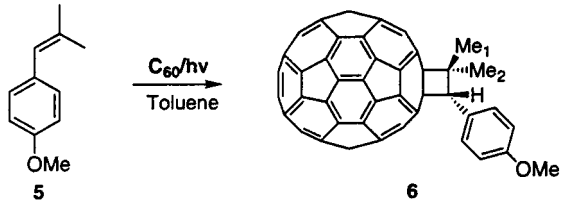
3-d_0 (**3**-d_3) **3**-d_0 (**3**-d_1)

solvent	substrate	time (min)	conversion,[a] %	k_H/k_D[b]
toluene	**3**-d_0/**3**-d_3	30	30	0.75 ± 0.05
toluene	**3**-d_0/**3**-d_1	30	30	1.08 ± 0.05

[a] Based on recovered C_{60}. [b] Determined by integration of the proper ^{1}H NMR signals.

To measure the intermolecular isotope effects of the photocycloaddition reactions, equimolar amounts of **3**-d_0, **3**-d_1 as well as **3**-d_0, **3**-d_3, in 200-fold molar excess to C_{60}, were dissolved (in separate experiments) in deoxygenated toluene. After 30 min of irradiation, both reactions afforded [2 + 2] adducts in 30% yield, based on the recovered C_{60}. Reactions were monitored by HPLC. After purification of the reaction products by flash column chromatography (2:1 toluene:hexane), the secondary kinetic isotope effects k_H/k_D were measured by integration of the ^{1}H NMR signals of the [2 + 2] products at 5.46 ppm (k_H) and 7.72 ppm ($2k_H + 2k_D$). A small normal isotope effect ($k_H/k_D = 1.08$) was found due to isotopic substitution at the α-carbon of the olefin. The substantial total inverse secondary isotope effect in the intermolecular competition between **3**-d_0 and **3**-d_3 due to the isotopic labeling at α- and *β*-carbon (eq 1), indicates extensive bond making between $^3C_{60}$ and *β*-carbon of the alkene in the transition state of the first, rate-determining step.[20] Thus, isotopic labeling at the *β*-carbon gave an α-secondary kinetic isotope effect, while isotope substitution at the α-carbon showed a *β*-secondary kinetic isotope effect. Substitution of $(k_H/k_D)_\beta$ with the value of 1.08 in eq 1 gave $(k_H/k_D)_\alpha^2 = 0.69$, which corresponds to $(k_H/k_D)_\alpha = 0.83$ per deuterium atom.[19]

Scheme 4. [2 + 2] Photocycloaddition of *β*,*β*-Dimethyl-*p*-methoxystyrene to C_{60}



5 **6**

$$(k_H/k_D)_{obsd} = (k_H/k_D)_\alpha^2(k_H/k_D)_\beta = 0.75 \qquad (1)$$

β,*β*-Dimethyl-*p*-methoxystyrene (**5**) is also photochemically reactive with C_{60}, forming exclusively the [2 + 2] adduct **6** (Scheme 4) under the previously described experimental conditions.

To further study the stereochemistry of the [2 + 2] addition of *p*-methoxyarylalkenes to C_{60}, (*E*)-1-(*p*-methoxyphenyl)-2-methyl-1-propene-*3,3,3*-d_3 (*trans*-**5**-d_3) was prepared by selectively labeling the anti methyl group with respect to the *p*-methoxyphenyl moiety. Synthesis of *trans*-**5**-d_3 in 97% isomerical purity was accomplished through the stereoselective formation of methyl (*E*)-2-methyl-*p*-methoxycinnamate, by a Wittig−Horner reaction with *p*-methoxybenzaldehyde, followed by $LiAlD_4$/$AlCl_3$ reduction,[21] and subsequent chlorination of the resulting allylic alcohol,[22] followed by $LiAlD_4$ reduction of the allylic chloride[23] (Scheme 5). The only nonstereospecific step of the synthesis was the conversion of the allylic alcohol to the allylic chloride, in which 3% of the *Z*-isomer was formed.

Photochemical addition of *trans*-**5**-d_3 to C_{60} led to the formation of a mixture of the two possible [2 + 2] diastereomeric adducts, *trans*-**6**-d_3 and *cis*-**6**-d_3. After 45 min of irradiation, a 40% yield of the [2 + 2] adduct was obtained, based on the recovered C_{60}. The ratio of the purified [2 + 2] products was measured by integration

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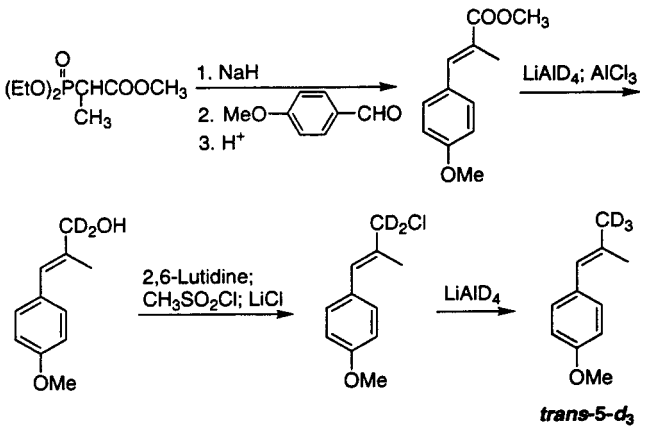
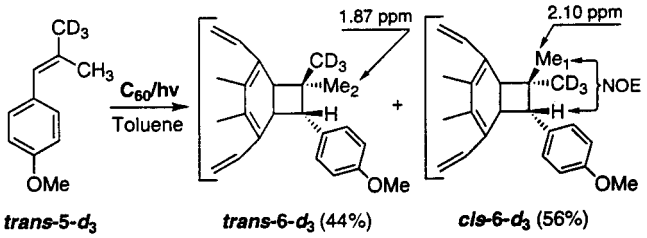
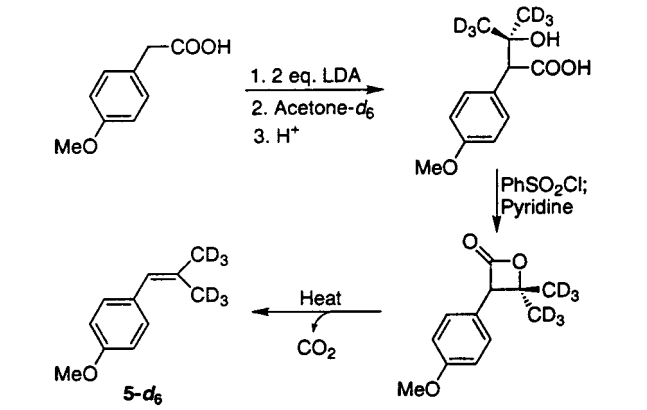
Scheme 5. Stereoselective Preparation of *trans*-5-d_3



Scheme 6. Stereochemistry of the Photochemical [2 + 2] Cycloaddition of *trans*-5-d_3 to C_{60}



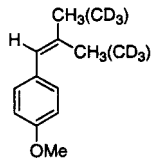
Scheme 7. Preparation of 5-d_6 by Thermolysis of the Corresponding β-Lactone



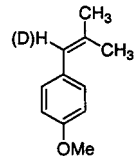
of the ^{1}H NMR methyl resonances at 1.87 and 2.10 ppm and found to be 56:44 (Scheme 6). ^{1}H NMR examination of the unreacted arylalkene at the end of the reaction showed no isomerization. In a control experiment, irradiation of a mixture of C_{60} and a 3-fold excess of *trans*-**5**-d_3 for 1 h showed no isomerization to the cis isomer of the starting material.

The stereochemistry of the major and the minor adduct were determined by nuclear Overhauser effect (NOE) experiments. Upon irradiation of the methyl group at 2.10 ppm of the major adduct, a positive 0.7% NOE was measured for the benzylic hydrogen. In contrast, irradiation of the methyl group at 1.87 ppm of the minor adduct gave no similar enhancement for the benzylic hydrogen (Scheme 6). These results indicate that the major [2 + 2] adduct is *cis*-**6**-d_3, which corresponds to a change in stereochemistry relative to the starting alkene.

To elucidate the reaction profile, intermolecular secondary kinetic isotope effects H/D were measured in the competition of β,β-dimethyl-p-methoxystyrene versus analogues deuterated at allylic (**5**-d_6) and vinylic (**5**-d_1) positions. Alkene **5**-d_6 was synthesized by thermolysis of the corresponding β-lactone (Scheme 7).[24] The deuterium content on the allylic position was >96% measured by ^{1}H NMR spectroscopy. Attempts to synthesize **5**-d_6 by Wittig coupling of the semistabilized aryl ylide with acetone-d_6 resulted in significant deuterium scrambling between the allylic and the olefinic hydrogens. Alkene **5**-d_1 was prepared by Wittig coupling of *p*-methoxybenzaldehyde-*1*-d_1 with triphenylphosphoranylidene isopropane.



5-d_0 (5-d_6)



5-d_0 (5-d_1)

solvent	substrate	time (min)	conversion,[a] %	k_H/k_D[b]
toluene	**5**-d_0/**5**-d_6	30	30	0.94 ± 0.05
toluene	**5**-d_0/**5**-d_1	30	30	1.02 ± 0.05

[a] Based on recovered C_{60}. [b] Determined by integration of the proper ^{1}H NMR signals.

The secondary kinetic isotope effect in the intermolecular competition of **5**-d_0 vs **5**-d_6 was measured by integration of the ^{1}H NMR signals of the [2 + 2] adducts at 1.87 ppm ($3k_H$), 2.10 ppm ($3k_H$), and both signals at 5.23 and 5.24 ppm ($k_H + k_D$). The measurement of the isotope effect in the intermolecular competition of **5**-d_0 vs **5**-d_1 was achieved by integration of the ^{1}H NMR signals at 7.74 ppm ($2k_H + 2k_D$), 6.83 ppm ($2k_H + 2k_D$), and 5.24 ppm (k_H).

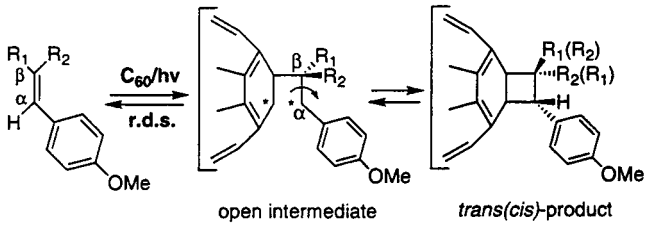
Discussion

In the present work the [2 + 2] photochemical cycloadditions of moderately electron-rich *p*-methoxyarylalkenes to C_{60} are reported. Under identical photochemical experimental conditions unsubstituted (at the phenyl group) styrenes are unreactive with C_{60}, which implies a significant role of the p-methoxy group in the reaction mechanism. These photocycloadditions reach an equilibrium between the reactants (*p*-methoxyarylalkenes and C_{60}) and the products ([2 + 2] adducts). For this reason ~200-fold excess of the p-methoxyarylalkene is needed to achieve a satisfactory conversion to the [2 + 2] adducts. Rapid and complete photolysis of the isolated [2 + 2] adducts into the starting reactants is consistent with an equilibrium that is shifted toward the reactants. A small equilibrium constant Keq of approximately 2.5×10^{-3} was calculated from the recovered C_{60}.

Stereochemical and Stereoisotopic Studies. Regardless of the initial stereochemistry of the double bond of *cis*-/*trans*-4-propenylanisole, the photocycloaddition to C_{60} is stereospecific in favor of the trans [2 + 2] adduct. A possible mechanism that could account for the exclusive formation of the *trans*-**2** adduct includes the formation of a common dipolar or biradical intermediate between $^3C_{60}$ and the arylalkene. Subsequent partial rotation of the aryl moiety around the former double bond $C_\alpha - C_\beta$, leads exclusively to the most thermodynamically

(24) Adam, W.; Baeza, J.; Liu, J. C. *J. Am. Chem. Soc.* **1972**, *94*, 2000.

Scheme 8. Proposed Stepwise Mechanism of the Photochemical [2 + 2] Cycloaddition of *p*-Methoxyarylalkenes to C_{60}



R_1	R_2	$(trans:cis)_{prod}$
$-CH_3$	-H	100 : 0
-H	$-CH_3$	100 : 0
-H	-D	50 : 50
$-CD_3$	$-CH_3$	44 : 56

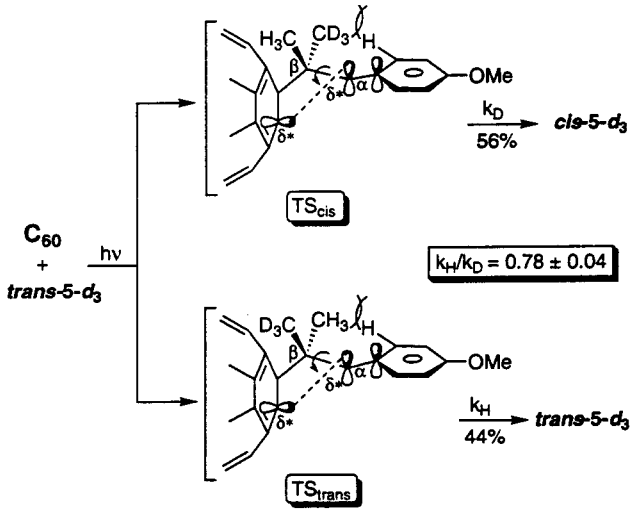
stable trans [2 + 2] adduct (Scheme 8). The unexpected stereospecificity is attributed to the difference in activation energy of the diastereomeric transition states in the second step of the reaction, involving collapse of the "open" intermediate to the [2 + 2] adduct. These results thus exclude a synchronous mechanism. The formation of an open intermediate whose closure is faster than bond rotation (libration) is also excluded.

The possibility of a concerted addition of *trans*-**1** and *cis*-**1** to C_{60} has been excluded for the following reasons: (a) Retention of configuration in the cycloadducts would have been expected because no substantial isomerization of *cis*-**1** to *trans*-**1** under the experimental conditions was observed (~3%). Thus, the stereospecificity would not be attributed to an unexpected greater reactivity of *trans*-**1**, produced from isomerization (~3%) of the starting alkene. (b) The equimolar formation of cis and trans [2 + 2] adducts in the addition of *cis*-**3**-d_1 to C_{60}. In the last case, both initial (*cis*-**3**-d_1) and isomerized (*trans*-**3**-d_1) alkenes are equally reactive toward $^3C_{60}$.

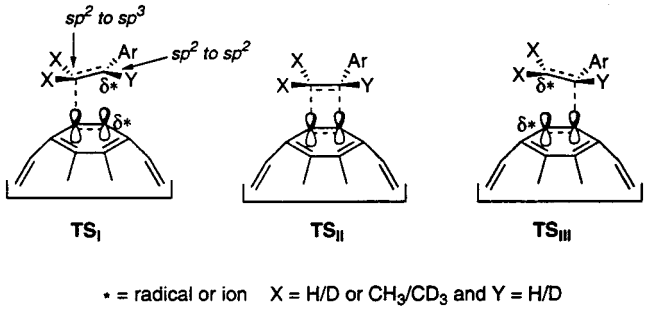
The most interesting result is the 12% preference for cis [2 + 2] adduct formation in the addition of *trans*-**5**-d_3 to C_{60}.[25] Partial rotation of the phenyl group around the previous $C_\alpha - C_\beta$ double bond in the intermediate leads to the transition states TS_{trans} and TS_{cis} (Scheme 9). It is reasonable to assume that the conjugation between the p-orbital of the α-carbon and the aromatic system prevents free rotation around the bond between α-carbon and the aryl ring (Scheme 9). Due to congestion, TS_{cis} involving nonbonding interactions between the smaller $-CD_3$ group and the *o*-phenyl hydrogen is favored. The resulting steric isotope effect (k_H/k_D = 0.78) was attributed to the smaller effective size of the C−D bond relative to the C−H bond in the methyl groups.[20] Remote steric isotope effects are less common. Mislow and coworkers[26] earlier reported a classical example.

Intermolecular Secondary Kinetic Isotope Effects. Secondary kinetic isotope effects provide a powerful mechanistic tool for studying the extent of bond making and bond breaking in the transition states of the reactions.[20] The small normal isotope effect (k_H/k_D = 1.08) that was found for deuterium substitution at the α-carbon

Scheme 9. Transition States TS_{cis} and TS_{trans} of the Second Step of the [2 + 2] Photocycloaddition of *trans*-5-d_3 to C_{60}



Scheme 10. Possible Transition states TS_I, TS_{II}, and TS_{III} of the Rate-Determining Step of the [2 + 2] Photocycloaddition of *p*-Methoxystyrenes to C_{60}



(**3**-d_0 vs **3**-d_1) in combination with a substantial inverse isotope effect (k_H/k_D = 0.83, eq 1) for deuterium substitution at the β-carbon (**3**-d_0 vs **3**-d_3) requires the formation of a dipolar or biradical intermediate in the rate-determining step (first step) through the transition state TS_I (Scheme 10). Furthermore, the small steric inverse ***β***-secondary kinetic isotope effect in the competition between **5**-d_0 and **5**-d_6 (k_H/k_D = 0.94) is in agreement with bond formation between the β-carbon and $^3C_{60}$, in the rate-determining step (late transition state) of the reaction.

The small positive β-secondary isotope effects derived from substitution at the α-carbon in competitions between **3**-d_0 vs **3**-d_1 and **5**-d_0 vs **5**-d_1 (k_H/k_D = 1.02) exclude the transition states TS_{II} (concerted mechanism) and TS_{III} since in these cases an inverse isotope effect would have been expected (Scheme 10). With respect to the competition between **5**-d_0 vs **5**-d_6, the formation of a positive charge or spin at the β-carbon in the transition state TS_{III} (Scheme 10) would have given a normal and large β-secondary isotope effect (k_H/k_D = 1.05−1.10),[20] attributed to a hyperconjugative effect involving the six hydrogen atoms in **5**-d_0 vs the six deuterium atoms in **5**-d_6. Such a normal secondary isotope effect was recently found in a typical dipolar [2 + 2] cycloaddition of tetracyanoethylene (TCNE) to 2,5-dimethyl-2,4-hexadiene.[27]

In conclusion, based on the stereochemical and stereoisotopic results, the mechanism of the photochemical

(25) Hatzimarinaki, M.; Vassilikogiannakis, G.; Orfanopoulos, M. *Tetrahedron Lett.* **2000**, *41*, 4667.
(26) Mislow, K.; Graeve, R.; Gordon, J. A.; Wahl, G. H., Jr. *J. Am. Chem. Soc.* **1964**, *86*, 1733.

[2 + 2] cycloaddition of *p*-methoxyarylalkenes to C_{60} proceeds through the formation of an open intermediate (dipolar or biradical) between the triplet excited state of C_{60} and the ground state of *p*-methoxyarylalkenes. The competition between internal rotation and ring closure of the intermediate in the second step allows rotational equilibrium to be fully attained before ring closure. The secondary kinetic isotope effects reveal extensive bond making between $^3C_{60}$ and C_β of the *p*-methoxyarylalkenes in the first and rate-determining step of the photocycloaddition.

Experimental Section

General Considerations. Analytical scale HPLC analysis was done on a Separon C_{18}, 7 μm, 200 mm × 4.6 mm i.d., reversed phase column using a mixture of toluene:acetonitrile (1:1) as eluent, at 1 mL/min flow rate and UV detection at 310 nm. ^{1}H NMR and ^{13}C NMR spectra were attained using 250 and 500 MHz spectrometers and $CDCl_3$ as the solvent. ^{1}H NMR spectra of C_{60} adducts were attained using a mixture of CS_2:C_6D_6 (4:1). Geometrical isomeric purities were determined by ^{1}HNMR and by analytical gas chromatography with 50%−50% phenyl methyl silicone capillary column and FID detector. FAB mass spectra were obtained on a VG-ZAB-SE mass spectrometer using *m*-nitrobenzyl alcohol as the matrix. Photocycloadditions were achieved using a xenon Variac Eimac Cermax 300 W lamp. Flash column chromatography was carried out on SiO_2 (silica gel 60, SDS, 230−400 mesh ASTM). Organic extracts were dried during workup over $MgSO_4$. C_{60} was gold grade (>99.9% purity) and purchased from Hoechst Co.

General Procedure for Photocycloadditions of *p*-Methoxyarylalkenes to C_{60}. A solution of C_{60} (15 mg, 0.0208 mmol) and 200-fold excess of *p*-methoxyarylalkene (4 mmol) in HPLC grade toluene (30 mL) was stirred and bubbled with argon for 30 min and subsequently irradiated for 30 min. Prolonged irradiation did not affect the reaction yields. During irradiation, the reaction mixtures were cooled with ice water and the reaction was monitored by HPLC. Toluene was removed under reduced pressure. In all cases, [2 + 2] products were separated from the unreacted C_{60} by flash column chromatography using a mixture of toluene:hexane (2:1) as eluent. The retention time of [2 + 2] adducts is longer than that of C_{60}. After concentration, the residue was sonicated with hexane. Hexane was decanted from the precipitated solid, and the remaining volatile substance was removed by pumping the sample under high vacuum.

The ^{1}H NMR and FAB-MS spectroscopic data for *trans*-**2**, **4**-d_0, (*trans*-**4**-d_1 + *cis*-**4**-d_1), **6**, (**6**-d_0 + **6**-d_6), (**6**-d_0 + **6**-d_1), and (*trans*-**6**-d_3 + *cis*-**6**-d_3) are given below.

Compound *trans*-2. ^{1}H NMR (250 MHz): δ 2.01 (d, J = 7.0 Hz, 3 H), 3.64 (s, 3 H), 4.63 (qd, J_1 = 8.8 Hz, J_2 = 7.0 Hz, 1 H), 4.98 (d, J = 8.8 Hz, 1 H), 6.85 (d, J = 8.6 Hz, 2 H), 7.69 (d, J = 8.6 Hz, 2 H).

Compound 4-d_0. ^{1}H NMR (250 MHz): δ 3.62 (s, 3 H), 4.22 (m, 2 H), 5.46 (dd, J_1 = 10.4 Hz, J_2 = 8.6 Hz, 1 H), 7.29 (AA'MM', $\Delta\delta$ = 0.85 ppm, J_1 = 8.6 Hz, J_2 = 3.1 Hz, J_3 = 2.1 Hz, 4 H). β-Secondary kinetic isotope effects in the intermolecular competition of **3**-d_0 vs **3**-d_1 and **3**-d_0 vs **3**-d_3 were measured by integration at 5.46 ppm (k_H) and 7.72 ppm (2 k_H + 2 k_D).

Compounds (*trans*-4-d_1 + *cis*-4-d_1). ^{1}H NMR (250 MHz): δ 3.65 (s, 3 H of *cis*-**4**-d_1 + 3 H of *trans*-**4**-d_1), 4.21 (d, J = 10.4 Hz, 1 H of *cis*-**4**-d_1), 4.29 (d, J = 8.3 Hz, 1 H of *trans*-**4**-d_1), 5.50 (d, J = 10.1 Hz, 1 H of *trans*-**4**-d_1 + 1 H of *cis*-**4**-d_1), 7.32 (AA'MM', $\Delta\delta$ = 0.85 ppm, J_1 = 8.6 Hz, J_2 = 3.1 Hz, J_3 = 2.1 Hz, 4 H of *trans*-**4**-d_1 + 4 H of *cis*-**4**-d_1). The ratio *trans*-**4**-d_1:*cis*-**4**-d_1 was measured by integration of doublets at 4.21 and 4.29 ppm.

Compound 6-d_0. ^{1}H NMR (500 MHz): δ 1.87 (s, 3 H), 2.10 (s, 3 H), 3.66 (s, 3 H), 5.24 (s, 1 H), 6.83 (d, J = 8.7 Hz, 2 H), 7.75 (d, J = 8.7 Hz, 2 H).

Compounds (*trans*-6-d_3 + cis-6-d_3). ^{1}H NMR (500 MHz): δ 1.87 (s, 3 H of *trans*-**6**-d_3), 2.10 (s, 3 H of *cis*-**6**-d_3), 3.66 (s, 3 H of *trans*-**6**-d_3 + 3 H of ***cis***-**6**-d_3), 5.24 (s, 1 H of *trans*-**6**-d_3 + 1 H of *cis*-**6**-d_3), 6.83 (d, J = 8.7 Hz, 2 H *trans*-**6**-d_3 + 2 H of *cis*-**6**-d_3), 7.75 (d, J = 8.7 Hz, 2 H *trans*-**6**-d_3 + 2 H of *cis*-**6**-d_3). The steric isotope effect was measured by integration of cyclobutanic methyls at 1.87 ppm which corresponds to *trans*-**6**-d_3 and 2.10 ppm which corresponds to *cis*-**6**-d_3.

Compounds (6-d_0 + 6-d_6). ^{1}H NMR (500 MHz): δ 1.87 (s, 3 H of **6**-d_0), 2.10 (s, 3 H of **6**-d_0), 3.68 (s, 3 H of **6**-d_0 + 3 H of **6**-d_6), 5.23 (s, 1 H of **6**-d_6), 5.24 (s, 1 H of **6**-d_0), 6.82 (d, J = 8.7 Hz, 2 H of **6**-d_0 + 2 H of **6**-d_6), 7.74 (d, J = 8.7 Hz, 2 H of **6**-d_0 + 2 H of **6**-d_6). β-Secondary kinetic isotope effect in the intermolecular competition of **5**-d_0 versus **5**-d_6 was measured by integration of both signals at 5.23 and 5.24 ppm (k_H + k_D) and 1.87 ppm (3k_H) or 2.10 ppm (3k_H). It is interesting to note that the cyclobutanic hydrogen of **6**-d_6 resonates at 5.232, while **6**-d_0 resonates at 5.240. The chemical shift change, $\Delta\delta$ = 0.008 ppm, is attributed to H/D substitution four bonds away from the resonating hydrogens. Thus, the higher electronegativity of the six hydrogens compared to six deuteriums causes a higher diamagnetic deshielding.

Compounds (6-d_0 + 6-d_1). ^{1}H NMR (500 MHz): δ 1.87 (s, 3 H of **6**-d_0 + 3 H of **6**-d_1), 2.10 (s, 3 H of **6**-d_0 + 3 H of **6**-d_1), 3.68 (s, 3 H of **6**-d_0 + 3 H of **6**-d_1), 5.24 (s, 1 H of **6**-d_0), 6.83 (d, J = 8.7 Hz, 2 H of **6**-d_0 + 2 H of **6**-d_1), 7.74 (d, J = 8.7 Hz, 2 H of **6**-d_0 + 3 H of **6**-d_1). β-Secondary kinetic isotope effects in the intermolecular competition of **5**-d_0 vs **5**-d_1 were measured by integration of both signals at 5.24 ppm (k_H) and 6.83 ppm (2k_H + 2k_D) or 7.74 ppm (2k_H + 2k_D).

Synthesis of *cis*-4-Propenylanisole (*cis*-1) and *cis*-1-(*p*-Methoxyphenyl)ethylene-2-d_1 (*cis*-3-d_1). These compounds were prepared according to the procedure shown in Scheme 2.

Bromomethyltriphenylphosphonium Bromide. A solution of triphenylphosphine (30 g, 114 mmol) and dibromomethane (44.6 g, 256 mmol) in 250 mL of toluene was refluxed for 24 h. After cooling to 0 °C, the phosphonium salt was collected as a white precipitant and washed with hot toluene. The filtrate was heated further at reflux for 24 h, affording an additional amount of the phosphonium salt. The total yield of the phosphonium salt was 41.2 g (82% yield). ^{1}H NMR ($CDCl_3$): δ = 5.85 (d, J = 5.8 Hz, 2 H), 7.69 (m, 6 H), 7.80 (m, 3 H), 7.94 (m, 6 H).

***cis*-1-Bromo-2-(*p*-methoxyphenyl)ethylene.** To a cooled mixture (−78 °C) of bromomethyltriphenylphosphonium bromide (20 g, 45.8 mmol) in dry tetrahydrofuran (THF), under N_2 atmosphere, was added solid *tert*-BuOH (5.15 g, 46.0 mmol). The solution was colored yellow due to the formation of bromomethylenetriphenylphosphorane. The temperature of the reaction is a crucial factor because at room temperature the ylide reacts with *tert*-BuOH which is produced from the base. To the resulting solution, after 1 h of stirring at −78 °C, was added dropwise a solution of *p*-methoxybenzaldehyde (5.44 g, 40.0 mmol) in 15 mL of dry THF and stirring continued for 1 h. Subsequently, the reaction mixture was heated at room temperature and poured into 50 mL of pentane. Triphenylphosphine oxide (Ph_3PO) precipitated out of solution. After filtration, the solution was concentrated and the residue was chromatographed (Et_2O:hexane = 2:1) yielding vinyl bromide (6.30 g, 74%) in 96% geometrical purity. ^{1}H NMR ($CDCl_3$): δ 3.82 (s, 3 H), 6.30 (d, J = 8.1 Hz, 1 H), 6.99 (d, J = 8.1 Hz, 1 H), 7.29 (AA'MM', $\Delta\delta$ = 0.76 ppm, J_1 = 8.9 Hz, J_2 = 2.9 Hz, J_3 = 2.1 Hz, 4 H).

***cis*-4-Propenylanisole (*cis*-1).** To a cooled solution (−78 °C) of *cis*-1-bromo-2-(*p*-methoxyphenyl)ethylene (3.15 g, 14.8 mmol) in dry THF, under N_2 atmosphere, was carefully added dropwise 9.3 mL of *tert*-BuLi (1.6 M) in hexane. After 1 h of stirring at −78 °C, addition of MeI (0.94 mL, 15 mmol) occurred. The reaction mixture was heated at room temperature, washed with a 5% solution of $NaHCO_3$ and dried over $MgSO_4$. After evaporation of the solvent, the product was

(27) Vassilikogiannakis, G.; Orfanopoulos, M. *Tetrahedron Lett.* **1996**, *37*, 3075.

purified by flash column chromatography using a mixture of hexane and Et_2O (4:1) as eluent. ^1H NMR ($CDCl_3$): δ 1.89 (dd, $J_1 = 7.2$ Hz, $J_2 = 1.8$ Hz, 3 H), 3.81 (s, 3 H), 5.71 (qd, $J_1 = 11.6$ Hz, $J_2 = 7.2$ Hz, 1 H), 6.38 (d with allylic coupling, $J_1 = 11.6$ Hz, $J_2 = 1.8$ Hz, 1 H), 7.07 (AA'MM', $\Delta\delta = 0.36$ ppm, $J_1 = 8.8$ Hz, $J_{2\,I} = 2.9$ Hz, $J_3 = 2.1$ Hz, 4 H). ^{13}C NMR ($CDCl_3$): $\delta = 14.5$, 55.1, 113.5, 125.0, 129.2, 129.9, 130.3, 158.1. HRMS for $C_{10}H_{12}O$: calcd 148.0888, found 148.0880.

***cis*-1-(*p*-Methoxyphenyl)ethylene-2-d_1 (*cis*-3-d_1).** This compound was prepared according to the previously described procedure for synthesis of *cis*-**1** using D_2O instead of MeI (Scheme 2). ^1H NMR ($CDCl_3$): δ 3.81 (s, 3 H), 5.11 (d, $J = 10.9$ Hz, 1 H), 6.66 (td, $J_{H-H} = 10.9$ Hz, $J_{H-D} = 2.6$ Hz, 1 H), 7.10 (AA'MM', $\Delta\delta = 0.49$ ppm, $J_1 = 8.8$ Hz, $J_2 = 2.9$ Hz, $J_3 = 2.1$ Hz, 4 H). MS *m*/*z* 135 (M^+, 100).

Synthesis of 1-(*p*-Methoxyphenyl)ethylene-1-d_1 (3-d_1). This compound was synthesized by reduction of *p*-methoxyacetophenone with $LiAlD_4$, followed by dehydration.

1-(*p*-Methoxyphenyl)ethanol-1-d_1. To a cooled (0 °C) mixture of $LiAlD_4$ (0.42 g, 10.0 mmol) in dry Et_2O, under N_2 atmosphere, was added dropwise a solution of *p*-methoxyacetophenone (3 g, 20.0 mmol) in dry Et_2O (10 mL). The mixture was stirred at room temperature for 2 h and quenched at 0 °C by addition of 0.4 mL of H_2O, 0.4 mL of a 15% solution NaOH, and 1.2 mL of H_2O, followed by filtration. The filtrate was washed with a 5% solution of $NaHCO_3$ and brine, dried over $MgSO_4$ and concentrated to give the alcohol (2.45 g, 80%). ^1H NMR ($CDCl_3$): δ 1.48 (s, 3 H), 1.88 (s, −OH), 3.81 (s, 3 H), 6.89 (d, $J = 8.6$ Hz, 2 H), 7.30 (d, $J = 8.6$ Hz, 2 H).

1-(*p*-Methoxyphenyl)ethylene-1-d_1 (3-d_1). In a sealed tube (rotaflon gastight tube) was added 2.45 g (16 mmol) of 1-(*p*-methoxyphenyl)ethanol-*1*-d_1 and a catalytic amount of *p*-toluenesulfonic acid. The neat mixture was heated at 120 °C for 1 h. After cooling to room temperature, the reaction mixture was dissolved in 50 mL of Et_2O and the ethereal layer was washed with a 10% solution of $NaHCO_3$ and brine. The organic extracts were dried over $MgSO_4$ and concentrated, giving a mixture of products. The desired product was separated from a less volatile unidentified byproduct by fractional distillation under vacuum (40 mmHg). ^1H NMR ($CDCl_3$): δ 3.81 (s, 3 H), 5.11 (d, $J = 0.9$ Hz, 1 H), 5.60 (dt, $J_{H-D} = 2.6$ Hz, $J_{H-H} = 0.9$ Hz, 1 H), 7.10 (AA'MM', $\Delta\delta = 0.49$ ppm, $J_1 = 8.8$ Hz, $J_2 = 2.9$ Hz, $J_3 = 2.1$ Hz, 4 H). MS *m*/*z* 135 (M^+, 100).

Synthesis of 1-(*p*-Methoxyphenyl)ethylene-1,2,2-d_3 (3-d_3). This compound was prepared by addition of CD_3MgI to *p*-methoxybenzaldehyde, followed by Jones oxidation, $LiAlD_4$ reduction, and dehydration.

1-(*p*-Methoxyphenyl)ethanol-2,2,2-d_3. To a mixture of Mg (0.61 g, 25.0 mmol) in dry Et_2O, under N_2 atmosphere, was added dropwise a solution of 1.25 mL (20.0 mmol) of CD_3I in dry Et_2O. The mixture became muddy, indicating the formation of CD_3MgI, which is an exothermic process. After heating at reflux for 1 h, the mixture was cooled to 0 °C and a solution of 2.58 g (19.0 mmol) of *p*-methoxybenzaldehyde in dry Et_2O was added. After 2 h of stirring at room temperature, the reaction mixture was quenched at 0 °C, by addition of 0.9 mL of H_2O. The organic layer was washed with a 5% solution of $NaHCO_3$ and brine, dried over $MgSO_4$, and concentrated to give 2.15 g of the alcohol (73%). ^1H NMR ($CDCl_3$): δ 1.88 (s, −OH) 3.81 (s, 3 H), 4.85 (s, 1 H), 6.89 (d, $J = 8.6$ Hz, 2 H), 7.30 (d, $J = 8.6$ Hz, 2 H).

***p*-Methoxyacetophenone-2,2,2-d_3.** To a solution of 1-(*p*-methoxyphenyl)ethanol-2,2,2-d_3 (2.15 g, 13.9 mmol) in acetone was added dropwise Jone's reagent, until the solution was colored slightly red. The excess of oxidizing reagent was quenched with some drops of 2-propanol. The reaction mixture was poured into 100 mL of Et_2O and washed with H_2O, a 5% solution of $NaHCO_3$ and brine, and dried over $MgSO_4$. Solvent evaporation afforded *p*-methoxyacetophenone-2,2,2-d_3 (1.87 g, 88%). ^1H NMR ($CDCl_3$): δ 3.87 (s, 3 H), 6.94 (d, $J = 8.7$ Hz, 2 H), 7.94 (d, $J = 8.7$ Hz, 2 H).

1-(*p*-Methoxyphenyl)ethanol-1,2,2,2-d_4. This compound was prepared by $LiAlD_4$ reduction of *p*-methoxyacetophenone-2,2,2-d_3 (1.87 g, 12.2 mmol) according to the experimental procedure followed in the synthesis of 1-(*p*-methoxyphenyl)-ethanol-*1*-d_1. A 1.60 g (84%) amount of the deuterated alcohol was isolated. ^1H NMR ($CDCl_3$): δ 1.88 (s, −OH), 3.81 (s, 3 H), 6.89 (d, $J = 8.6$ Hz, 2 H), 7.30 (d, $J = 8.6$ Hz, 2 H).

1-(*p*-Methoxyphenyl)ethylene-1,2,2-d_3 (3-d_3). This compound was prepared by dehydration of 1-(*p*-methoxyphenyl)-ethanol-1,2,2,2-d_4 (1.60 g, 10.2 mmol), using a catalytic amount of *p*-toluenesulfonic acid (see the experimental in the synthesis of 1-(*p*-methoxyphenyl)ethylene-1-d_1). ^1H NMR ($CDCl_3$): δ 3.81 (s, 3 H), 7.10 (AA'MM', $\Delta\delta = 0.49$ ppm, $J_1 = 8.8$ Hz, $J_2 = 2.9$ Hz, $J_3 = 2.1$ Hz, 4H). MS *m*/*z* 137 (M^+, 100).

Synthesis of (*E*)-1-(*p*-Methoxyphenyl)-2-methylprop-1-ene-3,3,3-d_3 (*trans*-5-d_3). This compound was prepared according to the procedure shown in Scheme 5.

Methyl (*E*)-2-Methyl-*p*-methoxycinnamate. A solution of methyl diethyl-2-phosphonopropionate (5.6 g, 25.0 mmol) in dry DME (20 mL) was added to a cooled (0 °C) mixture of NaH (60% in paraffin oil, 1 g, 27.0 mmol) in 30 mL of dry DME, under N_2 atmosphere. After 1 h of stirring at room temperature, a solution of (2.8 mL, 23.0 mmol) *p*-methoxybenzaldehyde in dry DME was injected. Stirring was continued for 1 h, and the reaction mixture was quenched with MeOH, poured into H_2O and extracted with Et_2O. The combined ether layers were dried over $MgSO_4$ and concentrated, affording exclusively the *E*-ester (3.4 g, 72%). ^1H NMR ($CDCl_3$): δ 2.11 (s with allylic coupling, $J = 1.0$ Hz, 3 H), 3.78 (s, 3 H), 3.81 (s, 3 H), 6.90 (d, $J = 7.0$ Hz, 2 H), 7.36 (d, $J = 7.0$ Hz, 2 H), 7.63 (s, 1 H).

(*E*)-3-(*p*-Methoxyphenyl)-2-methylprop-2-en-1-ol-1,1-d_2. To a cooled (0 °C) mixture of $LiAlD_4$ (0.38 g, 9.0 mmol) and $AlCl_3$ (0.4 g, 3.0 mmol) in dry Et_2O (20 mL), under N_2 atmosphere, was added dropwise a solution of the *E*-ester (3.4 g, 16.5 mmol) in dry Et_2O (10 mL). After 2 h of stirring at room temperature, the reaction mixture was quenched at 0 °C with a 2 M solution of HCl and filtered. The filtrate was washed with brine, dried over $MgSO_4$, and concentrated to give the corresponding *E*-alcohol (2.1 g, 70%). ^1H NMR ($CDCl_3$): δ 1.88 (s with allylic coupling, $J = 1.1$ Hz, 3 H), 3.80 (s, 3 H), 6.44 (s, 1 H), 6.86 (d, $J = 7.0$ Hz, 2 H), 7.21 (d, $J = 7.0$ Hz, 2 H).

(*E*)-3-(*p*-Methoxyphenyl)-2-methylprop-2-en-1-yl-1,1-d_2 Chloride. To a stirred mixture of 2.1 g (11.7 mmol) of the *E*-allylic alcohol and 1.5 mL (12.9 mmol) of 2,6-lutidine, under N_2 atmosphere was added 0.55 g (13 mmol) of LiCl dissolved in a minimum amount of anhydrous dimethylformamide (DMF). On cooling to 0 °C, a suspension was formed, which was treated dropwise with $MeSO_2Cl$ (1 mL, 12.9 mmol). After 10 h of stirring at room temperature, the reaction mixture was poured into a saturated solution of $CuSO_4$ to remove 2,6-lutidine, and extracted with Et_2O. The organic extracts were dried over $MgSO_4$ and concentrated to afford the allylic chloride in 96% geometrical purity (2.0 g, 86%). ^1H NMR of the *E*-isomer ($CDCl_3$): δ 1.96 (s with allylic coupling, $J = 1.0$ Hz, 3 H), 3.79 (s, 3 H), 6.84 (s, 1 H), 6.86 (d, $J = 6.8$ Hz, 2 H), 7.21 (d, $J = 6.8$ Hz, 2 H).

(*E*)-1-(*p*-Methoxyphenyl)-2-methylprop-1-ene-3,3,3-d_3 (*trans*-5-d_3). To a cooled (0 °C) mixture of $LiAlD_4$ (0.21 g, 5.0 mmol) in dry THF (20 mL), under N_2 atmosphere, was added dropwise a solution of 2.0 g (10 mmol) of allylic chloride in dry THF (10 mL). After 4 h of stirring at room temperature, the reaction mixture was quenched at 0 °C by addition of 0.4 mL of H_2O, 0.4 mL of 15% NaOH solution, and 1.2 mL of H_2O and then filtered. The organic layer was washed with a 5% solution of $NaHCO_3$, dried over $MgSO_4$, and concentrated. The residue was purified by flash column chromatography (petroleum ether:ethyl acetate = 10:1) to afford *trans*-**5**-d_3 in 96% geometrical purity (1.2 g, 73%). ^1H NMR of the *E*-stereoisomer ($CDCl_3$): δ 1.84 (s with allylic coupling, $J = 1.3$ Hz, 3 H), 3.80 (s, 3 H), 6.20 (s, 1 H), 6.85 (d, $J = 8.7$ Hz, 2 H), 7.14 (d, $J = 8.7$ Hz, 2 H).

Synthesis of 1-(*p*-Methoxyphenyl)-2-methylprop-1-ene-3,3,3,2′,2′,2′-d_6 (5-d_6). This compound was prepared according to the procedure shown in Scheme 7.

2-(*p*-Methoxyphenyl)-3-methyl-3-hydroxybutanoic Acid-4,4,4,3′,3′,3′-d_6. To a cooled (0 °C) solution of anhydrous diisopropylamine (3 mL, 21.3 mmol) in dry THF (20 mL) was added dropwise 13.7 mL of 1.6 M solution of *n*-BuLi in hexane,

under N_2 atmosphere. After 15 min, 1.57 g (9.4 mmol) of *p*-methoxyphenylacetic acid (to be converted into its lithium α-lithiocarboxylate) was injected as a 1 M solution in anhydrous THF to the cooled (0 °C) mixture of lithium diisopropylamide in THF. The resulting mixture was stirred for 1 h at room temperature. Subsequently, a solution of 0.7 mL (9.5 mmol) of acetone-d_6 in anhydrous THF (15 mL) was added at −78 °C and the mixture was allowed to stir overnight. The reaction mixture was poured onto ice. After several extractions with Et_2O, the aqueous layer was acidified with 6 M HCl. The aqueous mixture was extracted with Et_2O, and the combined ether extracts were dried over $MgSO_4$ and concentrated to provide the *β*-hydroxy acid (1.85 g, 85%). Approximately 4% scrambling was observed at the methyl groups ^{1}H NMR ($CDCl_3$): δ 3.55 (s, 1 H), 3.77 (s, 3 H), 6.84 (d, J = 6.8 Hz, 2 H), 7.29 (d, J = 6.8 Hz, 2H).

3-(*p*-Methoxyphenyl)-4,4-dimethyloxetan-2-one-5,5,5,-4′,4′,4′-d_6. A solution of 1.85 g (8.0 mmol) of *β*-hydroxy acid in dry pyridine was cooled to 0 °C and two mol of benzensulfonyl chloride (2.05 mL, 16.06 mmol) per mol of *β*-hydroxy acid were added. The mixture was well-shaken, sealed, and kept at −10 °C overnight. The reaction mixture was poured into a cooled (0 °C) saturated solution of $CuSO_4$ to remove pyridine and then was extracted several times with Et_2O. The combined ether layers were washed with a saturated solution of Na_2CO_3 and H_2O to remove unreacted *β*-hydroxy acid, dried over $MgSO_4$, and concentrated to afford the corresponding *β*-lactone (1.14 g) in 67% yield. ^{1}H NMR ($CDCl_3$): δ 3.78 (s, 3 H), 4.54 (s, 1 H), 6.88 (d, J = 7.0 Hz, 2 H), 7.10 (d, J = 7.0 Hz, 2 H).

1-(*p*-Methoxyphenyl)-2-methylprop-1-ene-3,3,3,2′,2′,2′-d_6 (5-d_6). Thermolysis of 5.4 mmol (1.14 g) of 3-(*p*-methoxyphenyl)-4,4-dimethyloxetan-2-one-5,5,5,4′,4′,4′-d_6 at 100 °C under vacuum provoked decomposition to **5**-d_6 and simultaneous distillation. The resulting alkene was purified by flash column chromatography using a mixture of petroleum ether and ethyl acetate (10:1) as eluent, affording 0.65 g (3.7 mmol) of **5**-d_6. ^{1}H NMR ($CDCl_3$): δ 3.80 (s, 3 H), 6.19 (s, 1 H), 6.85 (d, J = 8.6 Hz, 2 H), 7.14 (d, J = 8.6 Hz, 2 H). MS *m*/*z* 168 (M^+, 100).

Synthesis of 1-(*p*-Methoxyphenyl)-2-methylprop-1-ene-1-d_1 (5-d_1). This compound was synthesized by reduction of methyl *p*-methoxybenzoate with $LiAlD_4$, followed by PCC oxidation of the corresponding alcohol-d_2 and Wittig coupling of the resulting *p*-methoxybenzaldehyde-*1*-d_1 with triphenylphosphoranylidene isopropane.

***p*-Methoxyphenylmethanol-1,1-d_2.** This compound was prepared by $LiAlD_4$ reduction (0.74 g, 17.6 mmol) of methyl *p*-methoxybenzoate (3.9 g, 23.4 mmol) according to the experimental procedure followed in the synthesis of 1-(*p*-methoxyphenyl)ethanol-1-d_1. A 2.8 g (84%) amount of deuterated alcohol was isolated. ^{1}H NMR ($CDCl_3$): δ 3.79 (s, 3 H), 6.87 (d, J = 6.8 Hz, 2 H), 7.20 (d, J = 6.8 Hz, 2 H).

***p*-Methoxybenzaldehyde-1-d_1.** To a cooled (0 °C) solution of pyridinium chlorochromate (6.4 g, 29.7 mmol) in dry CH_2Cl_2 (140 mL) was added dropwise a solution of 2-(*p*-methoxyphenyl)ethanol-1,1-d_2 (2.8 g, 19.7 mmol) in dry CH_2Cl_2 (60 mL). The reaction mixture was stirred at room temperature for 3 h. Subsequently, the CH_2Cl_2 was evaporated and the remaining residue was diluted in anhydrous Et_2O. After filtration, the filtrate was concentrated and the residue was purified by flash column chromatography using petroleum ether and ethyl acetate (8/1) as eluent, to afford *p*-methoxybenzaldehyde-1-d_1 (1.6 g, 66%). ^{1}H NMR ($CDCl_3$): δ 3.87 (s, 3 H), 6.99 (d, J = 8.7 Hz, 2 H), 7.82 (d, J = 8.7 Hz, 2 H). MS *m*/*z* 137 (M^+, 75).

1-(*p*-Methoxyphenyl)-2-methylprop-1-ene-1-d_1 (5-d_1). To a cooled mixture (0 °C) of isopropyltriphenylphosphonium bromide (5.0 g, 13.0 mmol) in dry THF was added a solution of *n*-BuLi 1.4 M in hexane (11 mL), under N_2 atmosphere. The solution turned red due to the formation of triphenylphosphoranylidene isopropane. After stirring for 1 h at room temperature, a solution of *p*-methoxybenzaldehyde-1-d_1 (1.6 g, 11.9 mmol) in dry THF was added dropwise. The resulting mixture was stirred at room temperature for 30 min and poured into 100 mL of hexane. Triphenylphosphine oxide (Ph_3PO) precipitated out of solution. After filtration, the solution was concentrated and the residue was distilled in a vacuum, affording **5**-d_1 (1.3 g, 67%). ^{1}H NMR ($CDCl_3$): δ 1.84 (s, 3 H), 1.87 (s, 3 H), 3.80 (s, 3 H), 6.85 (d, J = 8.6 Hz, 2 H), 7.14 (d, J = 8.6 Hz, 2 H). MS *m*/*z* 163 (M^+, 100).

The precursor to ylide, isopropyltriphenylphosphonium bromide, was prepared by heating neat an excess of isopropylbromide (4.8 mL, 52 mmol) and triphenylphosphine (8.2 g, 31.2 mmol) in a sealed tube for 24 h at 140 °C. The phosphonium salt was collected as a white solid and was washed with hot toluene. ^{1}H NMR ($CDCl_3$): δ 1.29 (dd, J_{H-P} = 19 Hz, J_{H-H} = 6.8 Hz, 6 H), 5.56 (m, 1 H), 7.68 (m, 9 H), 7.95 (m, 6 H).

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Supporting Information Available: ^{1}H NMR spectra for *cis*-**1**, *trans*-**2**, *cis*-**3**-d_1, *cis*-**4**-d_1 + *trans*-**4**-d_1, **3**-d_1, **3**-d_3, **4**, **6**, *trans*-**5**-d_3, **5**-d_6, and *cis*-**6**-d_3 + *trans*-**6**-d_3 and NOE difference spectrum for *cis*-**6**-d_3 + *trans*-**6**-d_3. This material is available free of charge via the Internet at http://pubs.acs.org.

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