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# Stereochemistry and steric isotope effect on the [2+2] photocycloaddition of $\beta,\beta$ -dimethyl-*p*-methoxystyrene to $C_{60}$ : the nature of the transition state structures

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## Abstract

The photochemical [2+2] cycloaddition of  $\beta,\beta$ -dimethyl-*p*-methoxystyrene to  $C_{60}$  occurs with loss of stereochemical integrity. The substantial remote kinetic isotope effect in the title reaction, indicates the formation of an open, relatively long lived intermediate. © 2000 Published by Elsevier Science Ltd.

*Keywords:* fullerenes; photochemistry; [2+2] cycloadditions; isotope effects.

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Cycloaddition reactions involving fullerene  $C_{60}$  have been studied extensively over the last ten years. Among them, Diels–Alder and [1,3] dipolar cycloadditions are the most efficient functionalizing fullerene routes.<sup>1</sup> The [2+2] cycloadditions of  $C_{60}$  with unsaturated compounds, although less common, have recently received considerable attention. For example, the preparation and isolation of well characterized [2+2] monoadducts of  $C_{60}$  with alkynes,<sup>2</sup> arylalkenes,<sup>3</sup> dienes,<sup>4</sup> cycloenones,<sup>5</sup> acyclic enones<sup>6</sup> and diones<sup>7</sup> have recently been reported. The triplet excited state of  $C_{60}$  ( $^3C_{60}$ ) with a reduction potential close to 0.98 V<sup>8</sup> is more electrophilic than the ground state and responsible for most<sup>9</sup> of the [2+2] photocycloadditions to  $C_{60}$ . However, a few thermal [2+2] cycloadditions have also been reported.<sup>10</sup>

Recent studies have shown that the [2+2] photocycloadditions of alkenes,<sup>2,3</sup> dienes<sup>4</sup> and enones<sup>5,6</sup> occurs by a two-step mechanism, involving the formation of a dipolar/biradical or charge transfer intermediate in the rate determining step.

In this communication we report the stereochemistry and a remote secondary isotope effect in the [2+2] photocycloaddition of  $\beta,\beta$ -dimethyl-*p*-methoxystyrene to  $C_{60}$ . These results may shed some light on the nature of the transition states controlling product formation.

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To test the stereochemistry of the [2+2] cycloaddition of trisubstituted alkenes to  $C_{60}$ ,  $E$ -1-(*p*-methoxyphenyl)-2-methyl-propene-3,3,3- $d_3$ , ***trans*-1- $d_3$** , was prepared<sup>†</sup> in greater than 96% isomeric purity. This substrate is suitable for this purpose, because it bears a deuterated methyl group *trans* to the aryl moiety, which allows elucidation of the stereochemistry on the reaction. In the absence of light, a mixture of  $C_{60}$  and a 300-fold molecular excess of ***trans*-1- $d_3$**  did not react, as monitored by HPLC, when heated for 12 h at reflux in deoxygenated toluene. However, upon irradiation with a 300 W xenon lamp as the light source, a 40% yield of the [2+2] adduct was obtained after 45 min, based on the recovered  $C_{60}$  (Fig. 1). This adduct was purified by flash column chromatography (toluene:hexane, 2:1). The  $^1H$  NMR of the purified [2+2] adduct shows two unequal cyclobutanic methyl resonances at 1.87 and 2.10 ppm. Upon integrating the methyl signals, the ratio of the two adducts, ***trans*-2- $d_3$**  and ***cis*-2- $d_3$** , was measured to be 44:56. The lack of any considerable retention of configuration in this reaction supports a stepwise mechanism through an open biradical or dipolar intermediate as shown in Scheme 1. Examination of the unreacted arylalkene at the end of the reaction, showed no isomerization. Again, in a control experiment, irradiation of a mixture of  $C_{60}$  and a threefold excess of ***trans*-1- $d_3$** —compared to the 300-fold excess in the previous experiment—for 1 h, gave no scrambling of the starting *E*-stereochemistry. These results indicate clearly that, under the reaction conditions, no isomerization of the arylalkene occurs before its addition to  $C_{60}$ .

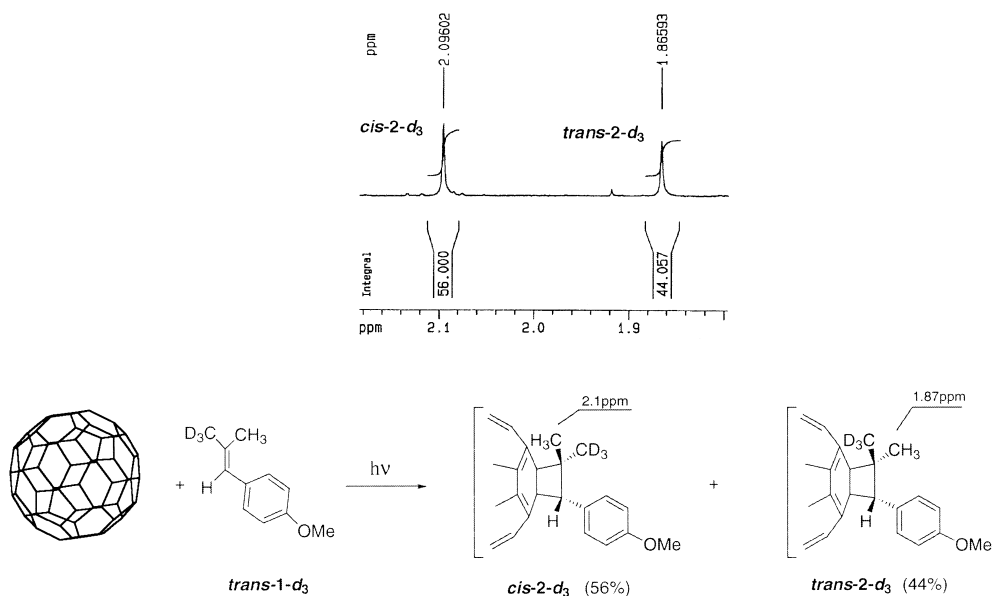
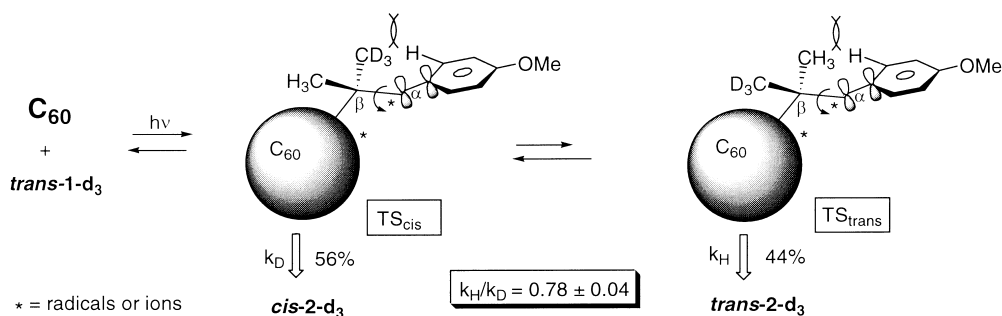


Figure 1. [2+2] Photocycloaddition of ***trans*-1- $d_3$**  to  $C_{60}$

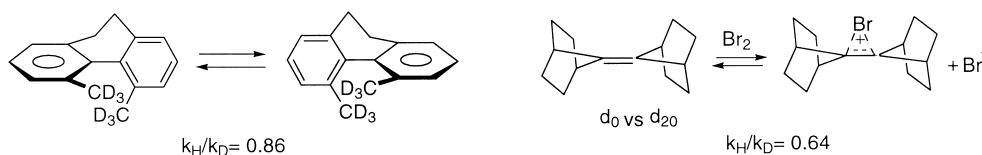
<sup>†</sup> ***trans*-1- $d_3$**  was prepared via stereoselective formation of *E*-2-methyl-*p*-methoxycinnamate by a Wittig–Horner reaction with *p*-methoxybenzaldehyde, followed by  $LiAlD_4/AlCl_3$  reduction and subsequent chlorination of the resulting allylic alcohol, followed by  $LiAlD_4$  reduction.<sup>11</sup> The desired product was obtained in good overall yield and in 96% isomeric purity.  $^1H$  NMR ( $CDCl_3$ ):  $\delta$  1.84 (s, 3H), 3.80 (s, 3H), 6.20 (s, 1H), 6.85 (d,  $J=8.7$  Hz, 2H), 7.14 (d,  $J=8.7$  Hz, 2H).



Scheme 1. Transition states in the [2+2] photocycloaddition of *trans*-1- $d_3$  to  $C_{60}$

In order to determine the stereochemistry of the major and the minor adduct, NOE experiments were performed. Irradiation of the more intensive methyl group at 2.10 ppm (major adduct) gave a positive 0.7% enhancement of the benzylic hydrogen at 5.23 ppm, whereas, irradiating the less intensive methyl group at 1.87 ppm (minor adduct), produced no NOE. These results demonstrate that the major adduct exhibits *cis* stereochemistry whereas the minor adduct *trans*. It is interesting to emphasize here that the *trans* configuration of the reactant alkene reverses, favoring by 12%, the *cis* configuration in the cycloadducts. This unexpected result can be rationalized by examination of the two transition states leading to the *trans*-2- $d_3$  and *cis*-2- $d_3$  products. Libration of the phenyl group around the previous  $C_\alpha$ - $C_\beta$  double bond, leads to the transition state  $TS_{cis}$  and  $TS_{trans}$  (Scheme 1). It is reasonable to assume that the conjugation between the  $p$ -orbital of the  $\alpha$ -carbon and of the aromatic system, prevents free rotation around the  $\alpha$ -carbon and the aryl ring (Scheme 1). In transition state  $TS_{trans}$  leading to the less favored adduct, the non-bonded interactions involving the larger  $CH_3$  group on the  $\beta$ -carbon and the *ortho*-phenyl hydrogen are expected to be stronger than those in  $TS_{cis}$  involving the non-bonded interactions between the smaller  $CD_3$  group and the *ortho*-phenyl hydrogen. Due to congestion, the zero point energy levels of the isotopically related diastereomeric transition states<sup>12</sup> are distinguishable in favor of  $TS_{cis}$ . The resulting steric isotope effect was attributed to the smaller effective size of the C–D bond relative to the C–H bond in the methyl groups.<sup>13</sup> The vibrational force constant of the C–H (D) bond arises in a sterically encumbered situation leading to inequality in the zero point energy difference between the isotopically related transition states. The remarkable steric isotope effect observed here is responsible for the unequal formation of the cycloadducts.

Remote steric isotope effects, are less common. A classical example was reported by Mislow and co-workers<sup>14</sup> in the mid 1960s. They observed that sterically hindered biphenyl derivatives (Scheme 2), that were deuterated at both methyl groups, underwent racemization 16% faster than the protonated analogue. In this case an inverse isotope effect of  $k_H/k_D = 0.86$  was measured. In a more recent example, Brown and his co-workers<sup>15</sup> reported a large inverse steric secondary isotope



Scheme 2. Steric secondary kinetic isotope effects

effect in the electrophilic addition of bromine to 7-norbornylidene-7'-norbornane which they attributed to the rate-determining formation of the bromonium ion (Scheme 2).

In conclusion, the [2+2] photocycloaddition of trisubstituted arylalkenes to C<sub>60</sub> proceeds via a stepwise mechanism. The remote steric secondary isotope effect observed in the second step of the reaction requires that the intermediate has a long enough lifetime for at least a few rotations of the aryl moiety before the ring closure to the [2+2] adduct.

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