

Enantioselectivity of Prochiral Radical-Pair Recombinations. Reaction Cavity Differentiation in Polyethylene Films

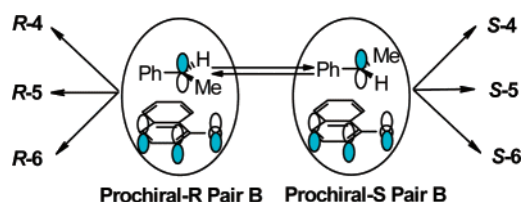
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ABSTRACT



Recombinations of prochiral radical pairs from irradiations of 1-naphthyl (*R*)-2-phenylpropanoate in polyethylene films occur with significant enantioselectivity due to templating effects in the reaction cavities. Photoreactions in PE films in their unstretched or stretched states and of different crystallinity have been employed to distinguish between the characteristics of reaction cavities in amorphous and interfacial regions of the polymer.

The stereoselectivity of reaction by a radical pair¹ can be mediated by varying the polarity or the viscosity of the solvent,² as well as by changing the spin multiplicity of the radical pair³ or applying external magnetic fields.⁴ Designing anisotropic media that optimize stereochemical integrity during radical pair recombinations is an important topic of current research.^{5,6} Previously, we investigated the fates of

singlet radical pairs generated during the photo-Fries reactions of aryl phenylacrylates in polymeric films⁷ and used an internal “clock”,⁸ the rate of decarbonylation of intermediate arylacyl radicals, to determine their rates of in-cage recombinations. We also determined the percent of in-cage recombination by triplet radical pairs from irradiation of 1-(4-methylphenyl)-3-phenyl-2-propanone in liquid-crystalline media⁹ and polymeric films,¹⁰ and used again the rate of

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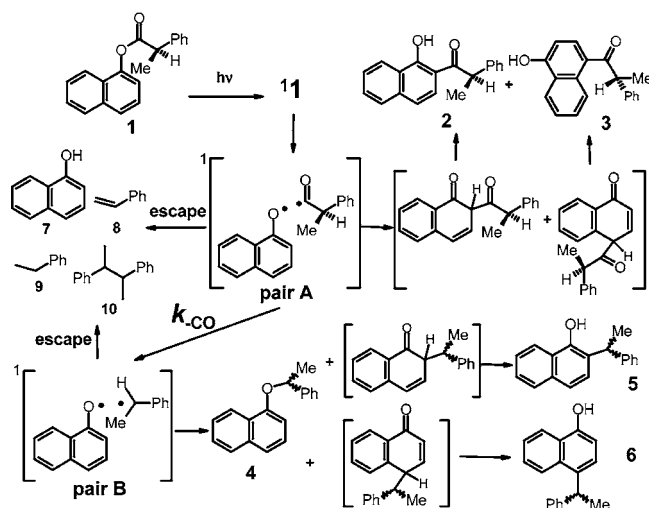
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Scheme 1. Proposed Mechanism for Photoreactions of **1**



decarbonylation of the arylacyl radicals to calculate the rate constants for radical escape from the polymer cages.

On the basis of these results, we conjectured that the *anisotropic* reaction cavities provided by polymer films may restrict specific movements of radical pairs, allowing significant retention of stereo integrity during the recombination processes. In support of this hypothesis, we report here the enantiomeric excess (*ee*) of each photo-Fries and decarbonylated product from room-temperature irradiations¹¹ of 1-naphthyl (*R*)-2-phenylpropanoate (**1**; Scheme 1) in three unstretched and stretched polyethylene (**PE**) films (Table 1),¹² as well as in hexane, a low viscosity, isotropic solvent of comparable polarity and functionality.¹³ **PE46** and **PE74** contain interfacial (at the lateral boundaries between crystallites and amorphous domains) and amorphous regions where guest molecules can reside; they do not reside inside the crystalline regions.¹⁴ The completely amorphous **PE0** lacks interfacial sites. As noted in Table 1, the mean hole free volume of the films, an indicator of the space allotted guest molecules in their reaction cavities, decreases with increasing crystallinity and stretching.^{7c,15}

(11) The temperature dependence of these enantiomeric excesses will be discussed elsewhere. The product distributions have been reported.⁷

(12) (a) Wang, C.; Xu, J.; Weiss, R. G. *J. Phys. Chem. B* **2003**, *107*, 7015. (b) MDI Jade 5 software for X-ray diffraction pattern processing from Materials Data, Inc., Livermore, CA. (c) Matthews, J. L.; Peiser, H. S.; Richards, R. B. *Acta Crystallogr.* **1949**, *2*, 85.

(13) **PE** films with doped **1** were irradiated under an N₂ atmosphere at 23 °C. After exhaustive extractions by CH₂Cl₂, the combined liquids were concentrated by bubbling N₂ or distillation. Product distributions from HPLC analyses (Allsphere silica column; 5 μ , 4.6 \times 250 mm; mixture of hexanes and ethyl acetate as eluant) are collected in Table S1 of the Supporting Information. Each photoproduct was prepared independently or isolated from irradiation mixtures. Enantiomeric mixtures of unreacted **1** (>99% initial chemical and enantio purity) and the photoproducts were separated on a silica or cyano HPLC column (IBM Instruments Inc.; 5 μ m, 10 \times 250 mm; mixture of hexanes and ethyl acetate as eluant for both columns) and their *ee* values were determined by HPLC, using a Chiralcel OJ-H column (Chiral Technologies, 5 μ m, 4.6 \times 250 mm; mixture of hexanes and 2-propanol as eluant). See Supporting Information for details.

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Table 1. Pertinent Physical Properties of **PE** Films

film	crystallinity (%) ^a		mean free vol (Å ³) ^b	
	unstretched	stretched ^c	unstretched	stretched ^c
PE0	0	0	177	129
PE46	46	47	139	121
PE74	74	70	129	120 ^d

^a By X-ray diffraction.^{12b,c} ^b From positron annihilation lifetime spectra of undoped films.^{7c} ^c Stretched ca. 2–3 \times (**PE0**) or ca. 4–6 \times (**PE46** and **PE74**). ^d Stretched ca. 2 \times .

It is unclear whether the previously reported high *regioselectivities* of photoreactions in **PE** films are due primarily to high viscosity (i.e., indiscriminate inhibitions to both translational and rotational motions on the time scale of the guest reactions) or also to templating effects (i.e., inhibition of some guest motions more than others).¹⁶ The *enantioselectivities* reported here separate the ability of the radicals to undergo internal and external rotational motions (that lead to loss of enantiopurity) and translational ones. They demonstrate that **PE** cavities are templates whose properties can be tuned by changing film crystallinity and by macroscopic film stretching. Furthermore, the properties of **PE** reaction cavities in amorphous and interfacial domains can be qualitatively differentiated.¹⁷

The mechanisms for photoreactions of **1** in **PE** films or hexane are summarized in Scheme 1. Each of the two in-cage radical pairs, carbonylated pair **A** and decarbonylated pair **B**, can recombine in-cage to form keto intermediates that enolize to yield the observed products **2** and **3** (in addition to **1** from pair **A**) and **5** and **6** (in addition to ether **4** from pair **B**).¹⁸ Alternatively, if one radical of a pair escapes from the initial cage, photoproducts **7–10**, but not photoproducts **2–6**,¹⁹ are formed.

The product distributions from irradiations in **PE** films and in hexane are very different.⁷ The data in Table 2 show that the *ee* values are as well, and that there are interesting variations among the *ee* values among the **PE** films. In hexane, the photo-Fries rearrangement products, **2** and **3**, retain the *ee* (\approx 99%) of **1** while the decarbonylated products, **4–6**, are almost totally racemized. The *ee* values of **4–6** are much higher in the **PE** films than in hexane (Figure 1), but the photo-Fries rearrangement products are partially racemized in some cases (Table 2).

Recombinations of Radical Pair B. The radical pairs **B** are the radical pairs **A** in which loss of CO has occurred. They may be intrinsic to a fraction of the guest molecules

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(17) Cavity types in **PE** have been differentiated recently by a thermal reaction (Wang, C.; Weiss, R. G. *Macromolecules* **2003**, *36*, 3833) but prior attempts to do so with photo-Fries reactions were unsuccessful.⁷

(18) Miranda, M. A.; Galindo, F. In *Photochemistry of Organic Molecules in Isotropic and Anisotropic Media*; Ramamurthy, V., Schanze, K. S., Eds.; Marcel Dekker: New York, 2003; Chapter 2.

(19) The absence of **10** in all **PE** films indicates that **2–6** arise only from reactions of radical pairs that remain in their original cage.^{7b}

Table 2. Enantiomeric Excesses (%)^a of Photoproducts from Irradiations of **1**^b in PE Films (1–7 mmol/kg) and Hexane (2 mM) at Room Temperature

medium ^c	2	3	4	5	6
hexane	99	99	0.8	1.0	0.2
PE0 (u)	99	99	19.3	21.3	21.6 ^d
PE0 (s)	99	99	18.9	20.9	23.9
PE46 (u)	97	99	12.3	15.6 ^d	16.5
PE46 (s)	76	99	7.1	7.2 ^d	9.6
PE74 (u)	97	99	16.8	13.4	10.0
PE74 (s)	81	99	6.6	7.6	9.0

^a ±1% except as indicated. In all cases, the (*R*) enantiomer is assumed to be in excess. ^b The ee of unreacted **1** remained >99% after irradiations. ^c The “u” and “s” refer to unstretched and stretched film states, respectively. ^d <±2%.

(i.e., excited **1** in conformations at the moment of lysis that place the radical pairs in orientations that are not conducive to recombination), to a fraction of the reaction cavities (i.e., **1** residing in cages that do not allow the rapid motions needed for radical pair recombinations), or to a combination of both. As such, the relative orientations and positions of the constituent radicals of a pair **B** at the moment of their creation cannot be established as well as those of pair **A**,⁷ and there must be important differences between the average initial orientations and/or mobilities of radical pair **A** and radical pair **B** within their PE cages. In support of this contention, the photo-Fries product ratios **2/3** from **1** irradiated in PE films are typically ~10 while the analogous decarbonylated ratios **5/6** are <1.⁷

Previously, we have found that the lifetimes of the radical pairs **A** that lead to **2** and **3** do not appear to depend on the degree of PE crystallinity. As a result, it has not been possible to probe the effects of reaction occurring from different populations of the “softer”¹⁶ and more voluminous cavities in amorphous regions and of the “stiffer” and smaller cavities in interfacial regions. The data reported here do so by monitoring the stereochemistries of the decarbonylated photoproducts **4–6**.

For reactions of the ensemble average of all reacting molecules in Scheme 1 when the medium is achiral, there

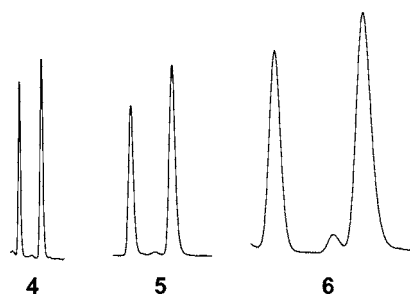
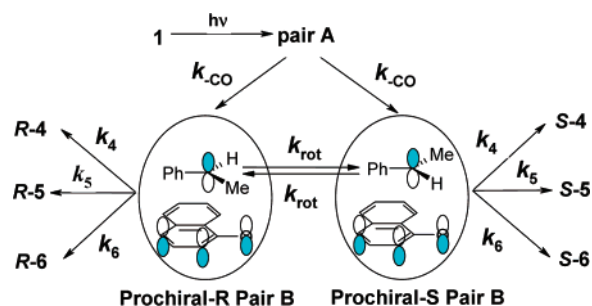


Figure 1. Representative HPLC traces of decarbonylated enantiomers of **4–6**. The small peaks in the chromatograms of **5** and **6** are unidentified impurities. Detector wavelength = 294 nm.

Scheme 2. Competition between Racemization and Product Formation^a



^a Note that k_5 and k_6 are actually the rate constants for formation of the keto intermediates of **5** and **6**.

are two basic requirements for a nonzero *ee* in products **4–6**: (1) the initial ratio of the prochiral radical pairs **B** (Scheme 2), prochiral-*R*/prochiral-*S*, must not be one and (2) $k_{rot} < k_4 + k_5 + k_6$. The rate constants are weighted averages for reactions in amorphous and interfacial reaction cavities. Only in **PE0** do we know that all reaction takes place in amorphous cavities, and even there, the initial prochiral-*R*/prochiral-*S* ratio is unknown. Therefore, our data treatment must be qualitative at this time.

In unstretched PE films, the *ee* values of **4–6** unexpectedly increase as crystallinities decrease and mean hole free volumes increase (see Figure S3 of the Supporting Information)! We expected that the stress exerted on the reaction cavities by **1** (and, thereby, the templating effect) would be greatest in **PE74**, the film with the smallest mean free hole volume, since the calculated van der Waals volume^{7b,20} of a molecule of **1**, 254 Å³, is much larger than the 129–177 Å³ mean free volumes of “holes” within the PE films. However, this reasoning does not consider that the partially crystalline polymers, **PE46** and **PE74**, offer two major site types for molecules of **1**. Our results lead to the surprising conclusion that racemization of decarbonylated photoproducts is more likely when a radical pair **B** resides in the stiffer (and probably smaller) reaction cavities^{7c} (i.e., within the interfacial regions, where the guest molecules prefer to reside^{7e,12a}).

The softer walls in amorphous cavities must facilitate the translational motions needed to orient radical pair **B** for formation of ether **4** or the keto precursors of **5** and **6** on the same time scale needed for the rotational motions of the planar 1-phenylethyl radicals. In interfacial cavities, the 1-naphthoxy radicals of radical pair **B** probably lie on the lamellar faces of crystallites,²¹ and motions orienting leading to **4–6** are primarily by the 1-phenylethyl radicals. Due to the relatively low mobility of the stiffer chains along the amorphous side of the interfacial regions,²² the translational motions associated with k_4 , k_5 , and k_6 will be more difficult than in cavities within the amorphous parts: $[k_{rot}/(k_4 + k_5 + k_6)]_{interfacial} > [k_{rot}/(k_4 + k_5 + k_6)]_{amorphous}$.

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(21) (a) Konwerska-Hrabowska, J. *Appl. Spectrosc.* **1985**, *39*, 434. (b) Konwerska-Hrabowska, J. *Appl. Spectrosc.* **1985**, *39*, 976.

(22) (a) Hentschel, D.; Sillescu, H.; Spiess, H. W. *Polymer* **1984**, *25*, 1078. (b) Wang, C.; Weiss, R. G. *Macromolecules* **2003**, *36*, 3833.

Film stretching of partially crystalline **PE** forces chains to pack more closely, increases the area of the interfacial region, decreases mean hole free volumes, and leads to a large increase in the fraction of guest molecules in interfacial cavities.^{12a} Consequently, the total relative yield of **4–6** increases (2–3)-fold²³ upon stretching **PE46** or **PE74** (but not the totally amorphous **PE0**), although the *ee* values decrease! The increased yields are consistent with the slower rates of recombination of radical pair **A**²⁴ and the much larger fractions of molecules of **1** residing in interfacial sites. The lower *ee* values follow from the arguments presented above concerning the relative rates of motions of radicals of pair **B** in amorphous and interfacial reaction cavities. They are supported by the nearly equal *ee* values of **4–6** in unstretched and stretched **PE0**.

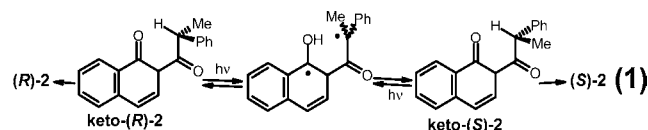
The calculated relative spin densities on the three positions of the 1-naphthoxy radical where a 1-phenylethyl radical must add to form **4** or the keto precursors of **5** and **6** are $C4 > C2 > O^{7d} \Rightarrow 6 > 5 > 4$, and the product yields correlate reasonably well in hexane (the medium whose control over product formation is expected to be smallest), in **PE0** (the polymer with the largest mean free hole volume and in which all molecules of **1** are in amorphous cavities), and in stretched **PE74** (where the mean free hole volume is smallest, the fraction of **1** in interfacial sites is largest, and medium control is expected to be largest)! Although the product ratios are $[6] > [5] \cong [4]$ in unstretched and stretched **PE46**, the free electron densities of 1-naphthoxy correlate with the *ee* values of the decarbonylated products in all of the films except unstretched **PE74**: $ee_6 \geq ee_5 \geq ee_4$. On this basis, the reaction cavities seem to act as templates. However, the exceptions indicate that other factors play an important role in the dynamics of the radical pair reactions.

Recombination of Radical Pair A. Because recombinations of radical pair **A** do not involve directly the stereocenter; near 100% *ee* values of the photo-Fries products **2** and **3** (as well as of unconverted **1**) were expected in all of the media. Significant loss of enantiopurity was found especially in **2** from irradiations in **PE** films containing a

(23) This phenomenon has been observed and its origin has been discussed previously.⁷ The data from this work are collected in Table S1 of the Supporting Information.

(24) The rate constants for formation of **2** and **3**, respectively, from radical pair **A** at room temperature decrease in **PE46** from 5.2×10^8 and 3.9×10^8 s⁻¹ (unstretched) to 2.2×10^8 and 1.7×10^8 s⁻¹ (stretched).⁷

significant interfacial content (i.e., not in **PE0** films), and the loss increased upon film stretching (Table 2). We conjecture that the keto intermediates of **2** and **3** are much longer lived in interfacial cavities (of stretched films especially) than in amorphous ones. During that prolonged lifetime, many of the keto intermediates are able to absorb a second photon,²⁵ allowing reversible γ -H abstraction from the stereocenter of keto-(*R*)-**2** (but not from the analogous keto-(*R*)-**3**) that leads to racemization (eq 1). In addition, keto-(*R*)-**2** (and keto-(*R*)-**3**) may revert to radical pairs, but this process does not lead to racemization of **2** (and **3**).



In conclusion, we have observed significant enantioselectivity of prochiral radical pair recombinations in **PE** matrices and have explored regio effects on the enantioselectivity. The regioselectivities of the photo-Fries and decarbonylation products from **1** are very different and the enantioselectivities of the decarbonylation products do not scale with local medium viscosity (as had been expected), but do depend on the properties of the cavities in which the radical pair precursor resides (such as wall stiffness and mean hole free volumes). Attempts to increase the enantiomeric excesses in other polymeric films and to understand better the factors responsible for them are in progress.

Acknowledgment. The authors are grateful to the National Science Foundation for financial support of this research and to Dr. Weiqiang Gu and Prof. Miguel A. Garcia-Garibay for helpful discussions.

Supporting Information Available: General experimental procedures for UV irradiations of **1** in hexane and in **PE** films and for determinations of product distributions and enantiomeric excesses included in one table and 3 figures. This material is available free of charge via the Internet at <http://pubs.acs.org>.

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(25) For a different photochemical course for cyclohexadienones, see: Jiménez, M. C.; Miranda, M. A.; Scaiano, J. C.; Tormos, R. *Chem. Commun.* **1997**, 1487.