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PHOTOINDUCED ELECTRON TRANSFER-INITIATED ENANTIOSELECTIVE CYCLIZATION OF *N*-BENZOYL-α-DEHYDROARYLALANINE *tert*-BUTYL ESTERS IN THE PRESENCE OF CHIRAL AMINE

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Abstract–The asymmetric photocyclization of the title compounds in 1,2-dichloroethane was found to proceed cleanly in the presence of primary, secondary, or tertiary chiral amine to give the corresponding *cis*- and *trans*-3,4-dihydrooxazole derivatives in enantiomeric excess (ee) of 11–38% and 6–33%, respectively, depending on the steric factor of the aryl substituent as well as on the hydrogen-bonding ability of the chiral amine.

Excited-state chemistry for organic molecules has continued to contribute to the development of novel synthetic methods that enable the construction of pharmaceutically useful hetero atom-containing ring systems.[1] While sophisticated organic photochemistry has also contributed to the enhancement of enantio- and diastereoselectivities in many asymmetric reactions,[2–5] there have been only a few enantio- and diastereodifferentiating photochemical reactions of synthetic utilities, particularly in liquid phase. Since photoinduced electron transfer (PET) reactions may construct various heterocyclic ring systems with high efficiencies,[6] we attempted to develop a new mode of diastereodifferentiating cyclization of *N*-benzoyl-α-dehydronaphthylalaninamides carrying some chiral auxiliaries via PET and found the highly diastereoselective formation of 3,4-dihydrobenzoquinolinone derivatives.[7] In addition, detailed analysis of the effects of tertiary amine, solvent, chiral auxiliary and temperature on the diastereomeric excess (de) demonstrated that diastereoselectivity in this photocyclization strongly depended on the steric and electronic factors of a given chiral auxiliary that affect the relative rate for tautomerization of the diastereomeric enol-type intermediate. On the other hand, it was quite recently found that the PET reaction of *N*-benzoyl-α-dehydroarylalanine alkyl ester derivatives selectively afforded substituted 4,5-dihydrooxazoles even in less polar solvents.[8] Because these products possess two asymmetric carbons in a dihydrooxazole ring, we undertook a mechanistic investigation regarding the diastereoselective cyclization of chiral auxiliary-substituted *N*-benzoyl-α-dehydro-(1-naphthyl)alanine alkyl esters via PET. Analysis of chiral auxiliary, solvent, and temperature effects on

This paper is dedicated to Professor Dr. Ekkehard Winterfeldt on the occasion of his 75th birthday.

the de for *cis*- and *trans*-3,4-dihydrooxazoles revealed that the introduction of the bulky phenylmenthyl auxiliary into the ester moiety enabled the asymmetric photocyclization to proceed in a high de and, additionally, the hydrogen-bonding interaction of a given intermediate with solvent and/or amine was a major factor controlling the observed asymmetric photoinduction.[9] Based on these previous findings we predict that chiral amine existing in the vicinity of the reaction intermediates may induce the enantioselective photocyclization of α-dehydroarylalanine alkyl esters. In order to develop a novel asymmetric photocyclization and to expand our study concerning this photocyclization, we synthesized (*Z*)-*N*-benzoyl-α-dehydroarylalanine alkyl esters having 1-naphthyl, 2-naphthyl, and phenyl substituents as aryl groups [(*Z*)-**1a**–**d**] and investigated substituent, chiral amine, and temperature effects on the asymmetric photocyclization of these alkyl ester derivatives in 1,2-dichloroethane containing (*S*)-2-phenylglycinol (*S*-PG), (*S*)-pyrrolidine-2-methanol (*S*-PM), (*R*)-pyrrolidine-2-methanol (*R*-PM), or (*S*)-1-methylpyrrolidine-2-methanol (*S*-MPM) (Chart 1).

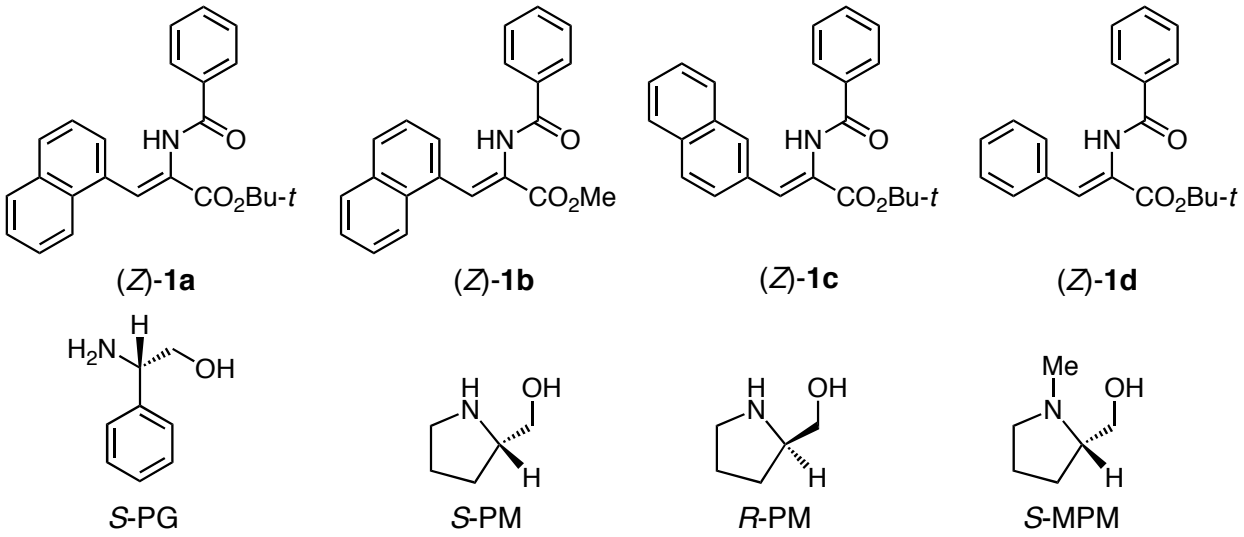
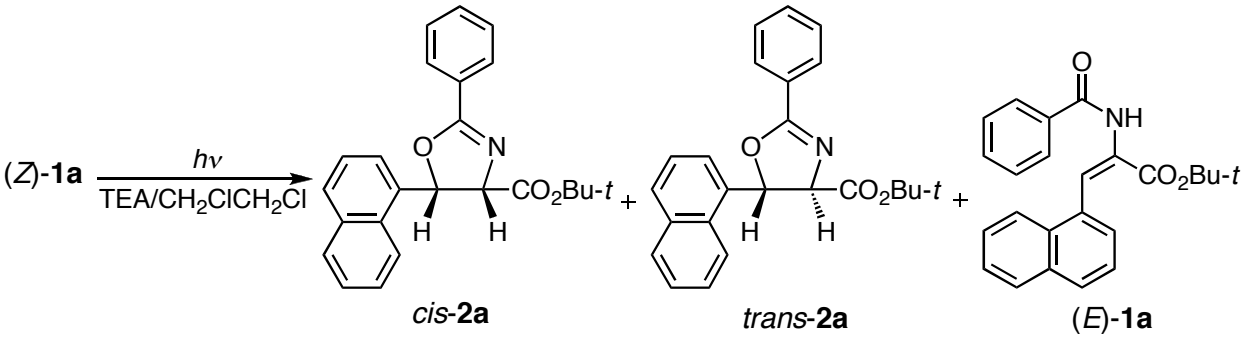


Chart 1

After a nitrogen-saturated 1,2-dichloroethane solution of (*Z*)-**1a** (4.0×10^{-3} mol dm^{-3}, 500 mL) containing triethylamine (TEA, 0.10 mol dm^{-3}) was irradiated with Pyrex-filtered light from a 400 W high-pressure Hg lamp for 5 h at room temperature (conversion, ≈100%), the reaction mixture obtained was subjected to preparative thin layer chromatography over silica gel. This chromatography allowed us to isolate *cis*- and *trans*-4-*tert*-butoxycarbonyl-5-(1-naphthyl)-2-phenyl-4,5-dihydrooxazoles as their enantiomeric mixtures [*cis*-**2a**: (4*R*,5*R*)-**2a** + (4*S*,5*S*)-**2a**, 56% yield; *trans*-**2a**: (4*S*,5*R*)-**2a** + (4*R*,5*S*)-**2a**, 28% yield] having the vicinal coupling constants ($J_{4,5}$) of 10.3 Hz and 6.2 Hz in DMSO-d_6, respectively, as shown in Scheme 1.[10] The (*E*)-isomer of **1a** was isolated independently from the reaction mixture, which was irradiated for 0.5 h under the same conditions, by similar workup.[10] The absolute configuration of the **2a**-derived enantiomers was determined based on the X-ray crystal structure of (4*S*,5*S*)-**2a** as well as on the sign of circular dichroism bands for (4*S*,5*S*)-**2a** and (4*R*,5*R*)-**2a** at 220 nm.[9] In order to estimate the retention time (t_R) of HPLC signal and enantiomeric excess (ee) for a given enantiomer, (4*S*,5*S*)-**2a** and (4*R*,5*R*)-**2a** were isomerized into (4*R*,5*S*)-**2a** and (4*S*,5*R*)-**2a**, respectively, in methanol containing TEA

to give the enantiomeric mixtures which were subjected to normal phase HPLC analysis using a 4.6×250-mm Chiralcel IA column [mobile phase, *i*-PrOH:$CHCl_3$:C_6H_{14} = 5:5:90 v/v; t_R/min= 15.4 for (4*S*,5*S*)-**2a**, 12.5 for (4*R*,5*R*)-**2a**, 7.1 for (4*R*,5*S*)-**2a**, and 8.8 for (4*S*,5*R*)-**2a**].[8] A nitrogen-saturated 1,2-dichloroethane solution of (*Z*)-**1a** (4.0×10^{-3} mol dm^{-3}, 10 mL) and *S*-MPM (0.10 mol dm^{-3}) was irradiated in parallel using a merry-go-round-type irradiation equipment (light source: 400 W high-pressure Hg lamp) for 6 h at room temperature and the resulting solution was subjected to HPLC analysis after the chiral amine was removed by treatment with hydrochloric acid. Based on the area ratios of HPLC signals for the *cis*-**2a**- and *trans*-**2a**-derived enantiomers, the ee values for (4*R*,5*R*)-**2a** and (4*R*,5*S*)-**2a** were estimated to be 19% and 33%, respectively, suggesting that the chiral amine is in the neighborhood of the previously assumed intermediates and interacts directly with these intermediates during the reaction, as predicted. The enantiomeric composition analysis of *cis*-**2b–d** and *trans*-**2b–d** was made in the same manner as mentioned above.



Scheme 1

While the irradiation of an 1,2-dichloroethane solution of (*Z*)-**1a** containing a given chiral amine afforded the corresponding dihydrooxazole derivative **2a** quantitatively, trace amounts of this derivative were only detected on irradiating a methanol solution of the starting **1a** under the same conditions. As already revealed in the previous study,[8] the photoreactivity of *N*-benzoyl-α-dehydro(1-naphthyl)alanine alkyl esters is much higher in 1,2-dichloroethane than in methanol. It is, thus, very likely that the chiral amines examined have lower electron donating abilities and subject to stronger hydrogen-bonding solvation in methanol, as compared to TEA. In Table 1 are summarized chiral amine and substituent effects on the ee value of each enantiomer for *cis*-**2a** and *trans*-**2a** formed in 1,2-dichloroethane. Examination of the amine effect on this ee confirms that the ability to induce the asymmetric cyclization is lowered in the order of *S*-MPM ≥ *S*-PM > *S*-PG. Because this order mainly reflects the difference in hydrogen bonding ability among these chiral amines, *S*-MPM was chosen as a chiral amine for investigating substituent and temperature effects on the ee. Additionally, *R*-PM used instead of *S*-PM gave *cis*-**2a** and *trans*-**2a** having inverse configurations, namely (4*R*,5*R*)-**2a** and (4*R*,5*S*)-**2a** in almost the same ee, thus substantiating negligible epimerization at the 4-position on the dihydrooxazole ring. The replacement of an 1-naphthyl group by a phenyl or a 2-naphthyl enhanced the ee value for (4*R*,5*R*)-**2** with a decrease in this value for the *trans*-isomer, whereas the introduction of a less bulky methyl group

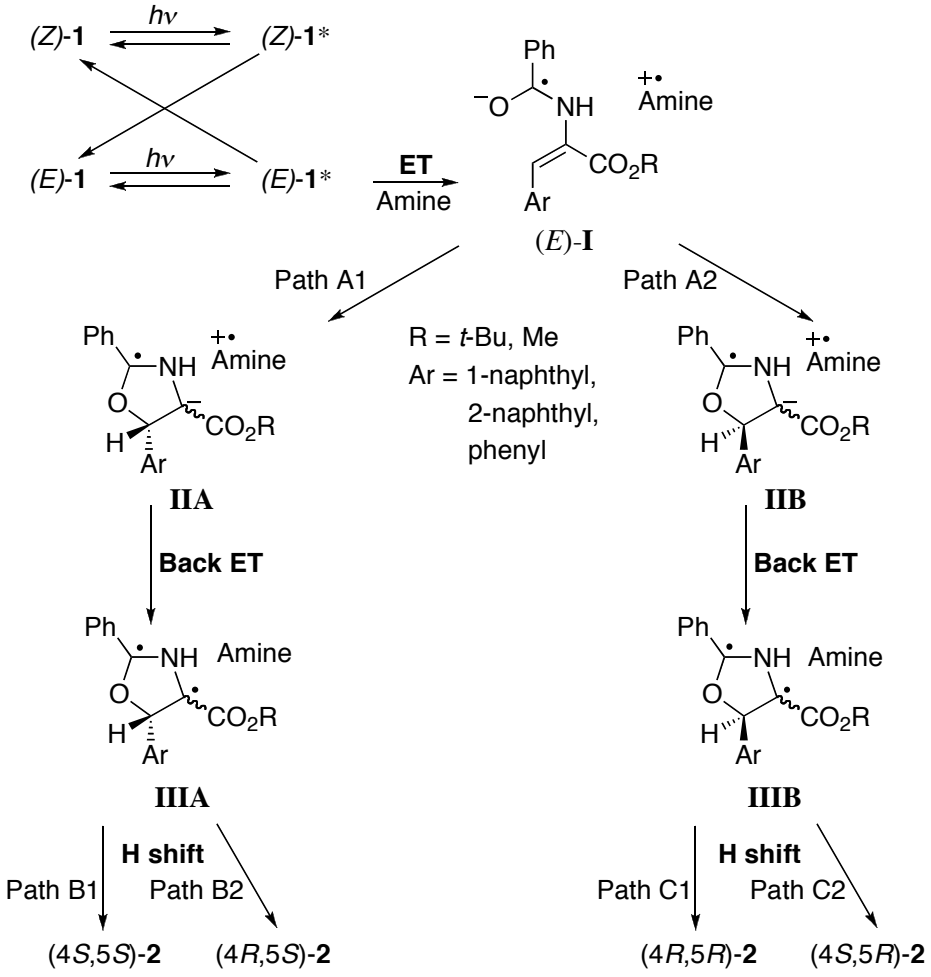
Table 1. Substituent and chiral amine effects on the selectivity and ee value for each enantiomer of *cis*-**2** and *trans*-**2**, obtained by the 6 h irradiation of (*Z*)-**1** (4.0×10^{-3} mol dm^{-3}) in 1,2-dichloroethane containing chiral amine (0.10 mol dm^{-3}) at room temperature

(*Z*)-**1**	Chiral Amine	Conversion (%)[a]	Selectivity[b] and ee (%)					
			cis-**2**			*trans*-**2**		
			(4*R*,5*R*)-**2**	(4*S*,5*S*)-**2**	ee	(4*R*,5*S*)-**2**	(4*S*,5*R*)-**2**	ee
1a	*S*-PG	95	18.6	23.4	11	27.3	30.7	6
1a	*S*-PM	97	13.0	23.6	29	26.3	37.1	17
1a	*R*-PM	97	23.8	12.8	30	37.1	26.3	17
1a	*S*-MPM	100	36.6	24.8	19	25.7	12.9	33
1b	*S*-MPM	100	33.4	23.6	17	27.0	16.0	26
1c	*S*-MPM	100	26.6	12.5	36	36.5	24.4	20
1d	*S*-MPM	100	24.2	10.8	38	39.0	26.0	20

[a] Conversion was estimated by dividing the sum of composition for *cis*-**2** and *trans*-**2** by the sum of composition for (*Z*)-**1**, (*E*)-**1**, *cis*-**2**, and *trans*-**2**.
[b] Selectivity for each enantiomer of *cis*-**2** and *trans*-**2** was evaluated by dividing the composition for each enantiomer by the sum of composition for *cis*-**2** and *trans*-**2**.

into the *tert*-butoxycarbonyl moiety of (*Z*)-**1a** exerted a minor steric effect on the ee for both the *cis*- and *trans*-dihydrooxazole isomers. We previously showed that asymmetric induction in the cyclization process eventually affording the dihydrooxazole derivative was achieved at the steps of the cyclization of the radical ion pair (*E*)-**I** into the **II** as well as of the hydrogen shift in the biradical **III**, as depicted in Scheme 2.[9,11] In the former step the steric bulkiness of a given chiral auxiliary group exerts a great effect on the magnitude of de whereas hydrogen-bonding interaction between the intermediate **III** and amine is a major factor governing this magnitude in the latter step. Thus, the above-mentioned minor effect of the alkoxycarbonyl substituent suggests that the chiral amine-derived radical cation exists in the vicinity of the (*E*)-**1**-derived radical anion to constitute the radical ion pair intermediate **II** but is not involved in the **II**-forming cyclization process. In addition, aryl substituent effects on the ee substantiate the asymmetric photocyclization mechanism in which steric bulkiness of the aryl group attached at the 5-position on the oxazole ring affects hydrogen shift in the *re* and *si* faces of the biradical intermediate **III** to a different extent. It is likely that this intermediate (hydrogen bonded to a given chiral amine) adopts a different conformation depending on steric and electronic interactions among the unpaired electrons, heteroatoms, and alkoxycarbonyl and aryl substituents in **III**.

If we consider hydrogen-bonding interaction between the biradical **III** and the chiral amine as one of the factors controlling the magnitude of ee for the cyclized product **2**, it is expected that ee for (4*R*,5*R*)-**2a** and (4*R*,5*S*)-**2a** estimated in 1,2-dichloroethane containing *S*-MPM is increased as temperature is lowered and also increased with an increase in the *S*-MPM concentration. Contrary to our expectation,



Scheme 2

ee for the latter enantiomer exhibited a very small temperature dependence and ee for the former had a tendency to decrease with a drop in temperature ([(*Z*)-**1a**]= 4.0×10^{-3} mol dm^{-3}, [*S*-MPM]= 0.10 mol dm^{-3}): ee for (4*R*,5*R*)-**2a** (temperature)= 21% (50 °C), 19% (room temperature), 10% (–78 °C; solvent, CH_2Cl_2) and ee for (4*R*,5*S*)-**2a**= 30% (50 °C), 33% (room temperature), and 28% (–78 °C). On the basis of temperature effects on the de value previously estimated in 1,2-dichloroethane,[9] we propose a temperature-dependent conformation of the hydrogen-bonded biradical intermediate **III**, which affects hydrogen shifts in the *re* and *si* faces to a similar extent. On the other hand, an increase in the concentration of *S*-MPM enhanced not only the conversion of **1a** but also the magnitude of ee for both the enantiomers (Table 2). These findings are consistent with our expectation and, hence, provide evidence in support of the involvement of the hydrogen-bonding interaction as one of the controlling factors of ee, as well as of the PET mechanism.

Because configurational interconversion between **IIA** and **IIB** or between **IIIA** and **IIIB** is very unlikely to occur during the irradiation, it is possible to estimate the compositions of **IIIA** and **IIIB** (or **IIA** and **IIB**), as well as the rate ratios of paths A, B and C, based on the composition of each enantiomer for *cis*-**2** and *trans*-**2** collected in Table 1 (Table 3). As already predicted, rate ratios for the **IIA**- and **IIB**-forming cyclization processes, paths A1 and A2, were unity irrespective of the starting α-dehydroaryl-

Table 2. Concentration effects of *S*-MPM on the conversion of **1a** and the ee value for each enantiomer of *cis*-**2a** and *trans*-**2a**, obtained by the 6 h irradiation of (*Z*)-**1a** (4.0×10^{-3} mol dm^{-3}) in 1,2-dichloroethane containing this chiral amine at room temperature

[*S*-MPM] (mol dm^{-3})	Conversion (%)	Composition and ee (%)							
		(*Z*)-**1a**	(*E*)-**1a**	*cis*-**2a**			*trans*-**2a**		
				(4*R*,5*R*)-**2a**	(4*S*,5*S*)-**2a**	ee	(4*R*,5*S*)-**2a**	(4*S*,5*R*)-**2a**	ee
0.010	43	24.7	32.0	8.1	6.8	9	15.9	12.5	12
0.050	58	18.1	24.4	13.7	10.1	15	21.2	12.5	26
0.10	100	0	0	36.6	24.8	19	25.7	12.9	33

Table 3. Substituent, chiral amine and temperature effects on the composition of **III** and the rate ratio (*R*r) of given two competitive paths, obtained by the irradiation of (*Z*)-**1** in the presence of the amine

(*Z*)-**1**	Chiral Amine	Temperature (°C)[a]	Composition of **III** (%) and *R*r				
			IIIA	**IIIB**	*R*r (A1/A2)	*R*r (B1/B2)	*R*r (C1/C2)
1a	*S*-MPM	rt	50.5	49.5	1.0	1.0	2.8
1b	*S*-MPM	rt	50.6	49.4	1.0	0.9	2.1
1c	*S*-MPM	rt	49.0	51.0	1.0	0.3	1.1
1d	*S*-MPM	rt	49.8	50.2	1.0	0.3	0.9
1a	*S*-MPM	50	49.3	50.7	1.0	1.0	2.8
1a	*S*-MPM	–78	50.7	49.3	1.0	1.6	3.5
1a	*S*-PG	rt	50.7	49.3	1.0	0.9	0.6
1a	*S*-PM	rt	49.9	50.1	1.0	0.9	0.4

[a] The symbol rt stands for room temperature.

alanine alkyl esters and reaction temperatures, thus allowing us to conclude that asymmetry at the 4-position on the dihydrooxazole ring is induced at the stage of hydrogen shift within the hydrogen-bonded biradical intermediates **IIIA** and **IIIB**. The presence of the chiral amine-derived radical cation is not considered to be a major factor controlling asymmetry at the 5-position on the ring. In addition, inspection of substituent effects on the *R*r (B1/B2) and *R*r (C1/C2) values forced us to assume that both the alkoxycarbonyl groups in **IIIA** and **IIIB** exist preferentially in the *re* face and exert steric effects on the hydrogen shift in this face resulting in an excess of (4*R*,5*R*)-**2** and (4*R*,5*S*)-**2**. As already suggested, steric and electronic interactions among the unpaired electrons, heteroatoms, and alkoxycarbonyl and aryl substituents in these two biradical intermediates may determine their most stable conformations. Interestingly, when the primary and secondary chiral amines *S*-PG and *S*-PM were used instead of the

tertiary amine *S*-MPM, the *cis*- and *trans*-enantiomers formed in excess changed from (4*R*,5*R*)-**2a** and (4*R*,5*S*)-**2a** to (4*S*,5*S*)-**2a** and (4*S*,5*R*)-**2a**, respectively (Table 1). The result of *R*r (A1/A2)= 1.0 for both *S*-PG and *S*-PM strongly suggests an alteration in the mode of hydrogen-bonding interaction between **III** and these chiral amines (Table 3). It is likely that while *S*-MPM assists hydrogen shift in the *si*-face, *S*-PG and *S*-PM block a part of this face (through a hydrogen bond between the amine N–H hydrogen and the N–H nitrogen in **III**) to promote hydrogen shift in the *re*-face (Figure 1).

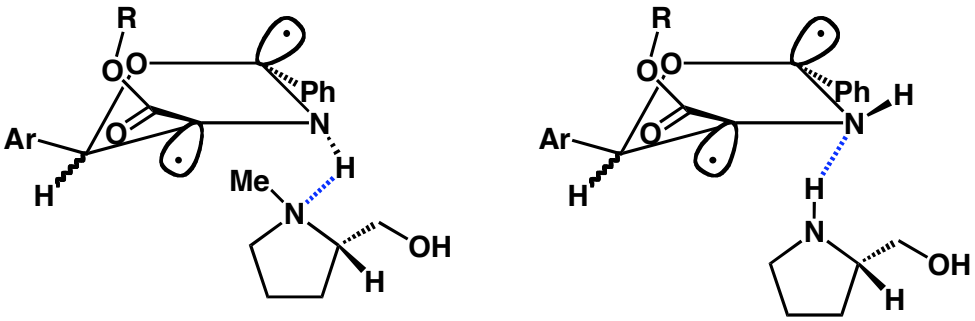


Figure 1. Schematic illustration for the hydrogen-binding interaction of the biradical intermediate **III** with *S*-MPM and *S*-PM.

The enantioselective photocyclization of **1** was achieved in 1,2-dichloroethane containing a chiral aliphatic amine such as *S*-MPM or *S*-PM. Careful analysis of chiral amine (structure and concentration), substituent, and temperature effects on the ee value for *cis*- and *trans*-3,4-dihydrooxazole derivatives led us to conclude that the mode of hydrogen-bonding interaction between the biradical intermediate **III** and the amine determines the configuration of the *cis*- and *trans*-enantiomers formed in excess.

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REFERENCES AND NOTES

1. ‘Synthetic Organic Photochemistry,’ ed. by W. M. Horspool, Plenum Press, New York, 1984; ‘Handbook of Photochemistry and Photobiology,’ Vol. 2, ed. by H. S. Nalwa, American Scientific Publishers, Stevenson Ranch, 2003; ‘Synthetic Organic Photochemistry,’ ed. by A. G. Griesbeck and J. Mattay, Marcel Dekker, New York, 2005.
2. S. Kohmoto, Y. Miyaji, M. Tsuruoka, K. Kishikawa, M. Yamamoto, and K. Yamada, *J. Chem. Soc., Perkin Trans. 1*, 2001, 2082; P. Formentin, M. J. Sabater, M. N. Chretien, H. Garcia, and J. C. Scaiano, *J. Chem. Soc., Perkin Trans. 2*, 2002, 164; S. C. Shim, D. S. Kim, D. J. Yoo, T. Wada, and Y. Inoue, *J. Org. Chem.*, 2002, **67**, 5718; A. Bauer, F. Westkämper, S. Grimme, and T. Bach, *Nature*, 2005, **436**, 1139.

3. A. Joy, J. R. Scheffer, and V. Ramamurthy, *Org. Lett.*, 2000, **2**, 119; J. R. Scheffer, *Can. J. Chem.*, 2001, **79**, 349; L. S. Kaanumalle, J. Sivaguru, N. Arunkumar, S. Karthikeyan, and V. Ramamurthy, *Chem. Commun.*, 2003, 116.
4. A. G. Griesbeck, W. Kramer, and J. Lex, *Angew. Chem. Int. Ed.*, 2001, **40**, 577; S. Jones and J. C. C. Atherton, *Tetrahedron: Asymmetry*, 2001, **12**, 1117; T. Bach, H. Bergmann, B. Grosch, and K. Harms, *J. Am. Chem. Soc.*, 2002, **124**, 7982; K. C. W. Chong, J. Sivaguru, T. Shichi, Y. Yoshimi, V. Ramamurthy, and J. R. Scheffer, *J. Am. Chem. Soc.*, 2002, **124**, 2858.
5. 'Chiral Photochemistry,' ed. by Y. Inoue and V. Ramamurthy, Marcel Dekker, New York, 2004.
6. F. D. Lewis, G. D. Reddy, D. M. Bassani, S. Schneider, and M. Gahr, *J. Am. Chem. Soc.*, 1994, **116**, 597; F. D. Lewis, D. M. Bassani, E. L. Burch, B. E. Cohen, J. A. Engleman, G. D. Reddy, S. Schneider, W. Jaeger, P. Gedeck, and M. Gahr, *J. Am. Chem. Soc.*, 1995, **117**, 660; K. Maekawa, T. Igarashi, K. Kubo, and T. Sakurai, *Tetrahedron*, 2001, **57**, 5515; K. Maekawa, A. Shinozuka, M. Naito, T. Igarashi, and T. Sakurai, *Tetrahedron*, 2004, **60**, 10293; A. G. Griesbeck, N. Hoffmann, and K. Warzecha, *Acc. Chem. Res.*, 2007, **40**, 128.
7. K. Maekawa, K. Kubo, T. Igarashi, and T. Sakurai, *Tetrahedron*, 2004, **60**, 1183; K. Maekawa, K. Kubo, T. Igarashi, and T. Sakurai, *Tetrahedron*, 2005, **61**, 11211.
8. K. Maekawa, T. Sasaki, K. Kubo, T. Igarashi, and T. Sakurai, *Tetrahedron Lett.*, 2004, **45**, 3663.
9. Y. Sasaki, K. Maekawa, H. Watanabe, T. Matsumoto, K. Kubo, T. Igarashi, and T. Sakurai, *Tetrahedron Lett.*, 2007, **48**, 4765.
10. Selected data for (*Z*)-**1a**: mp 120.0–121.0 °C (EtOAc-hexane); IR (KBr) ν/cm^{-1}= 3289, 1709, 1638; ^{1}H NMR (500 MHz, DMSO-d_6) δ= 1.50 (9H, s), 7.45 (2H, dd, *J* = 7.6, 8.2 Hz), 7.50 (1H, dd, *J* = 6.9, q, 8.2 Hz), 7.54 (1H, dd, *J*= 7.6, 7.6 Hz), 7.58 (1H, dd, *J* = 6.9, 8.2 Hz), 7.59 (1H, dd, *J* = 6.9, 7.6 Hz), 7.68 (1H, d, *J* = 6.9 Hz), 7.81 (2H, d, *J* = 8.2 Hz), 7.82 (1H, s), 7.92 (1H, d, *J* = 8.2 Hz), 7.96 (1H, d, *J* = 7.6 Hz), 8.01 (1H, d, *J* = 8.2 Hz), 9.88 (1H, s); ^{13}C NMR (125 MHz, DMSO-d_6) δ= 27.6 (3C), 80.7, 124.0, 125.4, 126.0, 126.5 (2C), 127.5 (2C), 128.2 (2C), 128.4, 128.6, 128.9, 130.4, 130.7, 130.9, 131.5, 133.1, 133.6, 163.7, 166.5. Anal. Calcd for $C_{24}H_{23}NO_3$: C, 77.19; H, 6.21; N, 3.75. Found: C, 77.35; H, 6.29; N, 3.74.

    Selected data for *cis*-**2a**: mp 144.0–145.0 °C (hexane-EtOAc); IR (KBr) ν/cm^{-1} = 1737, 1649; ^{1}H NMR (500 MHz, DMSO-d_6) δ= 0.50 (9H, s), 5.48 (1H, d, *J* = 10.3 Hz), 6.81 (1H, d, *J* = 10.3 Hz), 7.51 (1H, d, *J* = 8.2 Hz), 7.54 (1H, dd, *J* = 7.6, 8.2 Hz), 7.58 (1H, dd, *J* = 7.6, 7.6 Hz), 7.58 (2H, dd, *J* = 6.9, 7.6 Hz), 7.62 (1H, dd, *J* = 7.6, 8.2 Hz), 7.66 (1H, dd, *J* = 7.6, 7.6 Hz), 7.93 (1H, d, *J* = 7.6 Hz), 7.98 (1H, d, *J* = 7.6 Hz), 8.07 (2H, d, *J* = 6.9 Hz), 8.11 (1H, d, *J* = 8.2 Hz); ^{13}C NMR (125 MHz, DMSO-d_6) δ = 26.4 (3C), 72.5, 80.0, 80.2, 123.1, 124.0, 125.2, 125.9, 126.1, 126.8, 128.1 (2C), 128.31, 128.33, 128.8 (2C), 130.2, 132.1, 132.3, 133.0, 164.8, 167.6. Anal. Calcd for $C_{24}H_{23}NO_3$: C, 77.19; H, 6.21; N, 3.75. Found: C, 77.30; H, 6.03; N, 3.65.

    Selected data for *trans*-**2a**: Oily liquid; IR (NaCl) ν/cm^{-1} = 1728, 1647; ^{1}H NMR (500 MHz, DMSO-d_6) δ = 1.51 (9H, s), 4.65 (1H, d, *J* = 6.2 Hz), 6.61 (1H, d, *J* = 6.2 Hz), 7.50 (1H, d, *J* = 6.9 Hz), 7.54 (1H, dd, *J* = 6.9, 6.9 Hz), 7.58 (2H, dd, *J* = 7.6, 7.6 Hz), 7.60–7.63 (2H, m), 7.67 (1H, dd, *J* = 7.6, 7.6 Hz), 7.97 (1H, d, *J* = 6.9 Hz), 7.97 (1H, d, *J* = 6.9 Hz), 8.03–8.06 (1H, m), 8.06 (2H, d,

J = 7.6 Hz); ^{13}C NMR (125 MHz, DMSO-d_6) δ = 27.6 (3C), 76.4, 80.8, 82.1, 122.7, 122.8, 125.5, 126.2, 126.4, 126.6, 128.3 (2C), 128.92, 128.94 (2C), 129.0, 129.1, 132.4, 133.5, 134.7, 164.4, 169.6. Anal. Calcd for $C_{24}H_{23}NO_3$: C, 77.19; H, 6.21; N, 3.75. Found: C, 76.94; H, 5.96; N, 3.57.

Selected data for (*E*)-**1a**: mp 163.0–164.0 °C (EtOAc-hexane); IR (KBr) ν/cm^{-1} = 3198, 1724, 1628; ^{1}H NMR (500 MHz, DMSO-d_6) δ = 1.02 (9H, s), 7.24 (1H, s), 7.35 (1H, d, J = 6.9 Hz), 7.50 (1H, dd, J = 6.9, 8.2 Hz), 7.54–7.57 (2H, m), 7.56 (2H, dd, J= 7.6, 7.6 Hz), 7.63 (1H, dd, J = 7.6, 7.6 Hz), 7.90 (1H, d, J = 8.2 Hz), 7.90–8.10 (2H, m), 7.98 (2H, d, J = 7.6 Hz), 10.51 (1H, s); ^{13}C NMR (125 MHz, DMSO-d_6) δ = 27.0 (3C), 80.4, 120.1, 124.8, 125.2, 125.99, 126.01, 126.2, 127.69, 127.72 (2C), 128.2, 128.5 (2C), 131.2, 132.0, 132.5, 132.85, 132.94, 133.2, 163.0, 165.0. Anal. Calcd for $C_{24}H_{23}NO_3$: C, 77.19; H, 6.21; N, 3.75. Found: C, 77.09; H, 6.32; N, 3.73.

11. The intermediate (*Z*)-**I** should also be formed by an electron transfer (ET) from a given chiral amine to (*Z*)-**1*** but the cyclization of the (*Z*)-isomer is unable to proceed from this configuration to afford the corresponding intermediate **II**. Thus, (*Z*)-**I** is very likely to undergo exclusive back ET to regenerate (*Z*)-**1** and the amine.