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PAPER

Chiral ionic liquid-mediated photochirogenesis. Enantiodifferentiating photocyclodimerization of 2-anthracenecarboxylic acid†

Gaku Fukuhara,*[a] Takahiro Okazaki,[a] Marco Lessi,[b] Masaki Nishijima,[c] Cheng Yang,[a] Tadashi Mori,[a] Andrea Mele,[d,e] Fabio Bellina,[b] Cinzia Chiappe*[b] and Yoshihisa Inoue*[a]

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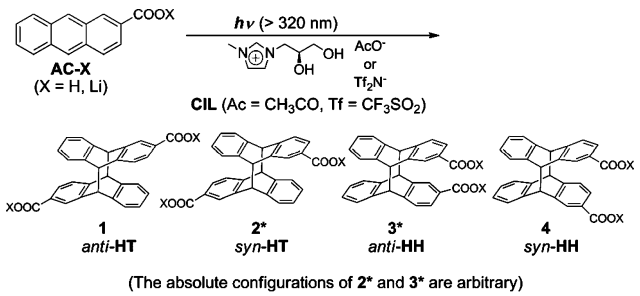
Enantiodifferentiating photocyclodimerization of 2-anthracenecarboxylic acid (AC-H) and its lithium salt (AC-Li) in chiral ionic liquid (CIL), (*R*)-1-(2,3-dihydroxypropyl)-3-methylimidazolium acetate {[(*R*)-GLYMI][AcO]}, gave a mixture of two *head-to-tail* (HT) and two *head-to-head* (HH) cyclodimers in HT/HH ratios of 1.3–1.7 (for AC-H) and 2.2–4.3 (for AC-Li) with low enantiomeric excesses (ee) of 0–3% for chiral *syn*-HT and *anti*-HH dimers. In contrast, irradiation of AC-H in an aqueous solution, containing cucurbit[8]uril (CB[8]) as a host and [(*R*)-GLYMI][AcO] or [(*R*)-GLYMI][Tf_2N] as a modifier of CB portals, afforded the HH dimers in 91–99% selectivity, although the *anti*-HH dimer was totally racemic. Interestingly, irradiation of AC-H in a dichloromethane solution, containing [(*R*)-GLYMI][AcO] as a chiral template, led to the formation of the HH-dimers in 98% selectivity with chiral *anti*-HH dimer in −14% ee, presumably by the dual ligation of two ACs to a CIL through electrostatic and hydrogen-bonding interactions.

Introduction

Photochemical asymmetric synthesis, or photochirogenesis,[1] provides us with unique, versatile routes to a variety of optically active compounds, which are alternatives to the conventional catalytic and enzymatic asymmetric synthesis,[2] but this still remains a challenge in current photochemistry. Of several approaches to photochirogenesis examined so far, the use of chiral solvent does not appear to be very attractive, necessitating a large excess amount of chiral source yet affording modest enantiomeric excesses (ee) in general.[3]

Ionic liquids (ILs), room-temperature molten salts of unique physical and chemical properties, have attracted much interest in recent years as environmentally benign media for various organic reactions.[4] Chiral ionic liquids (CILs) have also been prepared for conventional (thermochemical) asymmetric syntheses.[4,5] In contrast, photochemical reactions in ILs have been explored only recently,[6] and CILs have rarely been employed for photochirogenic reactions. In their pioneering work on photochirogenesis in CIL, Armstrong and co-workers performed the photochemical di-π-methane rearrangement of dibenzobarrelenedicarboxylic acid in CILs to give the corresponding tricyclic acid in 3–12% ee.[7] More recently, we performed the [4 + 4] photocyclodimerization of 2-anthracenecarboxylic acid and its alkali metal salts (AC-X; X = H, Li, K, Cs) in (*R*)-1-(2,3-dihydroxypropyl)-3-methylimidazolium bistriflimide {[(*R*)-GLYMI][Tf_2N]} (Scheme 1) to obtain *syn*-HT (**2***) in 41% ee for AC-H but in 4–10% ee for AC-M (M = Li, K, Cs) at −50 °C.[8] The contrasting results for AC-H *versus* AC-M led us to a conclusion that the hydrogen-bonding interaction of AC-H with the chiral diol moiety of CIL, rather than the ion-pairing interaction of AC anion with the imidazolium cation in CIL, is responsible for the higher ee obtained for AC-H.[8] This mechanistic



Scheme 1 Photocyclodimerization of 2-anthracenecarboxylic acid and its lithium salt (AC-X) in (*R*)-1-(2,3-dihydroxypropyl)-3-methylimidazolium acetate {[(*R*)-GLYMI][AcO]} and in the corresponding bistriflimide {[(*R*)-GLYMI][Tf_2N]}.

[a]*Department of Applied Chemistry, Osaka University, 2-1 Yamada-oka, Suita, 565-0871, Japan. E-mail: gaku@chem.eng.osaka-u.ac.jp, inoue@chem.eng.osaka-u.ac.jp; Fax: (+81) 6 6879 7923; Tel: (+81) 6 6879 7922*
[b]*Dipartimento di Chimica e Chimica Industriale, Università di Pisa, via Risorgimento 35, 56126 Pisa, Italy. E-mail: cinziac@farm.unipi.it; Fax: (+39) 050 2219669; Tel: (+39) 050 2219660*
[c]*Center for Advanced Science and Innovation, Osaka University, 2-1 Yamada-oka, Suita 565-0871, Japan*
[d]*Dipartmento di Chimica, Materiali e Ingegneria Chimica "G. Natta", Politecnico di Milano, via Mancinelli 7, 20131 Milano, Italy*
[e]*CNR-Istituto di Chimica del Riconoscimento Molecolare, via L. Mancinelli 7, 20131 Milano, Italy*

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insight prompted us to examine the effects of different CIL media by changing the counteranion from bistriflimide to acetate.[9]

In the present study to examine the effects of CIL's counteranion and polarity on the stereochemical outcomes of AC photocyclodimerization, we newly synthesized (*R*)-1-(2,3-dihydroxypropyl)-3-methylimidazolium acetate {[(*R*)-GLYMI][AcO]}. This new CIL was used not only as a chiral solvent but also as a chiral ligand to modify the portals of cucurbit[8]uril (employed as a host for AC) and as a dual-functional chiral template to attract two ACs through electrostatic and hydrogen-bonding interactions.

Results and discussion

Chiral ionic liquid as solvent

The ground-state interaction of AC-X (X = H, Li) with CIL was examined by measuring the UV/vis and circular dichroism (CD) spectra of AC-X in [(*R*)-GLYMI][AcO] at 25, 0 and −50 °C. As can be seen from the UV/vis spectra shown in Fig. 1, the ^1B_b band, and the ^1L_a and ^1L_b bands (insets) as well, of both AC-Li and AC-H became sharper and stronger at lower temperatures. The CD spectral behaviour differed appreciably between AC-Li and AC-H. For AC-Li in [(*R*)-GLYMI][AcO], only noisy broad CD signals were observed, irrespective of the ^1B_b or $^1L_{a,b}$ band. In contrast, AC-H dissolved in [(*R*)-GLYMI][AcO] exhibited appreciable induced CD (ICD) signals at the ^1B_b band centred at 260 nm in particular at lower temperatures. This indicates interaction of AC-H with [(*R*)-GLYMI][AcO] in the ground state, as was the case with [(*R*)-GLYMI][Tf_2N].[8] However, the ICD peak was opposite in sign between AcO^- and Tf_2N^- salts, suggesting a different binding mode or conformation upon interaction of AC with CIL.

Photoirradiation at >320 nm of AC-X in [(*R*)-GLYMI][AcO] was performed at temperatures ranging from +25 °C to −50 °C (in this wavelength region, the CIL used is totally transparent and not photodecomposed). The irradiated solution was diluted with the HPLC eluent (a 64 : 36 mixture of water and acetonitrile) and injected into a chiral HPLC column to give the relative yields of **1**–**4** and the ee's of chiral **2** and **3**, as listed in Table 1. The photolysis of AC-Li in [(*R*)-GLYMI][AcO] led to the dominant formation of HT dimers particularly at −50 °C, where the HT/HH ratio amounted to 4.3, while chiral dimers **2*** and **3*** were totally racemic, as might be anticipated from the lack of ICD signals mentioned above. This result is contrasting however to the photochirogenic behaviour of AC-Li in [(*R*)-GLYMI][Tf_2N],[8] where much smaller HT/HH ratios of 0.9–1.5 and better ee's of 5–10% were obtained as a result of the CIL-AC interaction facilitated by the ion-pairing of Tf_2N^- with Li^+.[10]

In contrast, AC-H behaved very differently from AC-Li upon photocyclodimerization in CIL (Table 1). In [(*R*)-GLYMI][Tf_2N], the HT/HH ratio was gradually reduced from 1.1 to 0.7 while the ee of **2*** was enhanced from 1% to 41% by lowering temperature

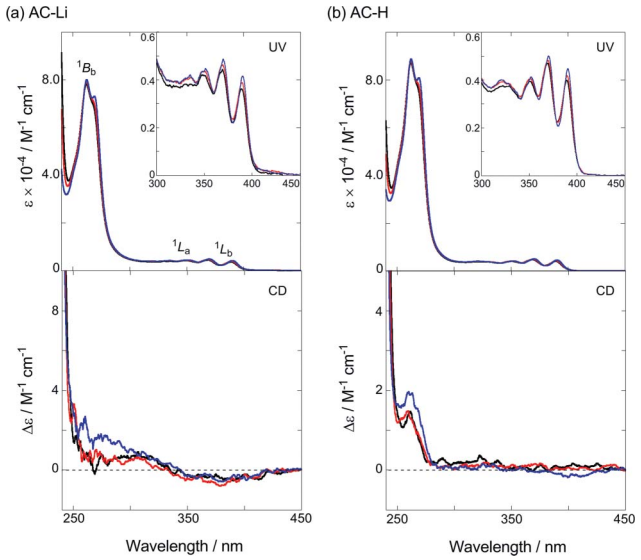

Fig. 1 UV/vis (top) and CD (bottom) spectra of [(*R*)-GLYMI][AcO] solutions of (a) 0.81 mM AC-Li and (b) 1.34 mM AC-H at 25 °C (black line), 0 °C (red line) and −50 °C (blue line), measured in a 0.1 mm cell.

Table 1 Enantiodifferentiating photocyclodimerization of 2-anthracenecarboxylic acid and its lithium salt (AC-X; X = H, Li) in (*R*)-1-(2,3-dihydroxypropyl)-3-methylimidazolium acetate {[(*R*)-GLYMI][AcO]} and in the corresponding bistriflimide {[(*R*)-GLYMI][Tf_2N]} at various temperatures[a]

Substrate	Counteranion	AC-X/mM	Temp./°C	Conv./%	Product distribution (ee)[b]/%				HT/HH[c]
					1	**2***	**3***	**4**	
AC-Li	AcO^-	0.81	25	51	41	31 (*0*)	17 (*0*)	11	2.6
			−20	15	36	33 (*0*)	20 (*0*)	11	2.2
			−50	3	44	37 (*0*)	12 (*0*)	7	4.3
	Tf_2N^-[d]	2.06[e]	25	57	25	23 (*7*)	27 (*−5*)	25	0.9
			−20	30	22	26 (*10*)	21 (*−10*)	31	0.9
			−50	33	32	28 (*10*)	15 (*−9*)	25	1.5
AC-H	AcO^-	1.34[f]	25	66	36	23 (*0*)	26 (*0*)	15	1.4
			−50	1	43	20 (*0*)	26 (*−3*)	11	1.7
		54.5[e,f]	−50	< 1	36	21 (*1*)	34 (*−3*)	9	1.3
	Tf_2N^-[d]	2.05[e]	25	78	29	24 (*1*)	26 (*−1*)	21	1.1
			−20	44	25	21 (*22*)	32 (*−8*)	22	0.9
			−50	48	21	19 (*41*)	34 (*−10*)	26	0.7

[a] Irradiated for 3 h under air in a quartz cell (1 mm thickness, unless noted otherwise) by using a 500 W ultrahigh-pressure Hg lamp fitted with a UV-35 glass filter. [b] Enantiomeric excess determined by chiral HPLC on an ODS + OJ-RH tandem column; the first-eluted enantiomer was given a positive sign; errors: ±1% for product distribution and ±2% for ee. [c] HT/HH = ([**1**] + [**2***])/([**3***] + [**4**]). [d] Data from ref. 8. [e] Saturated solution. [f] Cell thickness = 0.1 mm.

from +25 °C to −50 °C, as reported previously.[8] Interestingly, the solubility of AC-H was much larger in [(*R*)-GLYMI][AcO] than in [(*R*)-GLYMI][Tf_2N]; *i.e.*, 54.5 mM *versus* 2.05 mM, and the photocyclodimerization of AC in [(*R*)-GLYMI][AcO] gave more HT dimers (HT/HH = 1.3–1.7) and nearly racemic **2*** and **3*** (0–3% ee) even at −50 °C, irrespective of the AC concentration employed (1.34 and 54.5 mM).

The contrasting photochirogenic behaviour observed in [(*R*)-GLYMI][AcO] and [(*R*)-GLYMI][Tf_2N] suggests the operation of a different sort or degree of AC-CIL interactions in the two CIL media. To elucidate the predominant AC species existing in the CIL media, we measured the UV/vis and fluorescence spectra of AC-X in [(*R*)-GLYMI][AcO] and [(*R*)-GLYMI][Tf_2N]. As shown in Fig. 2a, both AC-H (light blue line) and AC-Li (blue line) gave essentially the same UV/vis spectra in [(*R*)-GLYMI][AcO], which is similar in 0–0 band energy with that of AC anion (dotted black line) measured in aqueous alkaline solution. In [(*R*)-GLYMI][Tf_2N] solution, AC-H (black line) and AC-Li (red line) absorbed at significantly longer wavelengths, indicating the existence of neutral AC-H rather than anionic AC. Thus, the above spectral change, as well as the increased solubility, are rationalized by assuming that [(*R*)-GLYMI][AcO] promotes the proton exchange of AC-H with excess AcO^- to give AC^-, facilitating the ion-paring of AC^- with chiral imidazolium cation, as evidenced by the CD spectra (Fig. 1b). This speculation sounds reasonable in view of the acidity order: AcOH < AC-H < Tf_2NH, pK_a of which are respectively 4.8, 4.2 and 2.8 in water.[11–13]

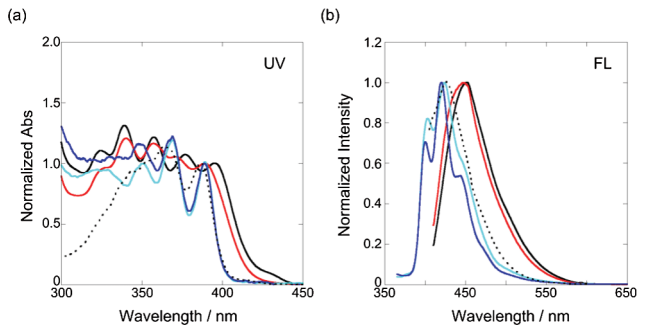

Fig. 2 (a) UV/vis and (b) fluorescence spectra of AC-H in [(*R*)-GLYMI][Tf_2N] (black line; 2.05 mM, λ_{ex} 394 nm) and in [(*R*)-GLYMI][AcO] (light blue line; 1.34 mM, λ_{ex} 350 nm), and of AC-Li in [(*R*)-GLYMI][Tf_2N] (red line; 2.06 mM, λ_{ex} 394 nm) and in [(*R*)-GLYMI][AcO] (blue line; 0.81 mM, λ_{ex} 350 nm). For comparison purposes, UV/vis and fluorescence spectra of AC anion (0.6 mM, λ_{ex} 394 nm, black dotted line) in aqueous 10 mM NaOH solution are overlaid. All the UV/vis and fluorescence spectra were normalized at the 0–0 band and at the peak top, respectively.

Fluorescence spectral behaviour also differed significantly in [(*R*)-GLYMI][AcO] and [(*R*)-GLYMI][Tf_2N]. As shown in Fig. 2b, AC-X (X = H, Li) exhibited structured fluorescence (λ_{max} 420–424 nm) in [(*R*)-GLYMI][AcO], which is comparable in energy (λ_{max} 426 nm) to AC anion in water but holds the vibrational fine structure due to the less polar nature of [(*R*)-GLYMI][AcO].[14] In contrast, the AC fluorescence became more defused and bathochromically shifted to 448–452 nm in polar [(*R*)-GLYMI][Tf_2N].

The above spectral examinations revealed that the use of [(*R*)-GLYMI][AcO] medium facilitates deprotonation of AC-H (due to the higher acidity of AC-H than AcOH) to give AC anion, which however does not interact electrostatically with chiral imidazolium cation at least in [(*R*)-GLYMI][AcO], as judged from the formation of racemic cyclodimers upon photoirradiation. In [(*R*)-GLYMI][Tf_2N] medium, AC-H is not deprotonated and hydrogen-bonds to the hydroxyl groups of CIL to give chiral **2*** and **3*** in good ee's at low temperatures. We may conclude therefore that the hydrogen-bonding, rather than electrostatic, interaction is advantageous in keeping the substrate in close contact with chiral CIL. In this context, simple ion-pairing of a chiral CIL cation with an anionic substrate is not enough, but the use of the hydrogen-bonding interaction[8] is more promising for critically controlling a photochirogenic reaction in CIL. Thus, hydrogen-bonding CIL with a less polar, less basic counteranion would be more advantageous.

Chiral imidazolium-cucurbituril complex as host

Cucurbit[*n*]urils (CB[*n*], *n* = 5–8), barrel-shaped synthetic macrocycles composed of 5–8 glycouril units, are known to strongly bind a variety of inorganic and organic cationic species,[15,16] including imidazolium ion,[17] in aqueous solutions mainly through ion-dipole and/or hydrophobic interactions. From the photochirogenic point of view, it is of particular interest to use a CIL, such as (*R*)-1-(2,3-dihydroxypropyl)-3-methylimidazolium {[(*R*)-GLYMI]}, as a chiral cationic ligand to convert achiral CB to a chiral supramolecular host for mediating the photocyclodimerization of AC, where the chiral hydrogen-bonding interaction of CIL ligand with included AC is expected to occur in the hydrophobic CB cavity. For this purpose, we chose CB[8] as host, AC-H as guest and [(*R*)-GLYMI][AcO] or the corresponding [Tf_2N] salt as chiral ligands (Fig. 3).

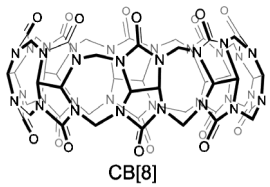

Fig. 3 Structure of cucurbit[8]uril (CB[8]).

Aqueous solutions containing AC, CB and/or CIL were prepared by mixing CB[8] (0.05 mM), CIL (0.1 mM) and AC-H (0.1 mM) in pure water, and the resulting mixtures were filtrated to give transparent solutions for UV/vis and CD spectral examinations and also for photoreactions.[18] As illustrated in Fig. 4 (top), the ability of CB[8] to solubilize AC, evaluated by the AC absorption at 260 nm, was significantly increased by the addition of CIL. Interestingly, only in the presence of [(*R*)-GLYMI][AcO] an appreciable CD signal was induced at the ^1B_b band of AC (Fig. 4, bottom), suggesting chiral interaction between AC and CIL, although the extremely low solubility of AC in the presence of [(*R*)-GLYMI][Tf_2N] hampered the detailed analysis of the CD spectral change.

The same aqueous solutions used in the spectral examinations were irradiated at 25 °C to give the results listed in Table 2. In a control experiment, an aqueous solution containing AC and CB[8], prepared by mixing both components in water and then filtering the resulting mixture, was irradiated without adding

Table 2 Photocyclodimerization of 2-anthracenecarboxylic acid (AC-H) in the presence and absence of CB[8] and CIL in water at 25 °C[a]

CIL	Irrad./min	Conv./%	Product distribution (*ee*)[b]/%				HT : HH[c]
			1	**2***	**3***	**4**	
None[d]	60	[e]	40	37 (*0*)	14 (*0*)	9	77 : 23
[(*R*)-GLYMI][AcO]	60	50	5	4 (*0*)	69 (*0*)	22	9 : 91
[(*R*)-GLYMI][Tf_2N]	60	[e]	0.6	0.4 ([e])	67 (*0*)	32	1 : 99

[a] Solutions prepared by mixing AC-H (0.1 mM), CB[8] (0.05 mM) and CIL (0.1 mM) with sonication in water and the subsequent filtration were irradiated under N_2 in a 10 mm cell, by using a 500 W ultrahigh-pressure Hg lamp fitted with a UV-35 glass filter, unless noted otherwise. [b] Determined by chiral HPLC on an ODS + OJ-RH tandem column; the first-eluted enantiomer was given a positive sign; errors: ±1% for product distribution and ±2% for ee. [c] HT : HH = ([**1**] + [**2***]):([**3***] + [**4**]). [d] Irradiated under Ar in a Pyrex tube, by using a 300 W high-pressure Hg lamp fitted with a uranium glass filter. [e] Not determined.

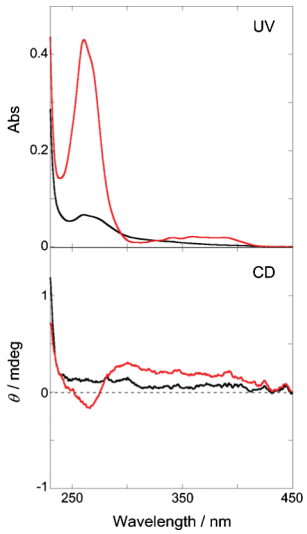

Fig. 4 UV/vis (top) and CD (bottom) spectra of aqueous solutions prepared by mixing 0.10 mM AC-H, 0.05 mM CB[8] and 0.10 mM [(*R*)-GLYMI][Tf_2N] (black line) or [(*R*)-GLYMI][AcO] (red line) in water at 25 °C and the subsequent filtration; measured in a 10 mm cell.

CIL to give predominantly the HT cyclodimers. The observed HT : HH ratio of 77 : 23 is very close to that (78 : 22) reported for the photocyclodimerization of AC anion in an aqueous buffer at pH 7,[19] indicating that AC anion dissolved slightly in water photocyclodimerized without forming an inclusion complex with CB[8].

Interestingly, the addition of CIL dramatically switched the HT/HH preference from HT to HH. Thus, the original HT : HH ratio of 77 : 23 obtained in the control experiment (without CIL) was altered to 9 : 91 for [(*R*)-GLYMI][AcO] or even to 1 : 99 for [(*R*)-GLYMI][Tf_2N]. The predominant formation of HH dimers may be rationalized by assuming that two AC-H molecules are aligned in an HH manner in a CB[8] cavity, which is facilitated by a dual hydrogen-bonding interaction of two AC-Hs to a dihydroxypropylimidazolium ligated to the CB portal. The formation of small, but appreciably larger, amounts of HT dimers in the presence of [(*R*)-GLYMI][AcO] rather than [(*R*)-GLYMI][Tf_2N] may be ascribed to the photocyclodimerization in the bulk water of AC^- derived from the proton exchange of AC-H with AcO^-, a process not available for less basic Tf_2N^-. However, the major HH product **3*** obtained was totally racemic, irrespective of the counteranion of CIL, suggesting that the hydrogen-bonding interaction inside the cavity is not strong or close enough to discriminate the enantiotopic faces of AC residing in the achiral CB cavity.

Chiral imidazolium as bidentate template

In contrast to the van der Waals and hydrophobic interactions operative upon supramolecular complexation in aqueous media, the electrostatic and hydrogen-bonding interactions become the major driving forces facilitating supramolecular complexation in hydrophobic media. In the supramolecular photochirogenic studies based on the template strategy, chiral hydrogen-bonding hosts were often employed to attract and organize prochiral organic substrates,[20] but the concurrent use of electrostatic interaction seems rare. In this context, our CIL may potentially function as a ditopic chiral template, possessing an imidazolium ion for electrostatic interaction and a chiral 1,2-diol moiety for hydrogen-bonding interaction. This new approach to organize two guest molecules near a single chiral template through different non-covalent interactions is intriguing and advantageous in particular for enantiodifferentiating photodimerization of AC. However, the simultaneous operation of electrostatic and hydrogen-bonding interactions of CIL with AC species should occur only under a rather limited condition that allows coexistence of neutral AC-H and AC anion. For such a purpose, [(*R*)-GLYMI][AcO], rather than [(*R*)-GLYMI][Tf_2N], is better suited as a chiral bidentate template, since AcO^- can partially deprotonate AC-H to give AC^-, whereas less basic Tf_2N^- cannot generate AC^- and no electrostatic interaction is expected to occur upon CIL-AC complexation.

We first examined the complexation behaviour of AC-H with [(*R*)-GLYMI][AcO] in dichloromethane at 25 °C, using UV/vis and CD spectroscopy. As shown in Fig. 5a (top) and 5b, gradual addition of CIL (0–0.8 mM) to a dichloromethane solution of AC-H (0.1 mM) caused obvious hypsochromic shifts at the ^1B_b and ^1L_b bands with accompanying isosbestic points, indicating deprotonation of AC-H to AC^-. Appreciable CD signals were induced at 240–350 nm upon addition of CIL (Fig. 5a, bottom), the intensity of which was however very weak and the concentration dependence was not straightforward. For a comparison purpose, we investigated the possible hydrogen-bonding interaction of AC-H with (*R*)-(−)-1,2-propanediol, a chiral side-chain analogue of CIL, under the same conditions to observe practically no UV/vis spectral change or no ICD signals (see Fig. S2 in the ESI). These results revealed that the UV/vis and CD spectral changes observed upon addition of [(*R*)-GLYMI][AcO] originate from

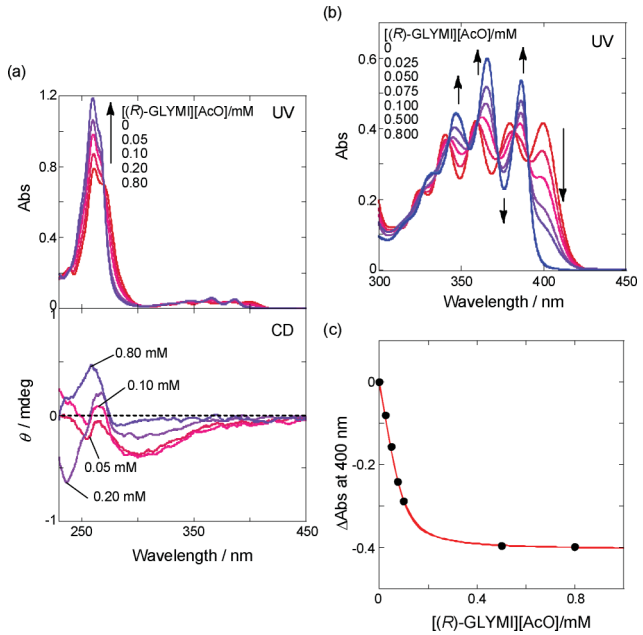

Fig. 5 (a) UV/vis (top) and CD (bottom) spectra of a dichloromethane solution of 0.10 mM AC-H in a 1 mm cell upon addition of various amounts of [(*R*)-GLYMI][AcO] (0, 0.05, 0.10, 0.20, 0.80 mM; from red to blue) at 25 °C. (b) UV/vis spectral changes of a dichloromethane solution of 0.10 mM AC-H in a 10 mm cell upon addition of various amounts of [(*R*)-GLYMI][AcO] (0, 0.025, 0.050, 0.075, 0.10, 0.50, 0.80 mM; from red to blue) at 25 °C. (c) UV/vis spectral titration data obtained from Fig. 5b and a non-linear least-squares fit assuming the 1 : 1 stoichiometry.

the deprotonation of AC-H and the weak ion-paring interaction of the resulting AC^- with CIL, but not from the hydrogen-bonding interaction. The UV/vis titration profile obtained by plotting the absorbance at 400 nm (Fig. 5b) allowed us to determine the equilibrium constant (K_a) of 80000 ± 11000 M^{-1} in dichloromethane at 25 °C, which is most probably assignable to the proton-exchange reaction (eqn (1)):

$$\text{AC-H} + \text{AcO}^- \overset{K_a}{\rightleftharpoons} \text{AC}^- + \text{AcOH} \qquad (1)$$

which would be facilitated by the ion-paring interaction of AC^- with CIL.

The AC-CIL interaction was also examined by ^{1}H NMR spectroscopy. As shown in Fig. 6, the addition of an equimolar amount of [(*R*)-GLYMI][AcO] to a CD_2Cl_2 solution of AC-H caused only slight changes in chemical shift of CIL protons at 25 °C (Fig. 6a,b). By reducing the solution temperature down to –25 °C, clearer upfield shifts of <0.1 ppm were induced for most of the CIL protons (Fig. 6c), suggesting weak electrostatic and/or hydrogen-bonding interactions of AC-H with CIL even at low temperatures.

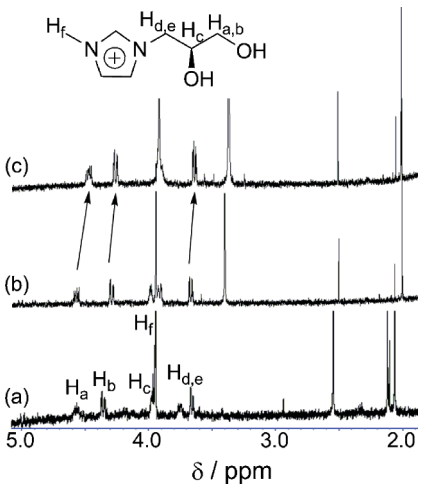

Fig. 6 ^{1}H NMR spectra of 0.1 mM [(*R*)-GLYMI][AcO] at 25 °C (trace a) and of 0.1 mM [(*R*)-GLYMI][AcO] in the presence of 0.1 mM AC-H at 25 °C (trace b) and –25 °C (trace c), measured in CD_2Cl_2.

Photoirradiation of AC-H was performed at >320 nm in the presence and absence of [(*R*)-GLYMI][Tf_2N] or [(*R*)-GLYMI][AcO] in dichloromethane at temperatures ranging from +25 to –90 °C to give cyclodimers **1**–**4** in varying ratios and ee's, as listed in Table 3. In the absence of CIL, the HT dimers were slightly favoured to give an HT : HH ratio of 54 : 46. Addition

Table 3 Photocyclodimerization of 2-anthracenecarboxylic acid (AC-H) in the presence and absence of [(*R*)-GLYMI][Tf_2N] or [(*R*)-GLYMI][AcO] in dichloromethane at various temperatures[a]

Counteranion	Temp./°C	[CIL]/[AC-H]	Conv./%	Product distribution (*ee*)[b]/%				HT : HH[c]
				1	**2***	**3***	**4**	
None	25	0	20	30	24 (*0*)	24 (*0*)	22	54 : 46
Tf_2N^-	25	1.0	18	33	23 (*0*)	24 (*0*)	20	56 : 44
		8.0	20	35	22 (*1*)	25 (*–1*)	18	57 : 43
AcO^-	25	0.5	45	14	9 (*0*)	32 (*–1*)	45	23 : 77
		1.0	60	12	7 (*0*)	33 (*–2*)	48	19 : 81
		8.0	53	14	10 (*1*)	30 (*2*)	46	24 : 76
	–50	0.5	34	2	1 (*e*)	54 (*–8*)	43	3 : 97
		1.0	37	2	1 (*e*)	52 (*–8*)	45	3 : 97
	–60	1.0	13	9	2 (*e*)	50 (*–7*)	39	11 : 89
	–70	1.0	12	4	1 (*e*)	59 (*–10*)	36	5 : 95
	–80	1.0	9	2	1 (*e*)	68 (*–12*)	29	3 : 97
	–90	1.0	11	1	1 (*e*)	79 (*–14*)	19	2 : 98
	–90[d]	1.0	2	8	4 (*0*)	33 (*1*)	55	12 : 88

[a] Irradiated under N_2 for 10 min in a 10 mm cell, by using a 500 W ultrahigh-pressure Hg lamp fitted with a UV-35 glass filter. [b] Determined by chiral HPLC on an ODS + OJ-RH tandem column; the first-eluted enantiomer was given a positive sign; errors: ±1% for product distribution and ±2% for ee. [c] HT : HH = ([**1**] + [**2***]):([**3***] + [**4**]). [d] In 1 : 99 (v/v) methanol–dichloromethane. [e] Not determined.

of [(*R*)-GLYMI][Tf_2N] (1–8 eq) to the AC-H solution did not affect the original product distribution or ee, affording practically the same HT : HH ratios (56 : 44 and 57 : 43) and racemic **2*** and **3***. This indicates the lack of specific interaction of AC-H with [(*R*)-GLYMI][Tf_2N], as demonstrated above in the spectral examinations.

Intriguingly, [(*R*)-GLYMI][AcO] added to the AC-H solution behaved very differently to accelerate the photodimerization and significantly alter the product distribution, although no appreciable chiral induction was observed for **2*** and **3*** at least at 25 °C (Table 3). Indeed, the conversion was enhanced by a factor of 2–3 and the HH dimers became the major products (76–81% of the total amount), irrespective of the CIL/AC-H ratio employed. The high HH preference observed upon addition of sub-stoichiometric 0.5 to excess 8 equivalent of CIL may be rationalized by the intervention of a 1 : 2 CIL–AC complex, in which two ACs are bound to one CIL in a HH manner presumably through the electrostatic interaction of AC^- with the imidazolium moiety and the hydrogen-bonding interaction of AC-H with the chiral diol moiety of CIL.

At –50 °C, the photocyclodimerization turned out to be more stereoselective to give the HH dimers in 97% combined yield (slightly favouring **3*** over **4**) and optically active **3*** in –8% ee, reinforcing the above assumption of an HH-oriented 1 : 2 CIL–AC complex. By lowering the temperature down to –90 °C, chiral dimer **3*** became the dominant product obtained in 79% yield, while the HH yield was kept high at 98%. More crucially, the ee of **3*** was further improved to –14% at –90 °C. The roles of hydrogen-bonding and electrostatic interactions in aligning two ACs in an *anti*-HH manner upon complexation with CIL was confirmed by adding methanol to the dichloromethane solution at the same temperature. As shown in Table 3, the addition of 1% methanol reduced not only the conversion (from 11% to 2%) and the HH yield (from 98% to 88%), in particular **3*** (from 79% to 33%), but also the ee of **3*** down to nearly zero, indicating total destruction of the hydrogen-bonding interaction of AC-H with the chiral dihydroxypropyl moiety of CIL. Although the contribution of the electrostatic interaction is not necessarily obvious from this experiment, the fact that [(*R*)-GLYMI][Tf_2N] cannot affect the product distribution (Table 3) indicates that anionic AC, generated in the proton exchange reaction with [(*R*)-GLYMI][AcO], is essential in affording the HH dimers, presumably through the electrostatic interaction with the imidazolium moiety of CIL.

Conclusions

In this exploratory study on CIL-mediated photochirogenesis, we investigated the effects of counteranion of CIL on the enantiodifferentiating supramolecular photocyclodimerization of AC-H and AC-Li, by using [(*R*)-GLYMI][AcO] and [(*R*)-GLYMI][Tf_2N] as chiral solvents, chiral modifiers of CB[8] and chiral templates. The use of [(*R*)-GLYMI][Tf_2N] as a chiral solvent for the photocyclodimerization of AC-H led to the formation of *syn*-HT dimer **2*** in 41% ee at –50 °C,[8] while [(*R*)-GLYMI][AcO], despite giving slightly higher HT : HH ratios, was totally ineffective in inducing appreciable ee, due to the ionization of AC-H through the proton exchange with AcO^-. The chiral supramolecular modification of CB[8] portal with [(*R*)-GLYMI][AcO] and [(*R*)-GLYMI][Tf_2N] enhanced the HH selectivity up to 99% upon photocyclodimerization of AC in aqueous solution, but the chiral dimers obtained were totally racemic. The supramolecular photochirogenesis using [(*R*)-GLYMI][AcO] as a chiral template in dichloromethane was more encouraging, giving exclusively the HH dimers and in particular *anti*-HH dimer **3*** of 14% ee in 79% yield, presumably through chiral hydrogen-bonding and electrostatic interactions.

The present study has expanded the scope of CIL application to the supramolecular photochirogenesis in CIL, aqueous and organic media. In particular, the use of CIL as a chiral template for mediating photochirogenic reaction appears most promising in view of the efficiency in chirality transfer. The modest ee obtained in this study may be improved through more sophisticated molecular design of the chiral moiety attached to the imidazolium and other cationic core of CIL.

Experimental

Instruments

^1H NMR and ^{13}C spectra were recorded at 600 MHz in CD_2Cl_2 on a Varian INOVA-600 instrument or at 300 MHz (75.7 MHz) in DMSO-d_6 on a Varian 300 instrument using TMS as internal standard. ESI-MS analyses were performed on a Finnigan LCQ Advantage (Thermo Finnigan, San Jose, CA, USA) ion trap instrument equipped with an Excalibur software. The IR spectrum was recorded on a JASCO FT/IR-460 Plus spectrometer. UV/vis and CD spectra were measured in a quartz cell (0.1, 1.0 or 10 mm thickness) on JASCO V-550, V-560, V-660 or V-670 spectrometer and J-720WI or J-820YH spectrometer, respectively, both of which were equipped with a Unisoku CoolspeK cryostat for UV/CD spectroscopy, model USP-203HP. Fluorescence spectra were recorded in a quartz cell (0.1 or 1.0 mm thickness) on a JASCO FP-6500 spectrofluorimeter; the cell was placed at 60° angle against the incident light and the emission was measured from the rear. HPLC analyses were performed on a JASCO HPLC system fitted with an FP-2025 fluorescence detector (λ_{ex} = 254 nm, λ_{em} = 420 nm). For the complete separation of **1–4** and enantiomeric **2*** and **3***, a tandem column of Cosmosil 5C18-AR-II (Nakalai) and Chiralcel OJ-RH (Daicel) was used at 35 °C with a 64 : 36 (v/v) mixture of deionized water and acetonitrile containing 0.1% trifluoroacetic acid eluted at a flow rate of 0.5 mL min^{-1}.

Materials

All chemicals were reagent grade and used as received. AC-Li, (*R*)-1-(2,3-dihydroxypropyl)-3-methyl-1*H*-imidazol-3-ium chloride {[(*R*)-GLYMI][Cl]}, and (*R*)-1-(2,3-dihydroxypropyl)-3-methyl-1*H*-imidazol-3-ium bistriflimide {[(*R*)-GLYMI][Tf_2N]} were synthesized as reported previously and showed satisfactory agreements with the IR, NMR and mass spectra reported.[8] The stereoisomeric cyclodimers (**1–4**) were characterized by Tamaki *et al.*[21] and also confirmed by us (see Figs. S3–S10 in the ESI).

Synthesis of (*R*)-1-(2,3-dihydroxypropyl)-3-methyl-1*H*-imidazol-3-ium acetate {[(*R*)-GLYMI][AcO]}

A solution of 4.66 g (24.2 mmol) of (*R*)-1-(2,3-dihydroxypropyl)-3-methyl-1*H*-imidazol-3-ium chloride {[(*R*)-GLYMI][Cl]} in EtOH (5 mL) was added dropwise to a solution of 2.85 g (29.0 mmol, 1.2 eq.) of AcOK in EtOH (20 mL) at 60 °C. The resulting

suspension was stirred at 60 °C for 15 h, cooled to room temperature and the KCl resulting from the anion metathesis was removed by filtration. The filtrate was concentrated, and the residue was treated with acetone (3 × 40 mL) at 40 °C in order to remove the excess of AcOK. The title compound was obtained as a pale yellow oil after drying *in vacuo* at 70 °C for 24 h (5.00 g, 96% yield). ESI-MS (MeOH): *m/z* 157.7 [(*R*)-GLYMI$^+$]; 60 [AcO$^-$]. $[\alpha]_D^{25}$: 28.08° (*c* 0.126, EtOH). ^{1}H NMR (300 MHz, DMSO): δ 9.41 (1 H, s), 7.75 (1 H, s), 7.68 (1 H, s), 4.29 (1 H, dd, J = 13.6, 2.9 Hz), 4.11 (1 H, dd, J = 13.5, 7.5 Hz), 3.83 (3 H, s), 3.72 (1 H, m), 3.35 (1 H, dd, J = 11.1, 4.8 Hz), 3.23 (1 H, dd, J = 11.3, 6.2 Hz), 1.60 (4 H, s). ^{13}C NMR (75 MHz, DMSO): δ 174.7, 137.6, 123.3, 122.9, 69.8, 62.8, 52.1, 35.6, 25.7. UV (neat): ≤245 nm. IR (KBr) ν 3415, 2144, 1646, 1566, 1410, 1344, 1171, 1108, 1050, 928, 750, 656, 621 cm^{-1}.

For the use of CIL as a solvent, the density of [(*R*)-GLYMI][AcO] was determined as 1.154 g cm^{-3} at 25 °C through comparison with that of water.

Sample preparation and photolysis procedures

CIL solvent. A given amount of AC-H was added to [(*R*)-GLYMI][AcO] placed in a test tube, and the mixture was sonicated for 8 h to give a transparent 1.34 mM solution of AC-H in [(*R*)-GLYMI][AcO]. The concentrations of AC-Li in [(*R*)-GLYMI][AcO] and in [(*R*)-GLYMI][Tf$_2$N] and of AC-H in [(*R*)-GLYMI][Tf$_2$N] were determined spectroscopically by comparing the absorbance with that of an authentic solution of AC-H in [(*R*)-GLYMI][AcO]. The CIL solution of AC-X placed in a quartz cell (0.1 or 1 mm) was irradiated for 3 h at temperatures ranging from +25 °C to −50 °C under aerated conditions, by using a 500 W ultrahigh-pressure Hg lamp fitted with a UV-35 glass filter. After irradiation, a 2 : 1 (v/v) mixture of aqueous 2 mM NaOH solution and acetonitrile was added to the photolyzed sample to give a homogeneous solution, which was subjected to the chiral HPLC analysis.

CIL ligand to CB[8]. To deionized water were added AC-H (0.1 mM), CB[8] (0.05 mM) and CIL (0.1 mM), and the mixture was sonicated for 2 h and then filtrated to give a transparent solution, which was subjected to the spectroscopic examinations in a 10 mm cell. After the spectroscopic measurement, the aqueous sample solution was bubbled with N_2 for 10 min and then irradiated for 60 min. A 5 μL aliquot of the photolyzed sample was subjected to the HPLC analyses as mentioned above.

CIL template. AC-H and CIL were dissolved in dichloromethane and the solutions were examined by UV and CD spectroscopy. The same solutions placed in a 10 mm cell were bubbled with N_2 for 10 min and then irradiated with the same light source at temperatures ranging from +25 °C to −90 °C. After irradiation, the solvent was evaporated and the residue was re-dissolved in a 2 : 1 (v/v) mixture of an aqueous 2 mM NaOH solution and acetonitrile for HPLC analyses.

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