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Enhanced asymmetric photocycloaddition of anthracene tethered to maleate versus fumarate through non-fluorescent exciplex intermediate

Makoto Ichikawa, Yoshihisa Inoue, Tadashi Mori*

Department of Applied Chemistry, Graduate School of Engineering, Osaka University, 2-1 Yamada-oka, Suita 565-0871, Japan

A B S T R A C T

The asymmetric photocycloaddition of anthracene-tethered maleate with a small (*S*)-1-methylpropyl auxiliary at the peripheral position (**1Z**) underwent much faster than that of the corresponding fumarate (**1E**). The absolute configuration of the newly created chiral center in the major product was ambiguously assigned as (4*S*) by X-ray crystallographic as well as CD spectral studies. The facile *E–Z* photo-isomerization was simultaneously observed for both **1Z** and **1E**, again much faster for **1Z**. The concurrent electron transfer works as a quenching process and the fumarate acted as a better quencher than maleate in both intramolecular and intermolecular systems. The fluorescence quenching and quantum yield investigations also supported such facile electron transfer from excited-state anthracene to acceptor in the singlet manifold. Observed diastereoselectivities in the photocycloaddition of **1Z** and **1E** were moderate but substantial (5–12% de), given the fact that the chiral auxiliary is introduced at the remote position from the reaction center (4-bond separation). The non-fluorescent exciplex, probably in a triplet manifold derived from the singlet exciplex, plays a crucial role in this efficient cyclization process, affording a biradical intermediate, that can either dissociate or undergo second bond formation to afford a diastereomeric *trans* adduct **2**. The diastereoselectivity was higher in less polar solvents, suggesting the polar nature of the exciplex.

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1. Introduction

As the Woodward–Hoffmann rule states [1], [4+2] photo-cycloaddition of anthracene to dienophile is orbital-symmetrically forbidden and would occur in a stepwise manner. The electron transfer (ET) usually occurs from the singlet excited anthracene to acceptor, affording the corresponding radical ion pair [2]. The pair can undergo recombination to form a biradical intermediate by the first bond formation, which is followed by the second bond formation to give a cycloadduct. On the other hand, exciplex (EX) intermediates were suggested to intervene in the reactions of 9,10-dicyanoanthracene with 1,2-diphenyl-cyclopropene-3-carboxyl-ate and of 9-cyanoanthracene with conjugated dienophiles [3,4]. Clear distinction between the ET and the EX mechanism, however, is quite challenging and the detailed mechanism still remains to be elucidated [5].
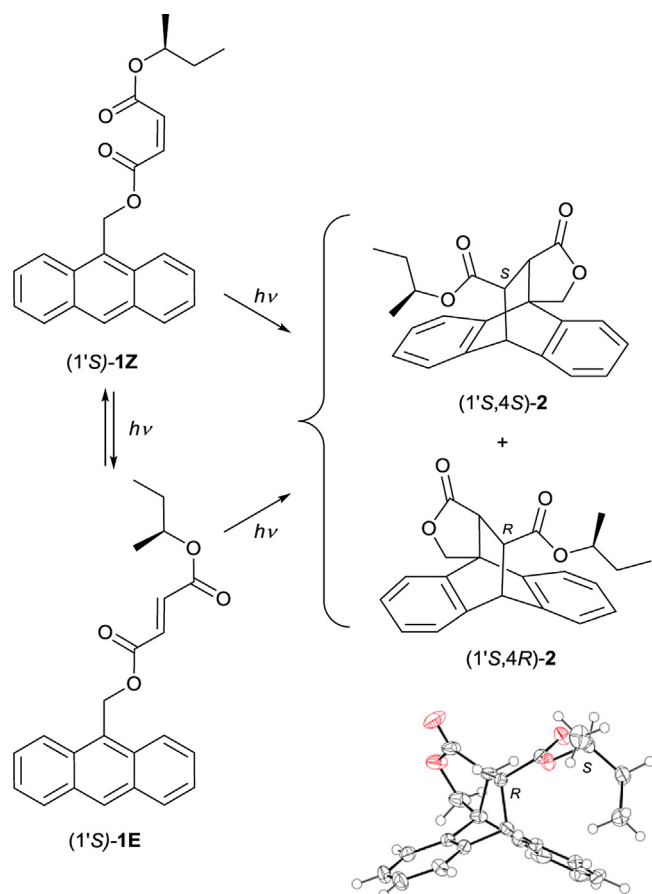
Intermolecular photocycloaddition of anthracene to dimethyl fumarate and maleate has been demonstrated to occur by Kaupp upon irradiation at >330 nm in 1972, but with a greater amount of dimerization of anthracene [6,7]. Intramolecular photoreaction of anthracene tethered to methyl fumarate has been also reported by Okada et al. in 1987 [8]. Accordingly, the [4 + 2] photocycloaddition underwent smoothly, without accompanying any apparent *E–Z* isomerization of the fumarate moiety. The cyclization product was obtained in 66% yield after 3 h irradiation in benzene with a high-pressure mercury lamp using a Pyrex cut-off. The corresponding maleate was reported to proceed facile *Z*-to-*E* isomerization (to afford fumarate) upon photoexcitation and the isomerization was completed within 20 min.

We have been studying a variety of asymmetric photoreactions of chiral donor-acceptor systems, in order to comprehensively understand the factors controlling the stereoselection process(es) [9–11]. We have demonstrated that the irradiation wavelength can be a convenient tool to tune the stereochemical outcomes, where the distinct excited species formed upon selective excitation of ground-state charge-transfer (CT) complex, leading to the forma-tion of excited CT complex (ECT), which is different from the conventional exciplex (EX) in geometry and reactivity [12]. We have been recently focusing on intramolecular chiral CT systems to further elucidate the detailed mechanisms comprising the ECT and

Scheme 1. Diastereodifferentiating intramolecular [4 + 2] photocycloaddition reaction of tethered anthracene-fumarate (**1E**) and maleate (**1Z**) systems. X-ray crystal structure of minor diastereomer of photoproduct **2** was also shown, the absolute configuration being determined as (1′S,4R)-**2**. Note that two independent structures of fundamentally the same geometries were found in the crystal, and one of them was arbitrarily chosen for clarity.

the EX [13,14]. In line with these studies, we prepared a chiral anthracene-fumarate system (1′S)-**1E**, where a small chiral (S)-1-methylpropyl group was appended at the terminal position (Scheme 1). This intramolecular donor-acceptor system is expected to undergo the [4 + 2] photocycloaddition reaction in a diastereoselective manner, which is expected to behave significantly differently from the concerted [2 + 2] photoreactions, proceeding typically through the singlet excited state.

Our own preliminary investigation on the photoreaction of **1E**, on the contrary, exhibited only slow cyclization reaction, along with efficient E-to-Z isomerization of the fumarate moiety (vide infra). Moreover, the photolysis of maleate **1Z** underwent facile reactions to directly afford the same cyclization products as **1E**. This contrasting behaviour prompted us to further investigate the detail of the [4 + 2] photocycloaddition reaction of **1E** together with **1Z**. Our detailed study revealed that the exciplex intermediate, although non-fluorescent, plays a crucial role in the present photocycloaddition of **1Z** and **1E**.

2. Experimental

2.1. Materials and measurements

Dichloromethane and toluene were refluxed over CaH_2 and distilled under nitrogen atmosphere, prior to use. For analytical runs, spectrophotomeric-grade acetonitrile, dichloromethane, diethyl ether, toluene, and methylcyclohexane were used as

received without further purification. The UV–vis spectra were recorded on a JASCO V-650 or V-670 spectrometer. ^{1}H- and ^{13}C NMR spectra were recorded in $CDCl_3$ or CD_3CN on a JEOL JNM-ESC400 (^{1}H: 400 MHz; ^{13}C: 100 MHz) or on a Bruker AVANCE III (^{1}H: 600 MHz; ^{13}C: 150 MHz). Mass spectra were recorded on a JEOL JMS-700 station. Steady-state fluorescence spectra were recorded on a JASCO FP-8500 for solutions under air with optical density of 0.02 at the wavelength of excitation (310 nm). Fluorescence quantum yields (Φ_f) were estimated by integrating the fluorescence band and compared with that of (9-anthryl) methyl acetate (**1R**) as a reference ($\Phi_f = 0.21$ in acetonitrile at 25 °C) [15]. Fluorescence lifetime measurements were performed on a Hamamatsu C11367 employing a picosecond light emitting diode ($\lambda_{ex} = 365$ nm) as excitation source. The decays of fluorescence emission were monitored at 410 nm and were analysed by Stern–Volmer treatments.

2.2. Synthetic procedures and characterizations

2.2.1. (9-Anthryl) methyl hydrogen maleate

This was prepared by similar procedure reported for a synthesis of benzyl hydrogen maleate [16]. To a solution of 9-hydroxymethylanthracene (1.00 g, 4.8 mmol) in dichloromethane (35 mL) was added triethylamine (1.0 eq.), and the mixture was stirred at an ambient temperature for 15 min under nitrogen atmosphere. Maleic anhydride (470 mg, 1.0 eq.) was added to the solution, and was refluxed for 5 h. After cooled down to an ambient temperature, the crude mixture was washed with a 1.5 M aqueous HCl solution (3 × 7 mL). The organic phase was dried over anhydrous Na_2SO_4 and filtrated. The solvent was evaporated in vacuo to afford essentially pure (9-anthryl) methyl hydrogen maleate as yellow crystals (1.38 g, 4.3 mmol, 90%), which was used without further purification. M.p.: 99–100 °C. ^{1}H NMR (400 MHz, $CDCl_3$): $\delta = 8.57$ (s, 1H), 8.30 (dd, J = 8.9, 0.8 Hz, 2H), 8.06 (dd, J = 8.4, 0.6 Hz, 2H), 7.62 (ddd, J = 8.9, 6.6, 1.3 Hz, 2H), 7.52 (ddd, J = 8.3, 6.6, 0.9 Hz, 2H), 6.43 (d, J = 12.8 Hz, 1H), 6.37 (s, 2H), and 6.35 (d, J = 12.8 Hz, 1H). ^{13}C NMR (100 MHz): $\delta = 168.1$, 164.2, 137.0, 131.4, 131.2, 130.3, 129.4, 129.2, 127.3, 125.4, 124.0, 123.5, and 61.5. HRMS (m/z, FAB$^+$): Calcd For $C_{23}H_{22}O_4$ 306.0892, found 306.0888.

2.2.2. (9-Anthryl) methyl acetate (**1R**)

This was obtained from 9-anthracenemethanol according to the literature procedure [17].

2.2.3. (1′S)-(9-Anthryl) methyl 1′-methylpropyl maleate (**1Z**)

This was prepared by similar procedure reported for a synthesis of benzyl methyl maleate [18]. To a mixture of (9-anthryl) methyl hydrogen maleate (1.30 g, 4.1 mmol), N,N-dimethyl-4-aminopyridine (39 mg, 0.3 mmol), and (S)-(+)-2-butanol (0.29 mL, 3.1 mmol) in dichloromethane (70 mL), a solution of N,N′-dicyclohexylcarbodiimide (0.96 g, 4.5 mmol) in dichloromethane was added dropwise at 0 °C under nitrogen atmosphere. The resulting solution was allowed to warm to an ambient temperature and continued to stir for 6 h. The resultant mixture was filtered through celite and the filtrate was washed with 2.0 M aqueous HCl (2 × 50 mL) and brine (50 mL). The organic phase was dried over anhydrous $MgSO_4$ and filtrated. The solvent was removed in vacuo and was purified by medium pressure silica gel column chromatography with n-hexane-ethyl acetate (91 : 9) as eluent to give pure **1Z** as yellow crystals (0.63 g, 1.74 mmol, 57%). M.p.: 92–93 °C. ^{1}H NMR (400 MHz, $CDCl_3$): $\delta = 8.56$ (s, 1H), 8.35 (dd, J = 9.0, 0.9 Hz, 2H), 8.03 (dd, J = 8.9, 0.8 Hz, 2H), 7.57 (ddd, J = 8.9, 7.0, 1.3 Hz, 2H), 7.49 (ddd, J = 9.0, 6.9, 1.0 Hz, 2H), 6.26 (s, 2H), 6.24 (d, J = 11.9 Hz, 1H), 6.19 (d, J = 11.9 Hz, 1H), 4.90 (pseudo sxt, J = 6.3 Hz, 1H), 1.43–1.62 (m, 2H), 1.16 (d, J = 6.3 Hz, 3H), and 0.85 (t, J = 7.4 Hz, 3H). ^{13}C NMR (100 MHz): $\delta = 165.6$, 164.8, 131.3, 131.1, 130.4, 129.4, 129.3, 129.0, 126.7, 125.4,