

Formation of 2,2′-Diacyl-9,9′-bifluorenylidene Isomers from 2-Acyl-9-bromofluorene and Base-Catalyzed Isomerization of the Formed Alkenes

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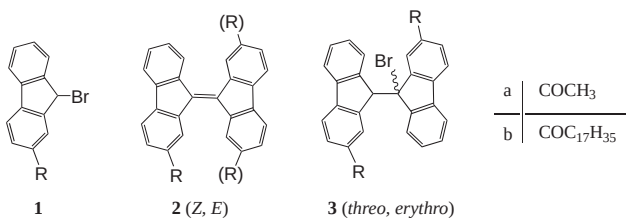
We studied the formation of 2,2′-diacyl-9,9′-bifluorenylidene from 2-acyl-9-bromofluorene. The *E*-isomer was obtained mainly when the acyl group was a short alkyl chain, such as an acetyl group, and *Z*-isomer was isolated predominantly when a long acyl chain such as stearoyl group was attached. 9,9′-Bifluorenylidene was formed via anti elimination of hydrogen bromide from the intermediate 9-bromo-9,9′-bifluorenyl. This indicated that the stereochemistry of 2,2′-diacyl-9,9′-bifluorenylidene was determined by the configuration of 9-bromo-9,9′-bifluorenyl isomers, giving *Z*- and *E*-isomers in a ratio of 1:1. Facile base-catalyzed *Z*/*E* isomerization of 9,9′-bifluorenylidenes followed the formation of the alkenes, which showed different stereoselectivity depending upon the length of the acyl side-chain. On the other hand, thermal treatment of 2,2′-diacyl-9,9′-bifluorenylidene afforded a ca. 1:1 mixture of *Z*- and *E*-isomers, suggesting that thermal isomerization took place through a different pathway than base-catalyzed isomerization.

We have reported that the reaction of 2-acetyl- (**1a**) and 2-stearoyl-9-bromofluorene (**1b**) with base affords (*Z*)- and (*E*)-2,2′-diacyl-9,9′-bifluorenylidenes, **2a** and **2b**, respectively.[1] Compound **1a** gives mainly the *E*-isomer, while **1b** yields *Z*-isomer predominantly (Scheme 1). (*E*)-**2a** is a little more stable than (*Z*)-**2a** by calculation and its side chains are positioned to decrease steric repulsion. On the other hand, (*Z*)-**2b** is more stable than (*E*)-**2b**; we attribute it to an increase in the amount of aggregative intra-molecular interaction between side chains.[1] The reaction of **1** proceeds via the intermediate 9-bromo-9,9′-bifluorenyl (**3**), and the rate-determining step of **1** to **2** is involved in the conversion of **1** to **3**.[2] The dehydrobromination of **3** takes place via an E2 pathway. The reaction of **1a** between insufficient amount of base roughly gives a 1:1 mixture of *threo*- and *erythro*-**3a**, and the configuration of **3a** influences the diastereomeric ratio of **2a**, or *Z*/*E* is 1:1. We assume that the selectivity discussed above is caused by the facile isomerization of **2** in the presence of base during the reaction, based on preliminary experiments of the base-catalyzed isomerization of **2**.[2]

Alkene **2** is easily prepared by the reaction of **1** with methanolic potassium hydroxide in acetone, which is a conventional method[3,4] in many procedures.[5–10] Unsubstituted compound **2** (R = H) is nonplanar, twisting at the central C_9–$C_{9'}$ double bond with an angle of about 43 degree.[11–13] The *Z*/*E* isomerization of derivatives of **2** having substituents at the 1,1′-[14–16] and 2,2′-positions[16–18] has been studied experimentally and theoretically. ΔG value for the *Z*/*E* isomerization of 2,2′-dimethyl-9,9′-bifluorenylidene was determined to be 104 kJ mol^{-1}.[18] To the best of our knowledge there is no study concerning the stereoselective synthesis of derivatives of **2**, except for 1,2-[(*Z*)-9′,9″-bifluorenylidene-1′,2″-diyldioxy]ethane and its analogs.[17]



1 **2** (*Z, E*) **3** (*threo, erythro*)

Scheme 1.

Selectivity, i.e., formation of a single product, is a very important in organic synthesis. For example, the Wittig reaction is a stereo-controlled procedure for alkene synthesis,[19] and the reaction between a stable ylide and carbonyl compound gives mainly an *E*-alkene, and the reaction with a reactive ylide affords *Z*-isomer as a main product. Another example is the selective formation of methyl cinnamate from both methyl *threo*- and *erythro*-2,3-dibromo-3-phenylpropionate by microwave irradiation in 1-methyl-3-pentylimidazolium fluoroborate.[20]

In the present paper, the stereoselective synthesis of the alkene moiety of **2**, controlled by the length of the acyl side-chains is reported. The framework of **2** is one of the partial structural motifs found in fullerenes, and thus, **2** and its derivatives may be useful materials for the bottom-up synthesis of elaborate fullerene derivatives.[21–24]

First, the reaction of **1** having various acyl groups with potassium hydroxide in methanol/acetone is discussed, and it is shown that the observed *Z*/*E* ratio depends upon the length of the acyl side-chain. Then, the dehydrobromination of a mixture of *threo*- and *erythro*-**3a** and **3b** is presented and suggest that an E2 pathway is involved. The third section concerns the

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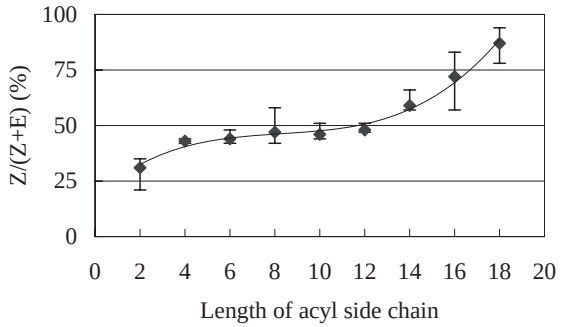
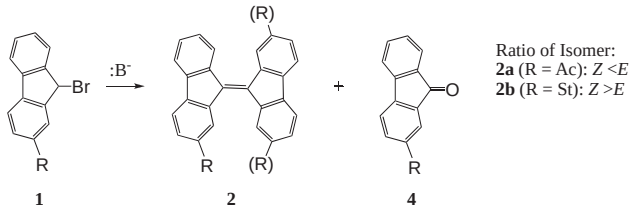


Fig. 1. Z/E selectivity vs length of acyl side chain.



Scheme 2.

Table 1. Z/E Ratio of **2** by the Dimerization of **1** with a Non-Alkanoyl Moiety

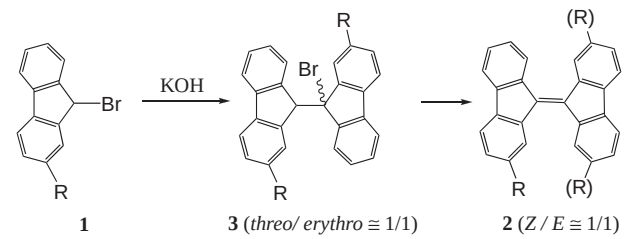
Run	**1**		Reaction conditions		**2**					
	Substituent	Mp (°C)	Molar ratio of KOH/**1**	Ratio of acetone/**1** (mL/mmol)	Yield /%	Z/E	Chemical shift (part)/ppm Z H(8)	Z H(1)	E H(8)	E H(1)
1	$COOCH_3$	103–104	0.9	30	91	46/54	8.43	8.99	8.35	9.04
2	$COOC_{10}H_{21}$	45–47	0.9	30	67	50/50	8.43	9.00	8.37	9.07
3	$COOC_{16}H_{33}$	78–79	0.9	30	72	51/49	8.44	9.01	8.38	9.08
4	$COCH_2CH_2COOCH_3$	112–115	0.9	30	75	38/62	8.45	8.99	8.37	9.03
5	$COCH_2CH_2COOC_{10}H_{23}$	69–71	0.9	30	32	44/56	8.45	8.99	8.37	9.03
6	$COCH_2CH_2COOC_{16}H_{33}$	82–83	0.9	30	15	48/52	8.45	8.99	8.37	9.03
7	COC_6H_5	135–137	2.1	30	82	36/64	8.41	8.73	8.34	8.78
8	COC_6H_4-CH_3(p)	129–131	2.0	30	72	44/56	8.40	8.70	8.34	8.76
9	C_2H_5	51–53	1.8	30	68	58/42	8.35	8.28	8.38	8.23
10	$C_{18}H_{37}$	66–68	1.8	30	47	58/42	8.35	8.28	8.38	8.23

base-catalyzed isomerization of **2**, which only occurs for acyl compounds, but not alkyl and halogen derivatives, indicating that the conversion occurs through an enolate species. The last topic of this paper is the thermal isomerization of **2**, which afforded ca. 1:1 mixture of (*Z*)- and (*E*)-**2**, despite of the length of the side chain. This transformation should be explained via biradical species at the central double bond.

Results and Discussion

Figure 1 shows the *Z*-selectivity versus the length of acyl side-chain in the formation of **2** by the reaction of **1** with methanolic potassium hydroxide in acetone.[1] These findings indicate that Z/E selectivity depends on the length of the acyl side-chain, despite the reproducibility of the data being low. Ratio of components in the reaction mixture was determined by comparing their characteristic signals on the ^{1}H NMR.[2] Solubility of acylated **1** and **2** was fairly low compared to that of unsubstituted **1** and **2**[25] and the amount of solvent significantly affected the yield and stereoselectivity of **2**. A large excess amount of solvent caused to the formation of an oxidized product, fluorenone **4**[26] (Scheme 2).

The separation of pure *Z* and *E* isomers of **2** has been unsuccessful because of their similar solubility and because they isomerize. The structures of the derivatives of **2** were determined by ^{1}H NMR. The spectrum of each isomeric mixture of **2** has two singlets (δ 8.95 and 8.99 ppm) and two doublets (δ 8.37 and 8.44 ppm). The peak at δ 8.99 ppm of **2a** correlates to the signal at δ 8.37 ppm on the NOESY spectrum, and thus, it is assigned to the 1-hydrogen of (*E*)-**2a**, and the signal at

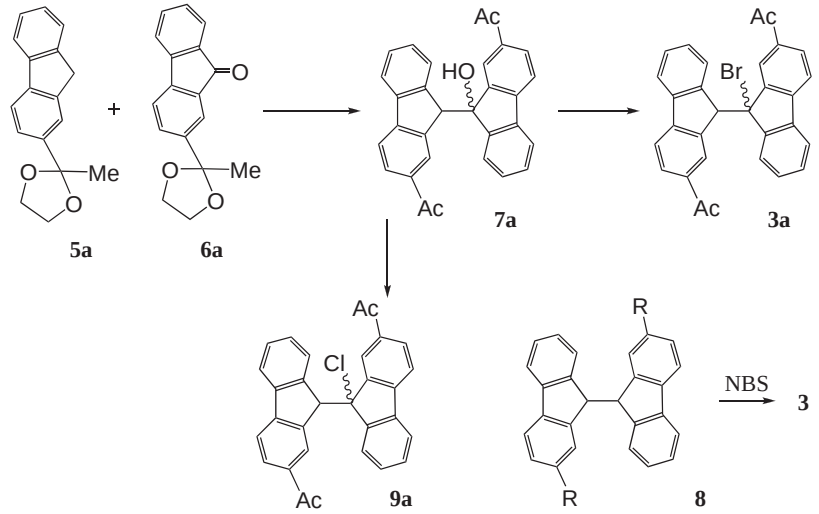


Scheme 3.

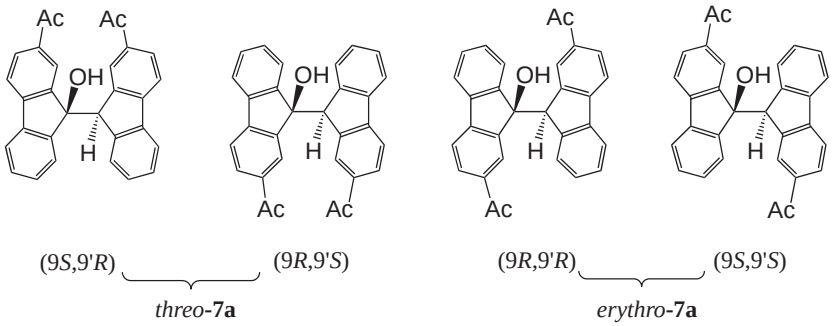
δ 8.37 ppm is the 8-hydrogen of (*E*)-**2a**. The other signals at δ 8.95 and 8.44 ppm did not correlate to each other are the 1- and 8-hydrogens, respectively, of (*Z*)-**2a**.

In order to clarify the effect of acyl substituent, reactions of **1** having substituent other than alkanoyl moiety were examined as are summarized in Table 1. In the cases of esters of 2-fluorenecarboxylic acid and -succinic acid, the Z/E ratio of **2** changes depending upon the length of side chain, but to a lesser degree than that of the simple acyl derivatives. The Z/E ratio of 2,2′-diethyl-9,9′-bifluorenylidene (**2**, R = Et) is similar to that of octadecyl derivative, suggesting that the carbonyl group attached to the 2-position of the fluorenyl ring is essential for Z/E selectivity depending on the side chain.

In our previous paper,[2] the reaction from **1** to **2** was shown to take place via the intermediate **3**, and the conversion of **1** to **3** proceeds non-stereoselectively giving a 1:1 mixture of *threo*- and *erythro*-**3**[27] (Scheme 3). Also, **3** is dehydrohalogenated via the E2 sequence, indicating that *threo*- and *erythro*-**3** afford *Z*- and *E*-**2**, respectively by anti-elimination. Here, we describe



Scheme 4.



Scheme 5.

Table 2. Crystallographic Data for *threo*-**7a**

Empirical formula	$C_{30}H_{22}O_3$
Formula weight	430.50
Crystal dimensions/mm^3	$0.45 \times 0.44 \times 0.30$
Temperature/K	93 ± 1
Crystal system	monoclinic
Space group	$P2_1/n$ (No. 14)
a/Å	12.0924(2)
b/Å	14.5204(2)
c/Å	12.6797(10)
β/deg	102.5653(10)
V/Å^3	2173.06(18)
Z value	4
D_{calcd}/g cm^{-3}	1.316
Radiation/Å	Cu Kα ($\lambda = 1.54187$)
μ(Cu Kα)/cm^{-1}	6.68
F_{000}	904.00
R factor	0.0472
Rw^2 factor	0.1197
Goodness of fit indicator	1.058

both the synthesis of **3a** in order to confirm the structure and the reaction between **3a** (or **3b**) and base to understand the Z/E isomeric ratio of **2**.

An isomeric mixture **3a** was synthesized as is shown in Scheme 4. 2-(2-Methyl-1,3-dioxolan-2-yl)fluorene (**5a**) was lithiated and reacted with the corresponding ketone **6a**, giving

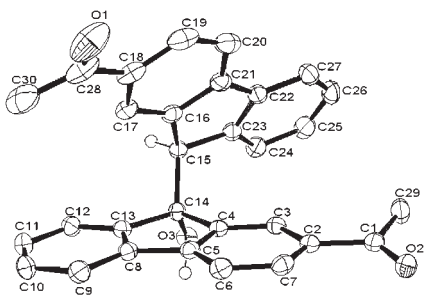


Fig. 2. ORTEP drawing of *threo*-**7a** with atomic labeling scheme. Aromatic and methyl H atoms are omitted for clarity.

threo- and *erythro*-2,2′-diacetyl-9,9′-bifluorenyl-9-ol (**7a**). The stereochemistry of *threo*- and *erythro*-**7a** (Scheme 5) was determined by comparison of the spectral and physical data with those of authentic *dl*- and *meso*-2,2′-diacetyl-9,9′-bifluorenyl (**8a**),[2] respectively. X-ray crystallographic analysis of *threo*-**7a** (racemic) was used to determine the molecular structure. Table 2 shows the crystallographic data for *threo*-**7a**. An ORTEP drawing of *threo*-**7a** (9*S*,9′*R*) is shown in Fig. 2. Both fluorene moieties are twisted from an eclipsed conformation by ca. 60 degree in the direction of the acetyl group on the opposite fluorene ring.

The treatment of *threo*-**7a** with phosphorus tribromide in the presence of pyridine afforded *erythro*-**3a** and a small amount

Table 3. Reaction of **3a** and **3b** with KOH

Run	Reactant			Reaction conditions[a)]			Products			Recovd.	
	3 (R)	*threo*/*erythro*	Wt /mg (μmol)	Molar ratio of KOH/**3**	MeOH /μL	Acetone /mL	**2** /%	**2** *Z*/*E*	**4** /%	Wt /%	*threo*/*erythro*
1	**3a** (Ac)	50/50	24.7(50)	0.5	50	5	31	43/57	3	65	49/51
2	**3a** (Ac)	87/13	49.6(100)	1	110	10	54	20/80	21		
3	**3b** (St)	50/50	94.7(101)	0.5	50	10	46	48/52	3	35	52/48
4	**3b** (St)	50/50	94.5(100)	1	110	10	91	94/6	4		
5[b)]	**3b** (St)	51/49	94.4(100)	1.2	100	10	83	99/1	6		

a) Stirred at room temperature for 1 h. b) *t*-BuOK was used instead of KOH.

Table 4. *Z*/*E* Isomerization of **2** in the Presence of KOH

Run	Reactant **2**			Reaction conditions[a)]				Products		
	Substituent	*Z*/*E*	Wt /μmol	Molar ratio of KOH/**3**	MeOH /μL	Acetone /mL	Temp. /°C	**2** /%	**2** *Z*/*E*	**4** /%
1	Ac (**2a**)	54/46	42	None	25	5	rt	97	53/47	3
2	Ac (**2a**)	53/47	50	0.5	50	5	26–30	85	11/89	10
3[b)]	Ac (**2a**)	50/50	28	0.5	25	2.8	36	94	3/97	
4	St (**2b**)	62/38	50	None	25	5	rt	89	64/36	
5	St (**2b**)	54/46	50	0.5	25	5	rt	82	82/18	5
6[c)]	St (**2b**)	60/40	25	2	110	5	rt	80	85/15	14
7[d)]	$COOCH_3$	45/55	50	0.5	50	5	23–25	91	10/90	
8	$COOC_{16}H_{33}$	52/48	25	0.5	50	2.5	22–24	90	73/27	
9	$COCH_2CH_2COOCH_3$	34/66	50	0.5	50	5	21–24	93	27/73	
10	$COCH_2CH_2COOC_{16}H_{33}$	52/48	25	1	50	2.5	23–26	88	70/30	
11	COC_6H_5	40/60	40	0.6	25	4	22–23	97	4/96	
12	C_2H_5	66/34	48	0.6	25	5	rt	90	64/36	
13	$C_{18}H_{37}$	56/44	50	0.6	25	5	rt	94	60/40	

a) Stirred for 1 h. b) *t*-BuOK in *t*-BuOH was used. c) Pyridine was used instead of acetone. d) Stirred for 30 min.

of *threo*-**3a**. Also, similar reaction of *erythro*-**7a** yielded mainly *threo*-**3a**. The ^{1}H NMR spectra of *threo*- and *erythro*-**3a** were similar to those of *threo*- and *erythro*-**7a**, respectively, although perfect separation of the isomers of **3a** was impossible. Compound **7a** was converted into 2,2′-diacetyl-9-chloro-9,9′-bifluorenyl (**9a**) in order to clarify the relationship between **7a** and **3a**. The reaction between *threo*-**7a** and thionyl chloride in the absence of base afforded *threo*-**9a** and a small amount of *erythro*-**9a** with a low yield (<20%). Treatment of *erythro*-**7a** showed a similar result, yielding mainly *erythro*-**9a**. On the other hand, treatment of *threo*-**7a** with thionyl chloride only gave *erythro*-**9a** in the presence of pyridine, and *threo*-**9a** was obtained from *erythro*-**7a** by a similar procedure.

A mixture of **3a** was also obtained by the reaction of **8a** with *N*-bromosuccinimide (NBS) in a ratio of ca. 1:1. A mixture of *threo*- and *erythro*-**3b** was obtained by a *meso* and *dl* mixture of **8b** and NBS, and its ^{1}H NMR spectrum was similar to that of **3a**.

Table 3 summarizes the dehydrobromination of **3a** and **3b** with base. Using less than a stoichiometric amount of base afforded a mixture of (*Z*)- and (*E*)-**2a** and **2b** in a ratio roughly corresponding to the composition of **3a** and **3b** (Runs 1 and 3). On the other hand, (*E*)-**2a** or (*Z*)-**2b** was the main product, independent of the ratio of **3a** and **3b**, in the presence of a stoichiometric amount of base. These findings are consistent with the results obtained from the treatment of **1a** and **1b** with base,[2] supporting that the conversion of **3** to **2** proceeds via anti-elimination. The preferential formation of (*E*)-**2a** and (*Z*)-**2b** (Runs 2, 4, and 5) suggests that the isomerization of **2** occurs after its formation in the presence of base, as summarized in the Table 4.

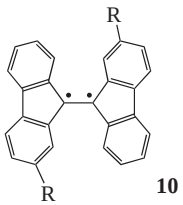
Dimer **2** was treated with base under the conditions similar to those of **3** to **2**, Table 4. Compound (*Z*)-**2a** converted into (*E*)-**2a** (Runs 2 and 3), and (*E*)-**2b** changed into (*Z*)-**2b** (Runs 5 and 6); however no change within experimental error was observed in the absence of base (Runs 1 and 4). Similar *Z*/*E* selectivity dependence upon the length of side chain was observed with different acyl groups were used (Runs 7–11), but not when 2-alkyl groups were used (Runs 12 and 13). The findings suggest both that the base-catalyzed transformation of **2** follows its formation from **3** in the presence of base (Table 3) and that the carbonyl group must be attached directly to the fluorene nuclei for the base-catalyzed isomerization.

Compound **2** was also heated in refluxing toluene, Table 5. The *Z*/*E* ratio after heating for 5 min approached 1:1 when either acyl or alkyl groups were present. On the other hand, the isomers of 2,2′-dibromo-9,9′-bifluorenylidene[28] did not thermally equilibrate within experimental error. The thermally promoted *Z*/*E* equilibrium has been explained by a biradical transition state (**10**)[14] (Scheme 6) via pyramidalization[17] of the crowded molecule. The isomerization is encouraged by both the ground-state strain[13] and the stabilized transition state, which has a relatively low barrier (84–105 kJ mol^{-1}).[14,16–18] The bulkier compound, (*Z*)-*N*,*N*′-bis(1-phenylethyl)-9,9′-

Table 5. Thermal Treatment of **2**[a)]

Run	Reactant **2**			Toluene	Products		
	Substituent	*Z*/*E*	Wt /μmol	/mL	**2** Yield/%	**2** *Z*/*E*	**4** /%
1	Ac (**2a**)	10/90	60	20	88	44/56	12
2	St (**2b**)	85/15	50	10	84	53/47	13
3[b)]	St (**2b**)	65/35	20	20	84	55/45	16
4	$COCH_2CH_2COOCH_3$	30/70	50	40	100	61/39	
5	COC_6H_5	9/91	50	10	83	40/60	14
6	COC_6H_4-CH_3(*p*)	12/88	50	5	92	43/57	5
7	$C_{18}H_{37}$	1/99	50	5	100	56/44	
8	Br	41/59	150	20	100	45/55	

a) Refluxed for 5 min. b) Cyclohexanone was used as solvent.



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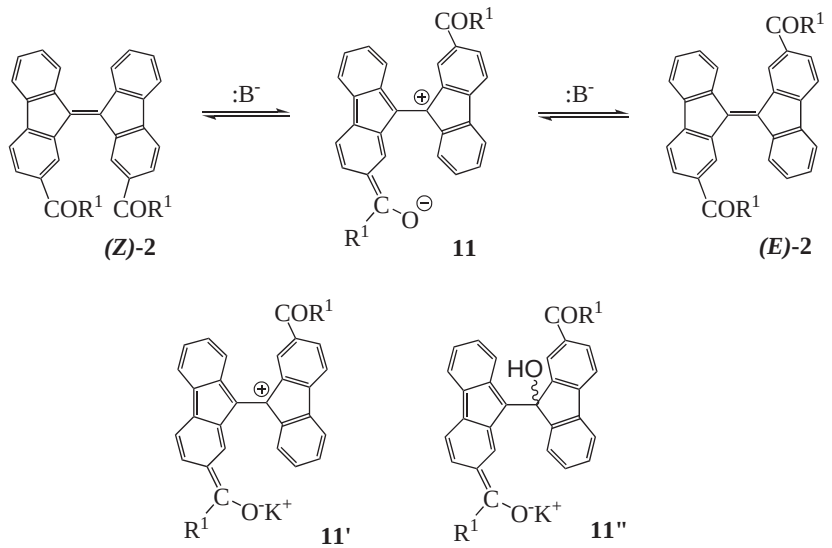
Scheme 6.

bifluorenylidene-2,2′-dicarboxamide isomerized in refluxing ethanol.[17] The reaction conditions in Table 5 should not be defined to be in equilibrium control; however, the findings suggest that thermal conversion proceeds via an another pathway than the base-catalyzed isomerization mentioned above.

The base-catalyzed isomerization of **2** took place in only the compounds with a carbonyl group. The base-catalyzed transformation most likely occurs through a dipolar transition state (**11**), Scheme 7, which is similar to the isomerization of heterofulvene derivatives.[29] Enolate **11** should be unstable, and the cation **11′** or alcohol **11″** is more reasonable species than **11** in the presence of KOH, even though an alcohol like **7** has not been detected in the isomeric conversion of **2**. In the case of short acyl side chains, they are in an *anti* arrangement to reduce steric repulsion, giving mainly (*E*)-**2**. On the other hand, long acyl chain in a kinetically *syn* arrangement is caused by the aggregative intra-molecular interaction between the long side chains, affording (*Z*)-**2** as a main product. This is supported by the enthalpy of formation (ΔH_f) and relative potential energy (E_{rel}) estimated by calculations on the optimized structure of **2** using quantum mechanics program PM3 and molecular mechanics program MM+, respectively.[1] For the acetyl derivatives, (*E*)-**2a** ($\Delta H_f = 240\,kJ\,mol^{-1}$, $E_{rel} = 94.5$) was equally or slightly more stable than (*Z*)-**2a** ($\Delta H_f = 240\,kJ\,mol^{-1}$, $E_{rel} = 98.0$). However, for the stearoyl derivatives, (*E*)-**2b** ($\Delta H_f = -474\,kJ\,mol^{-1}$, $E_{rel} = 117$) was clearly less stable than (*Z*)-**2b** ($\Delta H_f = -513\,kJ\,mol^{-1}$, $E_{rel} = 110$). The optimized structure of (*Z*)-**2b** showed two acyl chains stretched along one another (the nearest H–H distance, ca. 0.25 nm). The aggregative interaction between the side chains is tentatively assumed to be the van der Waals force between the alkyl groups, which is observed in some liquid crystals[30] and phospholipids.[31]

Experimental

The melting points are uncorrected. The NMR ($CDCl_3$) and IR (KBr pellet) spectra were recorded with a Varian VXR-300 and JASCO FT/IR-430, respectively. The elemental analyses and



Scheme 7.

mass spectra were measured with an EA 1108 CHNS-O (Fison Instruments) and JMX-AX 500 (JEOL, 70 eV), respectively.

Molecular modelings were performed using the program package HyperChem (version 5.1, HyperCube Inc.). Programs MM+ and PM3 were employed without any modification of the parameters provided. A structure was optimized initially by MM+, and then the structure that was obtained was optimized again by PM3. This was repeated until the energy of the model structure was nearly unchanged. ΔH_f and E_{rel} were calculated for the optimized structure by PM3 and MM+, respectively. The solvent effects were omitted in all calculations.

X-ray Crystallographic Analysis. The intensity data were collected at -180 ± 1 °C on a Rigaku RAXIS RAPID imaging plate diffractometer with graphite-monochromated Cu Kα radiation in ω scan mode up to $2\theta_{max} = 136.5°$. Unit-cell parameters were determined by a least-squares refinement. The crystal data and experimental details are listed in Table 2. Crystallographic data have been deposited with Cambridge Crystallographic Data Centre: Deposition number CCDC-609981 for *threo*-**7a**. Copies of the data can be obtained free of charge via http://www.ccdc.cam.ac.uk/conts/retrieving.html (or from the Cambridge Crystallographic Data Centre, 12, Union Road, Cambridge, CB2 1EZ, UK; Fax: +44 1223 336033; e-mail: deposit@ccdc.cam.ac.uk).

Materials. 2-Acylfluorene was obtained by a procedure similar to the synthesis of 2-acetylfluorene:[32] 2-Butanoylfluorene, mp 118–120 °C; 2-hexanoyl-, mp 119–120 °C; 2-octanoyl-, mp 102–103 °C; 2-decanyl-, mp 105–106 °C; 2-dodecanoyl-, mp 96–97 °C; 2-tetradecanoyl-, mp 97–98 °C; 2-hexadecanoyl-, mp 97–99 °C; 2-octadecanoyl- (or 2-stearoyl-), mp 94–95 °C. 2-Acyl-9-bromofluorene was obtained by the reaction of 2-acylfluorene with NBS in CCl_4:[33] 2-Acetyl-9-bromofluorene, mp 118–119 °C; 2-butanoyl-, mp 121–123 °C; 2-hexanoyl-, mp 93–95 °C; 2-octanoyl-, mp 70–71 °C; 2-decanoyl-, mp 83–84 °C; 2-dodecanoyl-, mp 86–89 °C; 2-tetradecanoyl-, mp 86–87 °C; 2-hexadecanoyl-, mp 86–88 °C; 2-octadecanoyl-, mp 92–94 °C.

Reaction of 1a with KOH. Typical Procedure. A solution of KOH (61.5 mg, purity 83%, 0.91 mmol) in MeOH (1 mL) was added to a mixture of **1a** (144 mg, 0.50 mmol) in acetone (30 mL) at 9–10 °C for 5 min, and the mixture was stirred for 1 h. The precipitate was collected by filtration, washed with water, and extracted with hot EtOH (5 mL) giving **2a**. All filtrates were poured into water, and the precipitate was collected and weighed. The ratio was determined by ^{1}H NMR: **2a** (88.2 mg, 86%; Z/E = 18/82) and **4a** (4.1 mg, 3.7%). ^{1}H NMR of (*Z*)-**2a**: δ 2.57 (s, 2Me), 7.34 (td, $J = 7.8$, 1.2 Hz, $H_{7,7'}$), 7.42 (td, $J = 7.8$, 1.2 Hz, $H_{6,6'}$), 7.78–7.82 (m, $H_{4,5,4',5'}$), 8.01 (dd, $J = 8.1$, 1.5 Hz, $H_{3,3'}$), 8.44 (d, $J = 7.8$ Hz, $H_{8,8'}$), 8.95 (d, $J = 1.5$ Hz, $H_{1,1'}$). (*E*)-**2a**: δ 2.57 (s, 2Me), 7.34 (t, $J = 7.5$ Hz, $H_{7,7'}$), 7.43 (t, $J = 7.5$ Hz, $H_{6,6'}$), 7.78–7.82 (m, $H_{4,5,4',5'}$), 8.01 (dd, $J = 8.0$, 1.4 Hz, $H_{3,3'}$), 8.37 (d, $J = 7.5$ Hz, $H_{8,8'}$), 8.99 (d, $J = 1.4$ Hz, $H_{1,1'}$). Anal for **2a** (Z/E mixture, recrystallized from AcOEt). Found: C, 87.47; H, 4.49%. Calcd for $C_{30}H_{20}O_2$: C, 87.35; H, 4.89%.

^{1}H NMR of (*Z*)-**2b**: δ 0.88 (t, $J = 7.2$ Hz, 2Me), 1.24 (bs), 1.68 (q, $J = 7.2$ Hz), 2.90 (t, $J = 7.2$ Hz), 7.30 (td, $J = 7.5$, 1.2 Hz, $H_{7,7'}$), 7.40 (td, $J = 7.5$, 1.2 Hz, $H_{6,6'}$), 7.76–7.82 (m, $H_{4,5,4',5'}$), 8.01 (dd, $J = 8.1$, 1.2 Hz, $H_{3,3'}$), 8.44 (d, $J = 7.5$ Hz, $H_{8,8'}$), 8.95 (d, $J = 1.2$ Hz, $H_{1,1'}$). (*E*)-**2b**: δ 0.88 (t, $J = 7.2$ Hz, 2Me), 1.24 (bs), 1.68 (q, $J = 7.2$ Hz), 2.90 (t, $J = 7.2$ Hz), 7.32 (td, $J = 7.5$, 1.2 Hz, $H_{7,7'}$), 7.42 (td, $J = 7.5$, 1.2 Hz, $H_{6,6'}$), 7.77–7.82 (m, $H_{4,5,4',5'}$), 8.01 (dd, $J = 7.8$, 1.5 Hz, $H_{3,3'}$), 8.37 (d, $J = 7.5$ Hz, $H_{8,8'}$), 8.99 (d, $J = 1.5$ Hz, $H_{1,1'}$). Anal for **2b** (Z/E mixture). Found: C, 86.43; H, 9.85%. Calcd for $C_{62}H_{84}O_2$: C, 86.45; H, 9.83%.

All of experiments in Fig. 1 and Table 1 were carried out under the following conditions:[25] a solution of KOH (1.2–2.3 molar amount to **1**) in MeOH (1.4–10 mL per 1 mmol of **1**) was added to a suspension of **1** in acetone (4.5–120 mL per 1 mmol of **1**) for 5 min at room temperature (10–20 °C), and the mixture was stirred for 1 h.

2-(2-Methyl-1,3-dioxolan-2-yl)fluorene (5a) and 2-(2-Methyl-1,3-dioxolan-2-yl)fluorenone (6a). A solution of 2-acetylfluorene (5.20 g, 25 mmol), ethylene glycol (7.75 g, 125 mmol), and *p*-toluenesulfonic acid monohydrate (190 mg, 1.0 mmol) in benzene (250 mL) was refluxed for 6 h. After cooling to room temperature, the reaction mixture was neutralized with K_2CO_3, the solvent was evaporated in vacuo, and the residue was chromatographed on alumina with benzene, giving **5a** (4.20 g, 67%): mp 103–104 °C (from hexane); ^{1}H NMR δ 1.72 (s, Me), 3.81–3.85 (2H, m), 3.90 (2H, s), 4.05–4.10 (2H, m), 7.29 (td, $J = 7.4$, 1.4 Hz, H_7), 7.37 (td, $J = 7.4$, 0.6 Hz, H_6), 7.51 (dt, $J = 8.1$, 1.5 Hz, H_3), 7.54 (d, $J = 7.5$ Hz, H_8), 7.66 (s, H_1), 7.75 (d, $J = 8.1$ Hz, H_4), 7.78 (d, $J = 7.5$ Hz, H_5); Ms m/z 252 (M^+), 237, 221, 193, 165. Anal. Found: C, 80.59; H, 6.46%. Calcd for $C_{17}H_{16}O_2$: C, 80.92; H, 6.39%.

A solution of 2-acetylfluorene (5.20 g, 25 mmol), triton B (1.0 mL, 40% in MeOH) in pyridine (150 mL) was stirred with bubbling air at room temperature for 3 h. Upon dilution with dil HCl, the precipitate was chromatographed on silica gel with toluene, yielding 2-acetyl-9-fluorenone (3.90 g, 70%): mp 158–160 °C (from EtOH). Acetalization of 2-acetyl-9-fluorenone (1.11 g, 5.0 mmol) by the manner similar to the case of **5a** afforded **6a** (1.01 g, 77%): mp 113–114 °C (from hexane); IR 1712 cm^{-1}; ^{1}H NMR δ 1.67 (s, Me), 3.78–3.82 (2H, m), 4.04–4.09 (2H, m), 7.29 (td, $J = 7.1$, 1.8 Hz), 7.45–7.53 (3H, m), 7.61–7.67 (2H, m), 7.80 (d, $J = 1.5$ Hz, H_1); Ms m/z 266 (M^+), 251, 207, 179. Anal. Found: C, 76.39; H, 5.27%. Calcd for $C_{17}H_{14}O_3$: C, 76.67; H, 5.30%.

***threo*- and *erythro*-2,2′-Diacetyl-9,9′-bifluorenyl-9-ol.** Butyllithium (3.5 mL, 1.6 M, 5.5 mmol) (1 M = 1 mol dm^{-3}) was added dropwise to a solution of **5a** (1.26 g, 5.0 mmol) in ether (50 mL) with stirring at -20 °C over 10 min under an argon atmosphere. After stirring for an additional 1 h, **6a** (1.07 g, 4.0 mmol) in ether (50 mL) was added, and the resulting mixture was refluxed for 30 min. After quenching with 1 M NH_4Cl solution (20 mL), the solvent was evaporated to give oily residue (2.16 g).

A mixture of the oily residue (3.55 g; collected after several runs as above) and *p*-toluenesulfonic acid (95 mg, 0.5 mmol) in acetone (50 mL) was refluxed for 1 h. After neutralization of the solution with K_2CO_3, the solution was poured into water, affording an oil of **7a** (2.60 g, 88%). Fractional recrystallization of **7a** from ether gave *threo*-**7a** (412 mg): mp 235–236 °C; R_f 0.75 (AcOEt/toluene = 1/1); IR 3448, 1676, 1659 cm^{-1}; ^{1}H NMR δ 2.24 (s, Me), 2.27 (s, Me), 2.61 (s, OH), 4.88 (s, H_9), 6.97–7.06 (2H, m), 7.32–7.60 (8H, m), 7.66 (1H, d, $J = 7.5$ Hz), 7.74–7.82 (3H, m). Ms m/z 430 (M^+), 368, 208, 165. Anal. Found: C, 83.42; H, 4.94%. Calcd for $C_{30}H_{22}O_3$: C, 83.70; H, 5.15%.

erythro-**7a** (700 mg) was isolated from the mother solution: mp 140–168 °C; R_f 0.68 (AcOEt/toluene = 1/1); IR 3478, 3225, 1672, 1659 cm^{-1}; ^{1}H NMR δ 2.38 (s, Me), 2.44 (s, Me), 2.61 (s, OH), 4.89 (s, H_9), 6.98–7.05 (1H, m), 7.06–7.14 (2H, m), 7.16–7.34 (3H, m), 7.46–7.52 (3H, m), 7.58 (1H, d, $J = 7.5$ Hz), 7.60 (1H, d, $J = 8.1$ Hz), 7.72–7.78 (1H, m), 7.87–7.96 (2H, m). Ms m/z 430 (M^+), 369, 208, 165. Anal. Found: C, 80.24; H, 5.27%. Calcd for $C_{30}H_{22}O_3 \cdot H_2O$: C, 80.33; H, 5.39%.

2,2′-Diacetyl-9-bromo-9,9′-bifluorenyl (3a). A solution of PBr_3 (670 mg, 2.5 mmol) in ether (5 mL) was added dropwise to a solution of *threo*-**7a** (215 mg, 0.5 mmol) and pyridine (395 mg, 5.0 mmol) in ether (300 mL) at −25 °C under an argon atmosphere, and the mixture was stirred at −10 °C for 1 h and 5 °C for 3 d. Upon quenching with water, neutralizing with $NaHCO_3$, drying with Na_2SO_4, and evaporating the solvent, a mixture of **3a** (173 mg) was obtained as an oil: ratio of *threo*- and *erythro*-**3a** was determined to be 26/74 by ^{1}H NMR. *erythro*-**3a**: R_f 0.67 (AcOEt/toluene = 1/2); IR 1670 cm^{-1}; ^{1}H NMR δ 2.26 (6H, s, Me), 5.22 (1H, s, H_9), 7.10–8.20 (m).

erythro-**7a** (215 mg, 0.5 mmol) was treated in a manner similar to above, and a mixture of *threo*- and *erythro*-**3a** was isolated in a ratio of 82/18. *threo*-**3a**: R_f 0.57 (AcOEt/toluene = 1/2); IR 1670 cm^{-1}; ^{1}H NMR δ 2.44 (3H, s, Me), 2.46 (3H, s, Me), 5.23 (1H, s, H_9), 7.10–7.94 (m).

A mixture of **8a**[2] (828 mg, 2.0 mmol; *meso*/*dl* = 77/23) and NBS (545 mg, 3.1 mmol) in CCl_4 (60 mL) was refluxed for 18 h, giving **3a** (*threo*/*erythro* = 45/55 by NMR).

2,2′-Diacetyl-9-chloro-9,9′-bifluorenyl (9a). A mixture of *erythro*-**7a** (108 mg, 0.25 mmol; *threo*/*erythro* = <1/>99), $SOCl_2$ (0.21 mL, 3.0 mmol), pyridine (800 mg, 10 mmol) in benzene (30 mL) was stirred at room temperature for 1.5 h. Upon addition of water, the organic layer was dried over Na_2SO_4, and the solvent was evaporated in vacuo. Based on ^{1}H NMR, the *threo*/*erythro* ratio of **9a** (mp 222–226 °C; 78 mg, 69%) was >99/<1. *Threo*-**9a**: R_f 0.57 (AcOEt/toluene = 1/2); IR 1685, 1673 cm^{-1}; ^{1}H NMR (50 °C) δ 2.43 (3H, s, Me), 2.44 (3H, s, Me), 5.08 (1H, s, H_9), 6.95–7.40 (6H, m), 7.44–7.66 (5H, m), 7.77 (1H, bs), 7.88–7.97 (2H, m).

threo-**7a** (108 mg, 0.25 mmol; *threo*/*erythro* = >99/<1) was treated by the manner similar to above, giving **9a** (mp 225–227 °C; 82 mg, 73%; *threo*/*erythro* = 2/98). *erythro*-**9a**: R_f 0.67 (AcOEt/toluene = 1/2); IR 1679 cm^{-1}; ^{1}H NMR (50 °C) δ 2.26 (6H, s, Me), 5.06 (1H, s, H_9), 6.99 (1H, bs), 7.07 (1H, bs), 7.34–7.52 (6H, m), 7.56–7.61 (1H, m), 7.65–7.70 (2H, m), 7.76–7.83 (2H, m), 7.96 (1H, bs).

A mixture of *erythro*-**7a** (43 mg, 0.1 mmol; *threo*/*erythro* = <1/>99) and $SOCl_2$ (2.88 mL, 40 mmol) in benzene (30 mL) was stirred at room temperature for 3 h, yielding 35 mg of a mixture, which is composed of **9a** (yield 10%; *threo*/*erythro* = <1/>99), **4a** (18%), and **7a** (72%, *threo*/*erythro* = <1/>99) by NMR.

Similar to above *threo*-**7a** with $SOCl_2$ for 5 h afforded a mixture of **9a** (4%; *threo*/*erythro* = 86/14), **4a** (16%), and **7a** (80%, *threo*/*erythro* = >99/<1).

2,2′-Distearoyl-9-bromo-9,9′-bifluorenyl (3b). To a mixture of **1b** (2.55 g, 5.0 mmol) in acetone (100 mL) was added NaI (1.63 g, 11 mmol) in acetone (25 mL), and the resulting solution was refluxed for 5 h, yielding a mixture of *meso*- and *dl*-**8b** (1.93 g, 88%, isomeric ratio = 50/50): mp 115–117 °C; IR 1680 cm^{-1}; ^{1}H NMR δ 0.88 (t, J = 6.8 Hz, Me), 1.21–1.33 (bs), 1.57 (q), 2.58 (t, J = 7.2 Hz, *dl*-$COCH_2$–), 2.73 (t, J = 7.2 Hz, *meso*-$COCH_2$–), 4.92 (s, *dl*-H_9), 4.93 (s, *meso*-H_9), 6.94–7.94 (m). Anal. Found: C, 86.16; H, 10.20%. Calcd for $C_{62}H_{86}O_2$: C, 86.24; H, 10.06%.

A mixture of *meso*- and *dl*-**8b** (860 mg, 1.0 mmol, isomeric ratio = 50/50) was treated with NBS, giving a mixture of *threo*- and *erythro*-**3b** (425 mg, 45%, isomeric ratio = 48/52): mp 72–76 °C; IR 1680 cm^{-1}; ^{1}H NMR δ 0.88 (t, J = 6.7 Hz, Me), 1.26–1.30 (bs), 1.57–1.66 (m), 2.56 (bs, *erythro*-$COCH_2$–), 2.74 (bs, *threo*-$COCH_2$–), 5.22 (s, *erythro*-H_9), 5.23 (s, *threo*-H_9), 6.98–7.97 (m). Anal. Found: C, 77.62; H, 9.01%. Calcd for $C_{62}H_{85}O_2Br\cdot H_2O$: C, 77.55; H, 9.13%.

Reaction of 3a (or 3b) with KOH. Typical Procedure. A suspension of **3a** (24.7 mg, 50 μmol, *threo*/*erythro* = 50/50) in acetone (5 mL) was stirred with KOH/MeOH (23 μmol of KOH in 50 μL of MeOH; 0.46 molar amount based on **3a**) at 24–26 °C for 1 h. After adding to water, **2a** (31.3%, Z/E = 43/57), **4a** (3%), and recovered **3a** (64.7%, *threo*/*erythro* = 49/51) were confirmed by ^{1}H NMR of the precipitates.

***Z*/*E* Isomerization of 2 in the Presence of KOH. Typical Procedure.** To a suspension of **2a** (20.6 mg, 50 μmol, Z/E = 53/47) in acetone (5 mL) was added KOH (25 μmol in 50 μL of MeOH) at once, and the whole was stirred at 26–30 °C for 1 h. Upon the usual treatment of the reaction mixture, **2a** (85.0%, Z/E = 11/89) and **4a** (10.3%) were determined by NMR.

Thermal Isomerization of 2. Typical Procedure. A mixture of **2a** (24.6 mg, 60 μmol, Z/E = 10/90) and toluene (20 mL) was refluxed for 5 min. Upon evaporation of the solvent, **2a** (87.9%, Z/E = 44/56) and **4a** (12.3%) were determined by NMR to be in the residue.

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25 The best conditions to obtain **2** (R = H) was reported as follows: A solution of KOH (1.8 molar amount to **1**) in MeOH (0.36 mL per 1 mmol of **1**) is added to a suspension of **1** in acetone (1.2 mL per 1 mmol of **1**) for 5 min at room temperature, the whole is stirred for 1.5 h, and the deposit is extracted with hot EtOH (0.6 mL/1 mmol of **1**). K. Suzuki, *Yuki Kagobutsu Gosei Hou*, Gihodo Inc., Tokyo, **1959**, Vol. 11, p. 53.

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27 In this paper, *threo*-**3a** means racemate of (9*S*,9′*R*)- and (9*R*,9′*S*)-**3a**, and *erythro*-**3a** is racemate of (9*R*,9′*R*)- and (9*S*,9′*S*)-**3a** (see Scheme 5). Also, same nomenclature is applied to **7a**, **7b**, and **9a**.

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