  Bull. Chem. Soc. Jpn., 55, 3267—3272 (1982)

Reactivities of Stable Rotamers. X. Reactions of 9-(2-Formyl-1-naphthyl)fluorene Rotamers and Related Compounds[1,2]

Ryo Saito and Michinori Ōki*

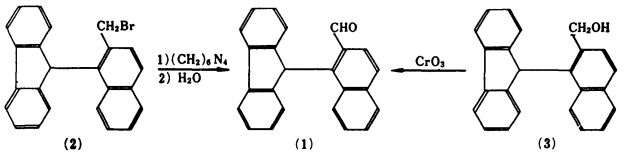
Department of Chemistry, Faculty of Science, The University of Tokyo, Bunkyo-ku, Tokyo 113

(Received April 30, 1982)

Rotational barrier (*ap*→*sp*) in 9-(2-formyl-1-naphthyl)fluorene was determined: $\Delta H^{\ddagger}$ 24.0 kcal/mol and $\Delta S^{\ddagger}$ −7.9 e.u. Oxidation of the aldehyde with chromium(VI) oxide was extremely slow in the *ap* form, whereas it proceeded smoothly in the *sp* form. As models of the 2 steps involved in the aldehyde oxidation, oxime formation of the aldehyde and oxidation of related alcohols were carried out to conclude that the second elimination step in the aldehyde oxidation is slow in the *ap* form because of the steric effect. Dehydration of the oxime of the aldehyde exhibited a large k_{sp}/k_{ap} value as well. Sodium tetrahydridoborate reduction and Grignard additions of the aldehyde were also carried out to show that the former gave a large k_{sp}/k_{ap} value whereas the latter exhibited rather a small k_{sp}/k_{ap}. The implication of the results is discussed.

Reactivity of rotational isomers is sometimes surprisingly different. We have demonstrated that deprotonation of 9-(2-methoxy-1-naphthyl)fluorene rotamers could differ by a factor of 1000.[3] Ionizing reactions of rotational isomers of 9-(2-bromomethyl-6-methylphenyl)-fluorene in ionizing-but-poorly-nucleophilic solvents exhibited striking difference: the *ap* form reacted to give a cyclized product, whereas the *sp* form was intact under the conditions.[4] Finding these differences, we were naturally interested in other reactions of rotamers and wished to extend to investigation to carbonyl compounds. This paper reports such an investigation on reactions of aldehydes and related compounds.

The synthesis of 9-(2-formyl-1-naphthyl)fluorene (**1**) rotamers was carried out in two ways. The first method is a Sommelet reaction[5] of 9-(2-bromomethyl-1-naphthyl)fluorene (**2**) which yielded a mixture of *ap*-**1** and *sp*-**1**. Chromatographic separation of the rotamers was found to be very difficult. However, as is discussed later, treatment of the rotameric mixture of **1** with chromium(VI) oxide oxidized the *sp*-form only, leaving the *ap*-



form intact. Thus this method is useful for the preparation of the *ap* isomer. The second method is oxidation of the corresponding alcohols (**3**). Since the separation of the rotamers of **1** was difficult, pure rotational isomers of **3**[6] were used. The high barrier to rotation in **3** enabled us to obtain *sp*-**1** and *ap*-**1** separately by this method.

Rotational Barriers and Populations of Rotamers. Conformations of the 9-arylfluorenes were determined by taking advantage of ^{1}H NMR spectral features. Due to the anisotropic effect of the fluorene ring, the proton in the 2-substituent of the naphthalene ring gives a high field signal if the conformation is *ap*, whereas it gives a signal at a low field if the conformation is *sp*. The chemical shift of the 8-proton of the naphthalene ring may also be used. It gives a low field signal in the *ap* conformation, whereas it gives a high field signal in the *sp*, due to the anisotropy effect of fluorene.

In order to discuss the reactivity of individual rotamers in a straightforward manner, it is necessary to establish that the conversion of one isomer to another is slow enough at a given temperature where a reaction is carried out. In this context, rotational barriers shall be discussed first together with populations of rotamers which can be obtained at the same time in the investigation of the barrier.

The rates of isomerization (*ap*→*sp*) of **1** are given in Table 1. From the results, $\Delta H^{\ddagger}$ 24.0±0.7 kcal/mol (1 cal=4.18 J) and $\Delta S^{\ddagger}$ −7.9±2.0 e.u. (1 e.u.=4.18 J/K mol) were obtained. Since the free energy of activation for rotation at ambient temperature is *ca.* 26.5 kcal/mol, we can claim that we look at the reactivities of individual rotamers if we run the reaction at ambient temperature within 24 h or at a lukewarm temperature for a shorter period. The equilibrium constant (*sp*/*ap*) is almost constant in the temperature range examined. The favoredness of the *sp* form may be ascribed to the steric effect including that for solvation, since the formyl group is polar and the oxygen in the formyl group can be larger than an sp^2 carbon.

Barrier to rotation of oximes (**5**) was not examined because they were sparingly soluble in nonpolar solvents. However, the height of the barrier may be assumed to be

Table 1. Rate constants for rotation and equilibrium constants of rotamers in 9-(2-formyl-1-naphthyl)fluorene (**1**)

Temperature/°C	$k(ap\rightarrow sp)/s^{-1}$	$K(sp/ap)$
55.6	1.28×10^{-5}	1.48
64.0	3.66×10^{-5}	1.49
73.2	9.58×10^{-4}	1.46
78.2	1.41×10^{-4}	1.49

Table 2. Rate constants for rotation and equilibrium constants of rotamers in 9-[2-(α-hydroxybenzyl)-1-naphthyl]fluorene (**7**)

Temperature/°C	$k(ap\rightarrow sp)/s^{-1}$	$K(sp/ap)$
96.4	1.28×10^{-5}	1.8
104.0	2.94×10^{-5}	1.8
114.0	9.37×10^{-5}	1.8
124.0	2.01×10^{-4}	1.8

almost equal to that of the aldehyde (**1**) because their steric structures are similar.

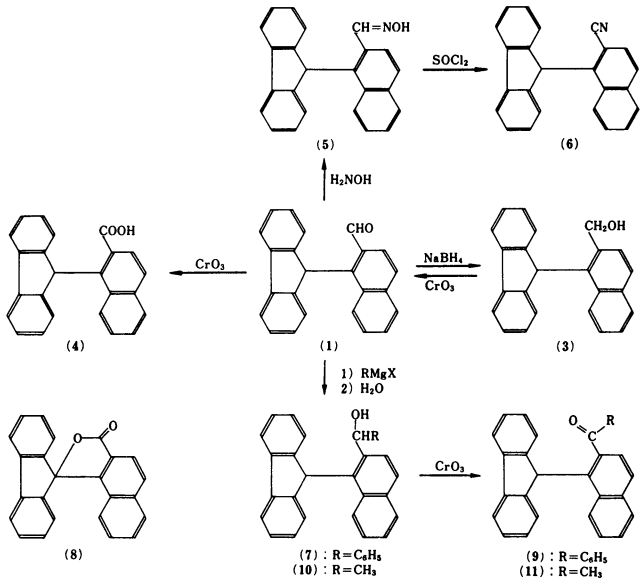
Barrier to rotation in 9-(2-cyano-1-naphthyl)fluorene (**6**) was determined at a temperature. At 77.0 °C in benzene-d_6, the nitrile gave a rate constant for rotation (*ap*→*sp*) of 1.08×10^{-3} s^{-1}. From the value, the free energy of activation for rotation was calculated to be 25.4 kcal/mol. Thus we may neglect isomerization of the nitrile if reactions are carried out at room temperature for a few hours. The equilibrium constant (*sp*/*ap*) was 7.3 at the temperature. The reason for the favoredness of the *sp* form is not well understood at the moment. Molecular models suggest no significant congestion in the *ap* form.

The rate constant for rotation and equilibrium constants in 9-[2-(α-hydroxybenzyl)-1-naphthyl]fluorene (**7**) are given in Table 2. From the rate constants, $\Delta H^{\ddagger}$ 29.1±1.1 kcal/mol and $\Delta S^{\ddagger}$ −2.7±2.9 e.u. were obtained. The free energy of activation (*ca.* 30 kcal/mol) for rotation at ambient temperature assures again that conversion of a rotamer to another at temperature below 50 °C is negligible if the reaction is run during a reasonable period. Although $C_6H_5CH(OH)$ is a large group, the barrier to rotation and equilibrium constants are almost the same as those of **3** reported earlier.[6] The results will imply the followings. If, by rotation about the $C_6H_5CH(OH)$–naphthyl bond, a large group, either phenyl or hydroxyl, comes closely to the fluorene ring, the conformation will be extremely disfavored because of the steric effect. Therefore, this compound will take a conformation in which the hydrogen of the α-hydroxybenzyl group is close to the fluorenyl group, in the ground state. If this effect is operative, the *ap* form of compound **7** may be unfavorable relative to *ap*-**3** because of the decrease in entropy: this effect is ambiguous as far as the experimental data concern, because it is small. Infrared spectrum of *ap*-**7** as a 1.0×10^{-2} mol/L solution in carbon tetrachloride showed an absorption due to OH stretching at 3600 cm^{-1}, ε being 61.3. *sp*-**7** under similar conditions showed an absorption at 3620 cm^{-1} of ε 47.1. The absorption of *ap*-**7** at a relatively low frequency may indicate the presence of the OH···π bond as was the case of the primary alcohol (**3**).[6] The small *K* value implies that the *ap* form is stabilized relative to the *sp*: the cause is most probably the OH···π bond. The similar barrier height for rotation in **7** with that in **3** implies that the transition state energy is also similar. We may approximate the transition state for rotation by the interaction of the fluorene ring with the CH of the α-hydroxybenzyl group and the naphthalene ring.

Reactions. Reactions carried out in this work are summarized in the following scheme. Relative rates are given in Table 3.

Table 3. Relative rates of reactions of rotameric 9-(2-formyl-1-naphthyl)-fluorene and related compounds

Reaction	Compound	k_{sp}/k_{ap}
Oxidation with Cr(VI)	Aldehyde (**1**)	Very large
	Primary alcohol (**3**)	0.67
	Secondary alcohol (**7**)	*ca.* 34
	Secondary alcohol (**10**)	*ca.* 27
Oxime formation	Aldehyde (**1**)	3.7
Dehydration with $SOCl_2$	Oxime (**5**)	*ca.* 18
Reduction with $NaBH_4$	Aldehyde (**1**)	7.6
Addition of C_6H_5MgBr	Aldehyde (**1**)	1.8
Addition of CH_3MgI	Aldehyde (**1**)	1.7



Oxidation of a mixture of rotamers of **1** with chromium(VI) oxide in aqueous acetone yielded the corresponding *sp*-acid (**4**) within a few minutes but left *ap*-**1** intact. If the oxidizing mixture was left overnight, instead of the *ap*-carboxylic acid (**4**), a lactone (**8**) was obtained as a main product. The lactone can be formally formed by oxidation at the 9-position of fluorene and at the formyl group followed by lactonization. It is not clear which is the precedent reaction of the two oxidations, but we prefer the first oxidation at the 9-position of fluorene for the following reasons. Firstly there was no indication that the *ap*-**4** was produced. Secondly although the rotamers of **1** are stable in chloroform for at least 5 d at room temperature, their isomerization is detected if a pyridine solution is allowed to stand overnight. This is because the fluorene ring is proton donating. Although there is no strong base present in the system, water or acetone may act as a base to form a minute amount of the fluorenide anion which should be oxidized easily to form a 9-hydroxy compound. If the 9-hydroxyl group is introduced, the rotational barrier must be lowered, as are known in other cases,[7] to facilitate rotation at room temperature. Then the formyl group, in the *sp* conformation, must be easily oxidized.

Indeed, the lactone (**8**) could be better made by chromium(VI) oxide oxidation of the aldehyde (**1**) in the presence of pyridine. The lactone was formed by still another method. Air oxidation of the aldehyde in ethanol in the presence of potassium hydroxide afforded the lactone smoothly. Since oxidation of 9-alkylfluorenes with air in the presence of base to afford hydroperoxides is reported,[8] it will be natural to assume that the first step in the oxidation of **1** is the

formation of a 9-hydroperoxy compound. Inversion at the anion formed as an intermediate or rotation about the C_9–C_{naph} bond in the hydroperoxide will make the formyl group vulnerable to further oxidation or an intramolecular redox reaction may take place to produce the lactone.

The lack of reactivity of *ap*-**1** was of interest. We wished to clarify an important factor which retards the oxidation of *ap*-**1**. Oxidation of an aldehyde is known to proceed *via* three steps:[9] coordination of the aldehyde oxygen to chromium, addition of water to the complex, forming a tetrahedral intermediate, and final E2 type elimination of chromate of a lower oxidation number. Therefore, we examine every step by using model reactions.

The first step, ligation of the aldehyde to chromium, does not seem to be significantly different of the two rotamers. A molecular model indicates that the aldehyde oxygen is exposed and is vulnerable to the chromium(VI) oxide attack even in the *ap* conformation. The ligation may be assumed to proceed without significant hindrance both in *sp* and *ap* forms.

As a model for the second step, we chose oxime formation under acidic conditions. Under the circumstances, the oximation is known to proceed *via* protonation of the aldehydic oxygen and addition of hydroxylamine to the protonated species,[10] the latter step being rate-determining. The results which are summarized in Table 3 together with others indicate that even *ap*-**1** was smoothly oximated and the relative rate (k_{sp}/k_{ap}) was 3.7. The reactivity of the *ap* form is indeed lower than that of the *sp* but the difference is not so large as is seen in oxidation of the aldehyde (**1**). Thus we may rule out the possibility that the addition step to the carbonyl of **1** is the key for the slow oxidation of *ap*-**1**.

As a model for the last step of oxidation, we chose chromium(VI) oxide oxidation of the corresponding alcohols, because the mechanism of the oxidation is similar with that of the last step in the aldehyde-oxidation.[11] Interestingly the primary alcohol (**3**) gave k_{sp}/k_{ap} 0.67, whereas 9-[2-(α-hydroxybenzyl-1-naphthyl]fluorene (**7**) gave the relative rate of *ca.* 30. Products were the aldehyde (**1**) and a ketone (**8**). Oxidation of 9-[2-(1-hydroxyethyl)-1-naphthyl]fluorene (**10**) gave also a large k_{sp}/k_{ap} value. The results indicate that the secondary alcohols (**7** and **10**) show similar reactivity ratio with the aldehyde (**1**), whereas the primary alcohol (**3**) shows about the same reactivity for the rotamers or even the *ap* form is slightly more reactive than the *sp*. This striking difference for the two types of compounds can be understood if one looks at the molecular models of the *ap* forms (Fig. 1). The models suggest that, for the primary alcohol, a proton to be removed after ligation of the oxygen to chromium is readily available because one of hydrogens in the α-position is exposed without significant hindrance. In contrast, in the secondary alcohol, the hydrogen to be removed as a proton is buried in a pocket made by phenyl (or methyl), naphthyl, and fluorenyl groups. Therefore, should the oxidation occur for the compound, additional energy is required to deform the molecule to make the attack to the proton possible. If the difference in reactivities of

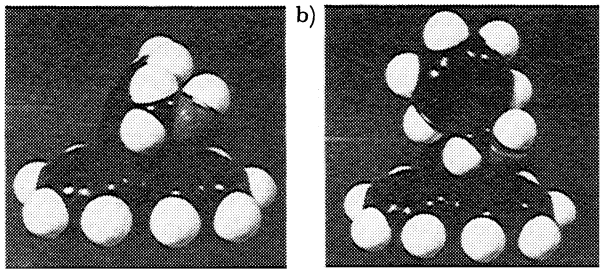


Fig. 1. CPK models of a) *ap*-9-[2-(hydroxymethyl-1-naphthyl)fluorene and b) *ap*-9-[2-(α-hydroxybenzyl)-1-naphthyl]fluorene.

ap-**3** and *sp*-**3** is significant, the cause may be the steric acceleration[12] because a tetrahedral carbon is larger than a trigonal carbon.

The situation of oxidation of aldehydes is close to that of the secondary alcohols, since it passes through a $RCH(OH)_2$ type intermediate. From the above results we conclude that oxidation of the *ap* form of the aldehyde (**1**) is very slow because of the steric effect in the last step relative to the *sp*. The key point of the last step in oxidation is that the transition state is space-demanding because of the concerted nature. Thus it becomes interesting to see whether other space-demanding reactions of the *ap* form are also slow relative to those of the *sp* form in this system.

As an example, we chose dehydration of oximes, since the reaction is known to be of E2 type if the conformation is anti (*Z*).[13] From the *ap* and *sp* aldehydes (**1**), only one form each of the oximes (**5**) was formed. Equilibration of the oxime by heating gave mixtures of the same composition of which components gave the identical NMR spectra with the starting material. This indicates that oximes are either both anti or both syn. There are various methods known for the determination of the stereochemistry of oximes. Of those, the NMR spectroscopic method is considered to be most reliable.[14] However, the chemical shifts in NMR spectroscopy may be affected by the ring current effect and the steric effect of the fluorene ring. Therefore, we prefered to use other methods, if available. Lanthanoid induced shifts (LIS) of syn and anti aldoximes are known.[15] However, attempted measurements of LIS of *sp* and *ap*-**5** failed because line-broadening occurred extensively when even a small amount of a shift reagent was added. In the preparation of aromatic aldoximes, the syn form is preferentially formed if the conditions are basic.[16] However, the syn oxime isomerizes to the anti form if acid is present. We therefore believe that we are dealing with the anti (*Z*) oximes. This assignment of stereochemistry is reasonable on the steric ground and is also consistent with the relative rates of dehydration discussed below.

Anti-oximes are easily dehydrated by acetic anhydride. However, heating was required for dehydration of oximes **5** with acetic anhydride. To avoid isomerization, more efficient dehydrating reagent is required. Dicyclohexylcarbodiimide is known to be an efficient dehydrating reagent.[17] However, to enhance the reactivity, triethylamine and copper ion are used in addition to the carbodiimide. As a result, the reaction

of *ap*-oxime afforded a mixture of various products. 1,1'-Carbonyldiimidazole is also known to be an efficient dehydrating reagent.[18] This reagent indeed dehydrated the oxime easily at room temperature. However, the product was found to be a mixture of *ap*- and *sp*-nitriles. We attribute the results to the basic property of imidazole which is formed by the reaction, although the basicity of imidazole is much lower than triethylamine. Thus it is necessary to carry out a reaction under non-basic conditions to avoid isomerization.

Finally we used thionyl chloride as a dehydrating reagent. It reacted smoothly to afford nitriles (**6**). The relative rate k_{sp}/k_{ap} is large 18 but not as large as that in oxidation of **1**, **7**, or **10**. We wish to attribute the results to the fact that the E2 type elimination takes place from a tetrahedral species in **1**, **7**, and **10**, whereas it occurs from a trigonal carbon in the oxime.

Sodium tetrahydridoborate reduction is claimed to take a four-membered ring transition state, carbonyl oxygen ligating to boron and hydride approaching the carbonyl carbon.[19] Therefore the transition state must be bulky in this reaction. It then is expected that *sp*-**1** will show a large reactivity relative to *ap*-**1**. The reduction proceeded smoothly from the both conformations to produce the primary alcohols (**3**). The relative rate k_{sp}/k_{ap} was 7.6. Although the difference is reduced somewhat from those in oxidation of the aldehyde (**1**) or the secondary alcohols (**7** and **10**) and dehydration of oximes (**5**), it is still significant. Space-demanding structure (transition state in this case) must be responsible to the result.

A Grignard addition reaction to a carbonyl compound is also cited very often that the transition state is a 4-membered ring and thus the reaction is concerted.[20] We have carried out the reaction of phenylmagnesium bromide with the aldehyde (**1**). Both conformations of **1** reacted smoothly to afford 9-[2-(α-hydroxybenzyl)-1-naphthyl]fluorene (**7**). However, the relative rate k_{sp}/k_{ap} was, to our surprise, low 1.8. Addition of methylmagnesium iodide also showed k_{sp}/k_{ap} of 1.7. Mechanism of Grignard addition to carbonyl compounds is complicated. A single-electron transfer process and a nucleophilic addition process are competing.[20] It may not be possible to exactly compare the reactivity of the aldehyde rotamers here, but it is at least clear that, in the reaction of *ap*-**1**, the process does not require much space. Ashby *et al.* depicted one of the Grignard reactions as it has coordination of oxygen to magnesium only.[21] The reaction of *ap*-**1** may be proceeding in this manner.

In conclusion, we wish to point out that, if a reaction passes through a bulky state, the relative rate k_{sp}/k_{ap} becomes very large in this system. Certain S_N2 type reactions of 9-(2-bromomethyl-6-methylphenyl)fluorene were also very slow in *ap* conformation relative to those in the *sp*.[4] Thus it is commonly noticed that the space-demanding reaction is slow in the *ap* of these systems. The technique may even be used for diagnosis whether a space-demanding transition state is really intervening in the reaction. If a reaction is not space-demanding, the k_{sp}/k_{ap} can be very close to unity in the system. Further study on other carbonyl compounds, which give a bulkier transition state, may exhibit even larger differences in reactivities.

Experimental

*9-(2-Formyl-1-naphthyl)fluorene (**1**).* *a)*: To a solution of 1.00 g (3.1 mmol) of *ap*-9-(2-hydroxymethyl-1-naphthyl)-fluorene (**3**)[6] in 30 mL of acetone was added a little excess of the Jones reagent prepared from 2.7 g of chromium(VI) oxide, 4.6 mL of concentrated sulfuric acid, and 8 mL of water. The excessive chromium(VI) oxide was decomposed with methanol or ethanol. The precipitate was filtered off and the filtrate was poured into water. After the usual treatment, the product was chromatographed on silica gel (benzene eluent) to afford 0.98 g *ap*-**1**, mp 127—128.5 °C. Found: C, 89.73; H, 4.73%. Calcd for $C_{24}H_{16}O$: C, 89.97; H, 5.03%. ^{1}H NMR ($CDCl_3$, δ): 6.21 (1H, s), 7.07—8.10 (13H, m), 8.50—8.73 (1H, m), 8.95 (1H, s).

sp-**1**, mp 102.5—104 °C, was similarly prepared in 95% yield. Care was exercised to avoid further oxidation by limiting the amount of the Jones reagent. Found: C, 90.21; H, 4.73%. Calcd for $C_{24}H_{16}O$: C, 89.97; H, 5.03%. ^{1}H NMR ($CDCl_3$, δ): 6.03 (1H, d, J=8.1 Hz), *ca.* 6.70 (1H, s), 6.73—8.13 (13H, m), 10.85 (1H, s).

b): A mixture of 0.17 g (0.44 mmol) of a rotameric mixture of 9-(2-bromethyl-1-naphthyl)fluorene (**2**)[6] and 0.2 g (1.4 mmol) of hexamethylenetramine in 4 mL of chloroform was heated under reflux for 2 h with stirring. The precipitate was collected after cooling and was heated with 30 mL of 50% aqueous acetic acid at 100 °C for 1 h. The mixture was poured into water and extracted with ether. The ethereal extract was washed with aqueous sodium hydrogencarbonate and dried. After evaporation of the solvent, the residue was submitted to chromatography on silica gel but the separation was very tedious. The mixture was obtained as an oil in 78% yield. Pure *ap*-**1** could be obtained after oxidation as described below because the *ap* aldehyde resisted oxidtaion.

sp-*(2-Carboxy-1-naphthyl)fluorene (**4**).* To a solution of 1.00 g of *sp*-**1** in 30 mL of acetone, was added a little excess of the Jones reagent at room temperature. After 30 min, the reaction mixture was poured into water and was extracted with ether. After evaporation of the solvent, the residue was purified by chromatography on silica gel (dichloromethane solvent) to afford 80% *sp*-**4**, mp 228—230 °C. Found; C, 85.78; H, 4.59%. Calcd for $C_{24}H_{16}O_2$: C, 85.69; H, 4.79%. ^{1}H NMR ($CDCl_3$, δ): *ca.* 6.56 (1H, s), 6.62 (1H, d, J=8.0 Hz), 7.73—9.01 (13H, m).

*Oxidation of a Rotameric Mixture of the Aldehyde (**1**).* To a solution of 100 mg of a mixture (*ca.* 1 : 1) of *sp* and *ap* aldehydes (**1**) in 30 mL of acetone, was added the Jones reagent with stirring in small portions. The addition was terminated when the reddish-orange color persisted after 20 min. Methanol was added to destroy the excess of chromium(VI) oxide and the precipitate was removed by filtration. The filtrate was poured into water and the whole was extracted with ether. After washing and drying of the ether layer, the solvent was evaporated. The residue was submitted to chromatography on silica gel (benzene eluent) to give *ca.* 40 mg of *ap*-**1** and *ca.* 50 mg of *sp*-**4**. No *ap*-carboxylic acid was detected.

*9-(2-Carboxy-1-naphthyl)-9-hydroxyfluorene Lactone (**8**).* *a)*: A solution of 30 mg of a mixture of *ap* and *sp*-**1** in 10 mL of pyridine was mixed with 50 mg of chromium(VI) oxide and the mixture was allowed to stand for 10 h at room temperature. The excess of chromium(VI) oxide was decomposed with methanol and the product was taken up in ether. The

ethereal layer was washed with dilute hydrochloric acid and then with water. After evaporation of the solvent, the residue was recrystallized from benzene–hexane, mp 247.5—249 °C. The yield was almost quantitative. Found: C, 86.28; H, 4.12%. Calcd for $C_{24}H_{14}O_2$: C, 86.21; H, 4.12%. ^{1}H NMR ($CDCl_3$, δ): 6.83—8.13 (14H, m). IR (KBr): 1760 cm^{-1}. MS showed a molecular ion peak at *m/e* 334 while $C_{24}H_{14}O_2$ requires that at *m/e* 334.

b): A solution of 40 mg of a mixture of *sp*- and *ap*-**1** in 20 mL of ethanol was mixed with 0.1 mL of a solution made from 0.5 g of potassium hydroxide and 2 mL of water. The mixture was stirred for 1.5 h at room temperature and poured into water. The product was treated in the usual manner to give *ca.* 40 mg of the lactone.

*9-(2-Hydroxyiminomethyl-1-naphthyl)fluorene (**5**).* A solution of 0.150 g (0.47 mmol) of the *sp*-aldehyde (**1**) in 40 mL of ethanol was mixed with a solution of 0.1 g (1.2 mmol) of sodium acetate in 3 mL of water. A solution of 0.045 g (0.64 mmol) of hydroxylamine hydrochloride in 2 mL of water was added to the mixture and the whole was stirred at room temperature for 10 min. The mixture was concentrated *in vacuo* and was poured into water. The organic material was extracted with ether and the product was chromatographed on silica gel (benzene eluent). The *sp*-oxime, mp 170.5—171.5 °C, was obtained in 96% yield. Found: C, 85.96; H, 9.85; N, 4.08%. Calcd for $C_{24}H_{17}NO$: C, 85.94; H, 5.11; N, 4.18%. ^{1}H NMR ($CDCl_3$, δ): 5.89 (1H, s), 6.48 (1H, d, J=7.2 Hz), 6.67—8.00 (13H, m), 9.03 (1H, s). The OH proton was not detected in the spectrum.

The *ap*-oxime, mp 171.5—172.5 °C, was similarly prepared quantitatively. Found: C, 85.68; H, 4.88; N, 4.48%. ^{1}H NMR ($CDCl_3$, δ): 6.12 (1H, s), 6.94 (1H, s), 7.07—8.03 (13H, m), 8.45—8.63 (1H, m). The OH proton was not detected in the spectrum.

*9-[2-(α-Hydroxybenzyl)-1-naphthyl]fluorene (**7**).* A Grignard reagent was prepared from 0.25 g of magnesium, 1.13 mL of bromobenzene, and 10 mL of dry ether. A 1.4 mL portion of the Grignard reagent was added to 0.30 g of *ap*-**1** in 30 mL of ether and the mixture was decomposed after 10 min. After a usual manipulation, the product was chromatographed on silica gel (benzene eluent) to afford 0.36 g of *ap*-**7**, mp 176—177 °C. Found: C, 90.19; H, 5.37%. Calcd for $C_{30}H_{22}O$: C, 90.42; H, 5.56%. ^{1}H NMR ($CDCl_3$, δ): 4.88 (1H, s), 6.25 (1H, s), 6.50—8.00 (18H, m), 8.57 (1H, d, J=9.6 Hz). The OH proton was not detected in the spectrum.

sp-**7**, mp 175—177 °C, was similarly prepared in 97% yield. Found: C, 90.60; H, 5.33%. Calcd for $C_{30}H_{22}O$: C, 90.42; H, 5.56%. ^{1}H NMR ($CDCl_3$, δ): 5.87 (1H, s), 6.63 (1H, s), 6.40 (1H, d, J=9.0 Hz), 6.50—7.97 (18H, m). The OH proton was not detected in the spectrum.

*9-[2-(1-Hydroxyethyl)-1-naphthyl]fluorene (**10**)* was similarly prepared from the aldehyde (**1**) and methylmagnesium iodide almost quantitatively.

ap-**10**, oil. High resolution MS exhibited a molecular ion peak at *m/e* 336.1516, whereas $C_{25}H_{20}O$ requires 336.1514. ^{1}H NMR ($CDCl_3$, δ): 0.70 (3H, d, J=6.0 Hz), 3.82 (1H, q, J=6.0 Hz), 6.12 (1H, s), 7.03—8.03 (13H, m), 8.42—8.65 (1H, m). The OH proton was not detected in the spectrum.

sp-**10**, mp 120—124 °C. Found: C, 89.24; H, 5.88%. Calcd for $C_{25}H_{20}O$: C, 89.25; H, 5.99%. ^{1}H NMR ($CDCl_3$, δ): 1.79 (3H, d, J=6.6 Hz), 5.67 (1H, q, J=6.6 Hz), 6.12 (1H, s), 6.40 (1H, d, J=9.0 Hz), 6.76—8.00 (13H, m). The OH proton was not detected in the spectrum.

*9-(2-Benzoyl-1-naphthyl)fluorene (**9**).* A solution of 0.30 g of *ap*- or *sp*-**7** in 20 mL of acetone was oxidized with the Jones reagent as described in the preparation of the aldehyde (**1**). It took 30—60 min for the oxidation of the *ap*-isomer, whereas the oxidation of *sp*-**7** was over within several minutes.

ap-**9**, mp 123—124 °C. Found: C, 90.61; H, 4.94%. Calcd for $C_{30}H_{20}O$: C, 90.88; H, 5.08%. ^{1}H NMR ($CDCl_3$, δ): 6.08 (1H, s), 6.73—8.10 (18H, m), 8.68 (1H, d, J=9.0 Hz).

sp-**9**, mp 162.5—164 °C. Found: C, 91.10; H, 4.82%. Calcd for $C_{30}H_{20}O$: C, 90.88; H, 5.08%. ^{1}H NMR ($CDCl_3$, δ): 5.44 (1H, s), 6.57 (1H, d, J=9.0 Hz), 6.77—8.13 (18H, m).

*9-(2-Acetyl-1-naphthyl)fluorene (**11**)* was similarly prepared from the alcohol (**10**) by oxidation with chromium(VI) oxide. The *ap* form reacted much more slowly than the *sp* form.

ap-**11**, mp 108—109 °C. Found: C, 89.80; H, 5.21%. Calcd for $C_{25}H_{18}O$: C, 89.79; H, 5.43%. ^{1}H NMR ($CDCl_3$, δ): 1.60 (3H, s), 6.09 (1H, s), 7.07—8.07 (13H, m), 8.67 (1H, d, J=9.0 Hz).

sp-**11**, mp 103—105 °C. Found: C, 89.94; H, 5.23%. Calcd for $C_{25}H_{18}O$: C, 89.79; H, 5.43%. ^{1}H NMR ($CDCl_3$, δ): 2.77 (3H, s), 5.84 (1H, s), 6.56 (1H, d, J=8.4 Hz), 6.73—8.00 (13H, m).

*9-(2-Cyano-1-naphthyl)fluorene (**6**).* To a stirred solution of 0.15 g (0.45 mmol) of *ap*-**5** in 30 mL of dry ether was added 0.5 mL of thionyl chloride and the whole was stirred for 5 h at room temperature. The mixture was poured into water and extracted with ether. The extract was washed, dried, and evaporated. The residue was chromatographed on silica gel (benzene eluent) to afford 0.12 g of *ap*-**6**, mp 150.5—152 °C. Found: C, 90.75; H, 4.62; N, 4.44%. Calcd for $C_{24}H_{15}N$: C, 90.82; H, 4.76; N, 4.41%. ^{1}H NMR ($CDCl_3$, δ): 6.18 (1H, s), 7.07—8.07 (13H, m), 8.58—8.80 (1H, m).

The *sp* form, mp 165.5—167 °C, was prepared similarly in 71% yield. Since the dehydration of *sp*-**5** was much easier than that of the *ap* form, 0.1 mL of thionyl chloride and stirring for 2 h sufficed for the dehydration. Found: C, 91.08; H, 4.46%. Calcd for $C_{24}H_{15}N$: C, 90.82; H, 4.76%. ^{1}H NMR ($CDCl_3$, δ): 6.00 (1H, s), 6.58 (1H, d, J=9.0 Hz), 6.80—8.00 (13H, m).

Determination of Barriers to Rotation. A sample solution was prepared by dissolving 30 mg of the *ap* form of arylfluorenes in 0.4 mL of hexachlorobutadiene and was placed in an NMR sample tube. The tube was immersed in an appropriate boiling-solvent bath, the temperature of which was directly measured by a thermometer. The rate of isomerization was followed by ^{1}H NMR spectroscopy and was treated as a reversible first-order reaction. The rate constants thus obtained were put into the Eyring equation to obtain activation parameters. The following solvents were used for the bath (solvent and approximate boiling point given): acetone (55 °C), methanol (64 °C), 1,1,1-trichloroethane (73 °C), benzene (78 °C), dioxane (96 °C), toluene (104 °C), 1 : 1 chlorobenzene–toluene (114 °C), chlorobenzene (124 °C).

Determination of Spectra. Infrared spectra were recorded on a Hitachi EPI-G spectrophotometer. The wave numbers are not calibrated. The spectra of solid were obtained as KBr disks. The spectra of solution were obtained with a KBr cell of variable length. With solutions of *ca.* 0.2 M in carbon tetrachloride, the cell length was 0.25 mm and, with those of *ca.* 0.01 M, the cell length was 5 mm. ^{1}H NMR spectra were obtained with either a Hitachi R-20B or a Varian EM 390 spectrometer.

Competitive Reactions. Relative reactivities of rotamers were obtained by competitive reactions. Dehydration of oximes did not give clear results with this method. Thus the relative rate was checked by measuring the rates of reactions of individual rotamers. If one assumes that the rate expressions of the reactions of *sp* and *ap* rotamers are the same and that the rate is first order in the substrate, then

$$[\text{Relative reactivity}] = k_{sp}/k_{ap} = \frac{\log[sp]/[sp]_0}{\log[ap]/[ap]_0}$$

Competitive oximation of the aldehyde (**1**) was carried out by treating 30 mg each of *ap* and *sp* forms in 20 mL of ethanol with 0.5 mL of aqueous hydroxylamine hydrochloride, which was made by dissolving 130 mg of the salt in 10 mL of water, and 0.5 mL of aqueous sodium acetate, which was prepared by dissolving 300 mg of the salt in 5 mL of water. After 30 min at room temperature, the mixture was treated as described in the preparation of oximes and the unreacted starting materials were analyzed with the use of ^{1}H NMR spectra. The relative reactivity was obtained as an average of three runs.

Competitive oxidation of rotamers of 9-[2-(α-hydroxybenzyl)-1-naphthyl]fluorene (**7**) was carried out using 20 mg each of *sp*- and *ap*-**7** in 20 mL of acetone and 0.1 mL of the Jones reagent prepared as above. ^{1}H NMR showed the presence of 17.5% unreacted *sp* but at least 95% of the *ap* form was found unreacted.

Competitive oxidation of *ap*- and *sp*-9-[2-(1-hydroxyethyl)-1-naphthyl]fluorene (**10**) was carried out similarly. ^{1}H NMR showed the presence of 25.1% unreacted *sp* form whereas at least 95% of the *ap* form remained unreacted.

Competitive oxidation of 9-(2-hydroxymethyl-1-naphthyl)-fluorene (**5**) was carried out similarly. The relative reactivity is the average of three runs.

Competitive reduction of *sp*- and *ap*-9-(2-formyl-1-naphthyl)-fluorene (**1**) was carried out by treating a solution of 30 mg each of the rotamers in 20 mL of methanol with 1.0 mL of methanolic solution of sodium tetrahydridoborate, which was prepared by dissolving 20 mg of the hydride in 10 mL of methanol. After 10 min at room temperature, the mixture was manipulated in the usual manner and the unreacted materials were analyzed by ^{1}H NMR spectroscopy. The relative reactivity was obtained as an average of three runs.

Competitive Grignard reactions of *sp*- and *ap*-9-(2-formyl-1-naphthyl)fluorene (**1**) were carried out by treating 30 mg each of the aldehyde rotamers in 20 mL of ether with 0.1—0.2 mL of methylmagnesium iodide or phenylmagnesium bromide solution which was prepared as described for the preparation of **7** and **10**. After 10 min, the mixture was decomposed and the unreacted materials were analyzed by ^{1}H NMR spectroscopy. The relative reactivities are the averages of 2—3 runs.

Competitive dehydration of *ap*- and *sp*-9-(2-hydroxyiminomethyl-1-naphthyl)fluorene (**5**) was carried out by treating a solution of 20 mg each of the rotamers in 20 mL of dry ether with 0.1 mL of thionyl chloride at room temperature. After 1 h, the mixture was separated by TLC into oximes and nitriles. The unreacted oximes were analyzed by ^{1}H NMR spectroscopy. This operation gave 86.1% unreacted *ap* and less than 5% unreacted *sp*. This gave k_{sp}/k_{ap} of *ca.* 20.

Relative Reactivity of 9-(2-Hydroxyiminomethyl-1-naphthyl)fluorene (5) toward Dehydration as Obtained by Individual Rate of Dehydration. *ap*-**5** (20 mg) in 20 mL of ether was stirred with 0.1 mL of thionyl chloride at room temperature. The reaction was quenched at appropriate intervals. After 5 h, the conversion ratio was 48.4%. Under the same conditions the conversion ratio of the *sp* form was 82.3% after 40 min. If one assumes that the formation rate of the nitriles is expressed by the product of the concentrations of the reactants and the change in the concentration in thionyl chloride is neglected, the results give k_{sp}/k_{ap} of *c. a.* 16.

References

1) For Part IX, see S. Murata, S. Kanno, Y. Tanabe, M. Nakamura, and M. Ōki, *Bull. Chem. Soc. Jpn.*, **55**, 1522 (1982).

2) A part of the results was reported in a preliminary form: M. Ōki and R. Saito, *Chem. Lett.*, **1981**, 649.

3) M. Nakamura and M. Ōki, *Chem. Lett.*, **1975**, 671.

4) S. Murata, S. Kanno, Y. Tanabe, M. Nakamura, and M. Ōki, *Angew. Chem., Int. Ed. Engl.*, **20**, 606 (1981). See also Ref. 1.

5) S. Angyal, *Org. React.*, **8**, 197 (1954).

6) R. Saito and M. Ōki, *Bull. Chem. Soc. Jpn.*, **55**, 2508 (1982).

7) A. Rieker and H. Kessler, *Tetrahedron Lett.*, **1969**, 1227.

8) Y. Sprinzak, *J. Am. Chem. Soc.*, **80**, 5449 (1958).

9) J. Rocek, "Oxidation of Aldehydes by Transition Metals," in "The Chemistry of the Carbonyl Group," ed by S. Patai, John-Wiley & Sons, New York (1966), pp. 462—478.

10) L. P. Hammett, "Physical Organic Chemistry," McGraw-Hill, New York (1940), p. 333; W. P. Jencks, *J. Am. Chem. Soc.*, **81**, 475 (1959).

11) K. W. Wiberg, "Oxidation in Organic Chemistry," Academic Press, New York (1965), Part A, pp. 69—184.

12) H. C. Brown and R. S. Fletcher, *J. Am. Chem. Soc.*, **71**, 1845 (1949).

13) D.T. Mowry, *Chem. Rev.*, **42**, 189 (1948); T.Mukaiyama, K. Tonooka, and K. Inoue, *J. Org. Chem.*, **26**, 2202 (1961).

14) C. G. McCarty, "syn-anti Isomerisation and Rearrangements," in "The Chemistry of Carbon-Nitrogen Double Bond," ed by S. Patai, John-Wiley & Sons, New York (1970), pp. 363—464.

15) Z. W. Wolkowski, *Tetrahedron Lett.*, **1971**, 825.

16) H. Hjeds, K. P. Hansen, and B. Jerslev, *Acta Chem. Scand.*, **19**, 2166 (1965).

17) E. Vowinkel and J. Bartel, *Chem. Ber.*, **107**, 1221 (1974).

18) H. G. Foley and D. R. Dalton, *J. Chem. Soc., Chem. Commun.*, **1973**, 628.

19) D. C. Wigfield and F. W. Gowland, *Tetrahedron Lett.*, **1979**, 2209 and papers cited therein.

20) E. C. Ashby, J. Laemmle, and H. M. Neuman, *Acc. Chem. Res.*, **7**, 272 (1974); E. C. Ashby, *Pure Appl. Chem.*, **52**, 545 (1980).

21) E. C. Ashby and J. R. Bowers, Jr., *J. Am. Chem. Soc.*, **103**, 2242 (1981).