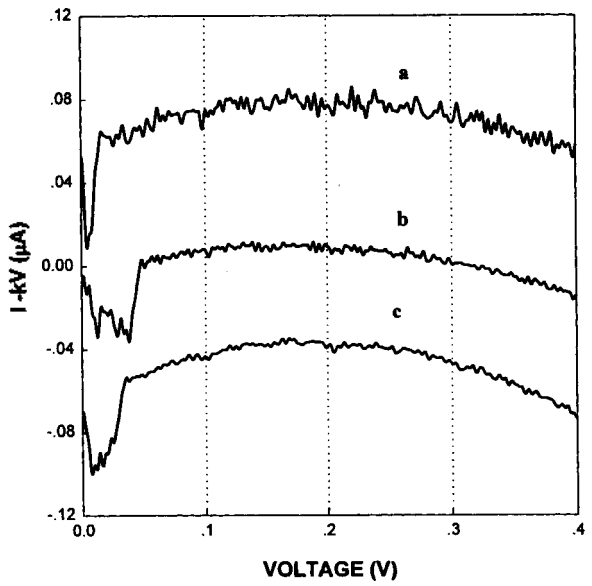

Figure 3. *I-kV vs. V* plots of ZnO(10$\bar{1}$0)-ZnO(10$\bar{1}$0) contact at 77 K. The sample assembly was evacuated at 773 K for 10 min. (a), exposed to 66.7 Pa oxygen for 30 min and evacuated at 573 K (b), and exposed to 66.7 Pa carbon monoxide for 30 min and evacuated at 573 K (c). The mean conductance k was 84.9 $\mu\Omega^{-1}$, 37.6 $\mu\Omega^{-1}$ and 52.2 $\mu\Omega^{-1}$ for a, b and c, respectively.

result could be explained as the oxygen species at 298 K (O_2^-) did not interact with CO at 298 K. For the case of the oxygen species adsorbed at 573 K (O^-), the bias voltage showing the inflections decreased during the interaction with CO at 298 K, and the voltage decreased additionally during the evacuation at 473 K. Since the adsorbed oxygen species at 573 K (O^-) could not be desorbed easily at 473 K, it could be suggested that the oxygen species, O^- reacted with CO at 298 K and a produced anion, probably CO_2^-, was completely desorbed at 473 K from the surface releasing electrons to ZnO. At the interaction at 573 K (Figure 3), it could be expected that O^- reacted with CO and the produced CO_2^- was directly desorbed at the temperature. This result is consistent with the previous investigations which described the reactivity of the oxygen species with CO on ZnO.[8-11]

The shapes of *V-I* characteristics also varied with the temperature at which the measurement was taken. We are expecting that the shape gives the information on the adsorbed states and the surface itself in near future.

Acknowledgment. This work was supported by the Korean Science and Engineering Foundation (961-0305-051-2).

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Stereochemical Course of the Reductive Decyanation of Cyclic α-Phenylnitrile. Dependence on the Added Alcohol and Metal of the Decyanation of 4-*t*-Butyl-1-phenylcyclohexanecarbonitrile

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Received October 8, 1996

Stereochemical course of the reductive decyanation of two stereoisomeric 4-*t*-butyl-1-phenylcyclohexanecarbonitriles **3** and **4** using solvated electron has been studied. While sodium-mediated reactions of both **3** and **4** in the presence of alcohols give the same ratio, 1.5 : 1, in favor of the thermodynamically more stable product **5** over the other one **6**, the ratios obtained from the potassium-mediated process are found to be very sensitive to the kind of H-donors. When reactions are performed without H-donors, **5** is only obtained from the experiments with both stereoisomers irrespective of the metal species.

Introduction

The nitrile function[1] has been widely used in introducing various substituents[2] at its neighboring position in synthetic organic chemistry. The maximum efficiency of the overall sequence involving the nitrile function usually requires the subsequent removal of the nitrile group in a convenient and facile manner. Many different methods[3] have been de-

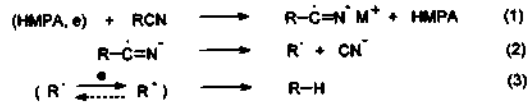


Figure 1.

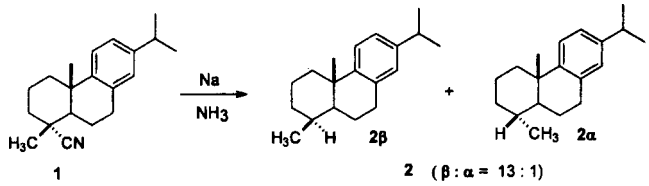


Figure 2.

veloped for the cleavage of the cabon-nitrile bond of the nitrile compounds. The reductive decyanation employing solvated electron in HMPA[4] is the most frequently used procedure among them. A widely accepted mechanism of this process proposed by Cuvigny[4a] involves a multi-step sequence; (1) generation of a radical anion by one electron transer to the nitrile function, (2) removal of cyanide anion from the radical anion to produce a free radical which may abstract hydrogen from a H-donor, (3) one electron transfer into the free radical to generate an anion which may capture a nearby proton (Figure 1).

Arapakos has made pertinent use of this process in the preparation of a novel steroid analog.[5] In his work, action of solvated electron was used for effecting the replacement of the nitrile group by hydrogen as in the conversion of dehydroabietonitrile **1** to dehydroabietene **2** (Figure 2). The particularly notable aspect of this example is the level of stereochemical control achieved in this process (93% retention of configuration). Such a high level of stereoselectivity observed in this reaction is striking. Since it is well known that the inversion barrier around a fully developed radical and carbanion center should be very low and this process involving a significantly flattened radical and a carbanion intermediate is expected to proceed with a low level of stereocontrol. However, the radical and carbanion intermediate produced from a sterically highly biased system as **1** might be less prone to undergo inversion of configuration and the above example could not provide a general description about the stereoselectivity in the decyanation process involving more common systems. We have now examined the reductive decyanation using solvated electron in HMPA of two stereoisomeric 4-*t*-butyl-1-phenylcyclohexanecarbonitriles **3** and **4** that have their nitrile functions at the axial and equitorial positions respectively in the locked 6-membered chair conformation (Figure 3). Comparison of stereochemical responses of the conformationally rigid cyclohexyl stereoisomers series could serve to explain the possible differences in the stereochemical course of axial and equitorial nitriles.

Results and Discussion

Two stereoisomeric substrates were prepared as shown in Scheme 1. The synthetic sequence began with Baeyer-Villiger ring expansion[6] of 4-*t*-butylcyclohexanone **7**. Conversion of the lactone **8** to bromo carboxylic acid **9** was

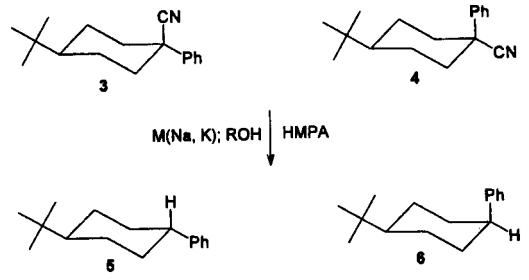
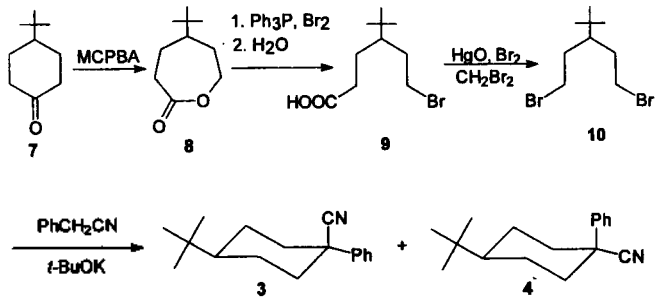


Figure 3.



Scheme 1.

Table 1. Reductive Decyanation of **3** and **4**

Reactant	Metal[a]	H-donor	Yield, %	5 : 6
3	Na	ethanol	89	1.5 : 1
		t-amyl alcohol	90	1.5 : 1
		no alcohol	91	5 (only)
	K	ethanol	58[b]	11.5 : 1
		t-amyl alcohol	90	1.4 : 1
		no alcohol	95	5 (only)
4	Na	ethanol	88	1.5 : 1
		t-amyl alcohol	90	1.5 : 1
		no alcohol	91	5 (only)
	K	ethanol	87	4.0 : 1
		t-amyl alcohol	90	1.5 : 1
		no alcohol	94	5 (only)

[a] No decyanated products were obtained from the condition employing lithium and HMPA. [b] Some of the starting material remained at the end of this experiment.

made following the procedures reported elsewhere.[6-8] Subsequent Hunsdiecker reaction of the bromoacid **9** to the symmetrical dibromide **10**[6] and spiroalkylation of the dibromide **10** with benzyl cyanide with potassium *t*-butoxide[9] gave a mixture of two stereoisomers (**3** : **4**=55 : 45). Two pure stereoisomers were obtained by using flash column chromatography on silica gel. The reductive decyanation of each isomer was carried out under the inert atmosphere using metal in HMPA solvent containing the necessary alcohol. The decyanated products were isolated as mixtures of two stereoisomers (**5** and **6**) that have been already characterized by Garbisch.[10] The ratios of two isomeric products were readily determined based on the analysis of areas of distinct benzyl and *t*-butyl protons in high resolution NMR. The results of series of reactions carried out on **3** and **4** are summerized in Table 1.

Formation of the thermodynamically more stable isomer

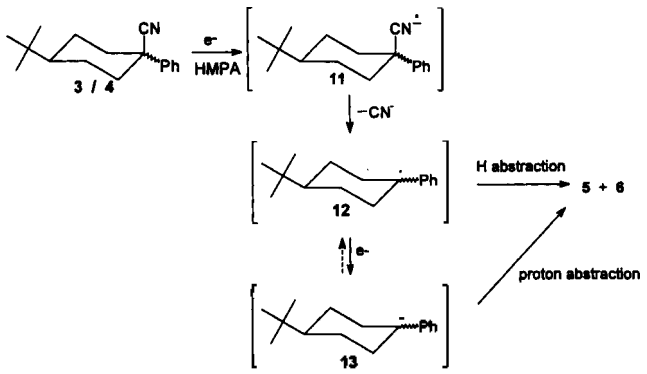


Figure 4.

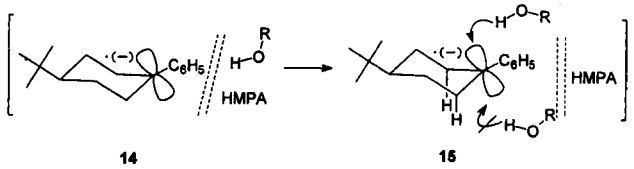


Figure 5.

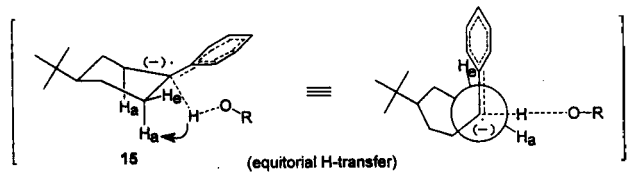


Figure 6.

in excess was invariably observed in the reductive decyanation of both **3** and **4** using solvated electron. The inherent trend of a predominance of **5** over **6** coming from the unfavorable thrust of the phenyl group against the axial position causing a steric interaction of the phenyl group with C-3 and C-5 axial hydrogens might dominate the decyanation reaction of α-phenyl substituted cyclic nitriles in all cases. However, the ratio of the favored product over the minor one strongly depends on the kind of the alcohol and the metal species. When the alcohol is present, two stereoisomers **3/4** invariably give the same ratio of the major product **5** over the minor one **6** in the sodium-mediated condition (*ca* 1.5 : 1) and that ratio does not show any dependence on the kind of the added alcohol, however, the distribution of isomeric products **5/6** derived from the potassium-mediated process is found to be quite sensitive to the H-donors added. When reactions were performed without H-donors, the thermodynamically more stable isomer **5** was only obtained in the experiments of both stereoisomers irrespective of the metal species. The plausible explanation for subtle variations of the isomeric ratios to the reaction conditions would be made by the consideration of the torsional strain arising between the incoming H-donor and the two axial C-H bonds at C-2 and C-6 during the equitorial H-transfer to the planar reaction centers.

The sodium-mediated reaction with H-donors. The torsional effect involved in the H-transfer. The sodium-mediated reductive decyanation of both **3** and **4** in the presence of the alcohols produces the thermodynamically more stable isomer **5** in excess. Following the sequence proposed by Cuvigny[4a] action of solvated electron on the nitrile function in both isomers (**3** and **4**) might produce an effectively planar radical[11] **12** and carbanion[12] intermediate **13** (Figure 4). The favored formation of **5** over **6** comes from the predominant axial H-transfer occurring around these reaction centers (Figure 5). The role of torsional effects[13,15a] involved in the H-transfer to the reaction centers is illustrated by Figure 6. The phenyl group at these significantly sp^2-hybridized centers would be quite eclipsed by the equitorial C-2 and C-6 C-H bonds, causing a torsional strain. Here the axial H-transfer to these reaction centers could relieve the torsional strain somewhat, but the equitorial approach should increase the strain, since the phenyl group must eclipse the equitorial hydrogens at C-2 and C-6 at some stage during the H-transfer process. Accordingly, the equitorial approach should be blocked and the axial H-transfer occurs favorably.

The concept of torsional effects has been widely used to describe the stereoselectivity observed in various processes[14] including an example of the bromination reaction of the 4-substituted cyclohexyl radical.[15] The enhanced ratio, *ca* 1.5 : 1, of the thermodynamically more stable isomer over the minor one in the decyanation process compared to the statistical ratio[15a] obtained from the usual radical process of cyclohexyl radical system without any α-substituent (*ca* 1 : 1) can be explained by the energetic consideration in the unfavorable conversion of **12/13** to **6** where the phenyl group is being thrusted into the axial position during the H-transfer. Instead, in the above radical reaction, a small H is to occupy the axial position. The H-transfer should be controlled by the frequency of the alcoholic molecule to escape from the HMPA medium and not much by the steric bulkiness of the alcohol, resulting the same ratio from both *t*-amyl alcohol and ethanol. Assuming common intermediates **14/15** with the effectively flattened geometry at their reaction centers are involved, the same product ratios are derived from both stereoisomers **3/4** expectedly.

The potassium-mediated reaction with H-donors. The different stereochemical responses of two isomers. Data from the potassium-mediated process show that the degree of the thermodynamically stable product formation can be varied by the kind of H-donors added. In a run when the reaction was performed with *t*-amyl alcohol present, both stereoisomers gave the same ratio of 1. 5 : 1 (the conventional torsional effect). Again the system may have little chance of deviating from the usual mode where common intermediates produced from both stereoisomers operate and two isomers gave the same ratio of stereoselectivity.

However, the stereochemical responses of two isomers derived from the experiments with H-donors of small steric bulkiness like ethanol are quite different: the stereoselectivity ratio of 11.5 : 1 with a high predominance of **5** over **6** from the isomer **3** and a modest value, 4 : 1 from the isomer **4** is obtained. In this condition, a substantive change of the pathways which two isomers may take is probably at play. It is recognized that potassium should generate more reactive reaction centers for the product pairs **16/18** and product-separated pairs **17/19** and the reaction centers will be less

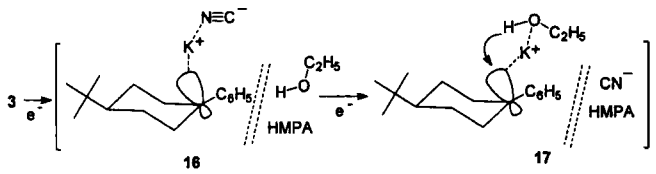


Figure 7.

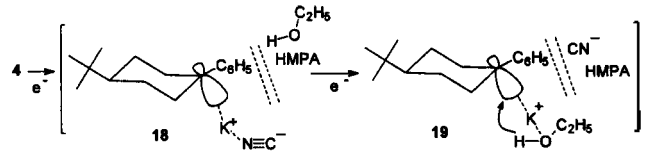


Figure 8.

tightly coordinated to the metal ion. Thus the relatively small ethanol molecule may break into the system quite efficiently before the system proceeds to be fully developed as a free radical **12** and carbanion species **13**. Since the ethanolic molecule will intercept into the space which the nitrile group has occupied, H-delivery will occur axially or equitorially depending on how the ethanol molecule now locates in the rigid chair conformation and affect the ratio of isomeric products.

For **3**, the ethanol molecule will intercept the system axially and H-delivery from the axially located alcohol might occur to the reaction center to produce **5**. The tendency of favoring **5** over **6** now increases strongly due to the conventional torsional effect in the intermolecular mode combined with the above axial H-delivery, resulting in a high ratio of **5** to **6** (11.5 : 1) (Figure 7). When the nitrile function is disposed equitorially as in **4**, the breakage of the ethanol molecule into the system should occur equitorially. And the axial H-delivery (the conventional torsional effect) may slow down overall, giving a modest ratio of **5** to **6** (4 : 1) (Figure 8). These results encompassing the examples of the different stereochemical responses shown by two isomers during the decyanation, may be of use to assess the possibility of controlling this process stereochemically *via* differentiation of stereochemical responses for two isomers.

The reaction in the absence of H-donors. The enhanced torsional effect. The reductive decyanation of **3** and **4** in the absence of alcohols produces exclusively the thermodynamically more stable isomer **5**, irrespective of the metal species present. In this condition, H-transfer that occurs from the powerful H-donors such as the alcohols to quench the reaction in the middle is not possible. Probably the THF molecule added as the co-solvent may serves as H-source in a way that the most reactive α-H's to the oxygen atom of the THF molecule is to deliver to the reaction centers. However, the inherent reluctance of H-delivery from a THF molecule might cause the process retarded more or less so that at the time of H-transfer the C-H bond at the α-position to the oxygen atom is still strong, *i.e.* less bond-broken compared to the O-H bond in case of the reaction with the H-donors. Correspondingly, the effective distance between the reaction center and the H-donor molecule should be much smaller when the THF molecule is a H-donor as shown in **21** than the case of the alcoholic H-

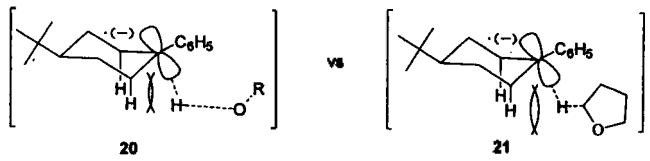


Figure 9.

donor as in **20** (Figure 9). Thus the strength of the torsional effect experienced during H-transfer in the former case would be very high and an extreme predominance of **5** over **6** is observed.

Although many stereochemical aspects of the reductive decyanation have been accounted for in terms of closely related phenomena associated with H-donors and the metallic species around reaction intermediates according to the above discussions so far, the actual state of affairs concerning the nature and involvement of the radical **12** and carbanion intermediate **13** still remains unclear at this moment. Differences of stereochemical courses of the reductive decyanation from the process occurring *via* carbanion intermediates such as the Haller-Bauer reaction of cyclic α-phenyl ketones are obvious : the latter process proceeds with a high level of configurational retention.[7] Recognizing the cabanionic species are readily affected by the counter metal ion and the H-donors present,[12] a carbanion intermediate **13** rather than a radical system **12** might dominate the reductive decyanation using solvated electron.

Experimental Section

Cis- and trans-4-*t*-Butyl-1-phenylcyclohexanenitrile (3 and 4). Potassium *t*-butoxide (1.67 mmol) was made by heating *t*-butanol (2 mL) containing potassium (65 mg) at reflux until most of all metal was consumed. To a potassium *t*-butoxide solution in *t*-butanol was added dropwise a solution of dibromide **10** (239 mg, 0.836 mmol) and benzyl cyanide (98.0 mg, 0.836 mmol) in *t*-butanol (2 mL) during 30 min while heating the reaction mixture. After 5 hours, water was added to the cooled reaction mixture and the product was extracted into ether. The concentrate was subject to flash column chromatography (silica gel, elution with 10% ethylacetate in *n*-hexane) to give 72.9 mg (36.3%) of **3** and 60.6 mg of **4** (30.1%) as a white solid.

For **3**: IR (KBr pellet, cm^{-1}) 3065, 3026, 2963, 2868, 2360, 2341, 2237 (CN), 1452, 1365; ^1H NMR (300 MHz, $CDCl_3$) δ 7.51-7.28 (series of m, 5H), 2.23 (m, 2H), 1.93 (m, 2H), 1.79 (td, *J*=12.9, 3.2Hz, 2H), 1.60 (m, 2H), 1.11 (tt, *J*=11.9, 3.4Hz, 1H), 0.93 (s, 9H); ^{13}C NMR (75 MHz, $CDCl_3$) ppm 141.20, 128.83, 127.78, 125.55, 122.67, 47.08, 44.28, 37.71, 32.42, 27.47, 24.65; MS (EI) m/z (M^+) 241.

For **4**: IR (KBr pellet, cm^{-1}) 3060, 3035, 3015, 2940, 2867, 2360, 2342, 2227 (CN), 1446, 1363; ^1H NMR (300 MHz, $CDCl_3$) δ 7.57-7.29 (series of m, 5H), 2.74 (m, 2H), 2.10 (m, 2H), 1.68 (m, 2H), 1.27-1.00 (series of m, 3H), 0.76 (s, 9H); ^{13}C NMR (75 MHz, $CDCl_3$) ppm 137.08, 128.98, 127.69, 127.19, 125.26, 47.04, 37.84, 35.18, 32.30, 27.21, 22.03; MS (EI) m/z (M^+) 241.

Reductive decyanation of 3 and 4. Solvated electron from the metal was generated by stirring the metal (3

equivalents) in anhydrous HMPA (0.25 mL) containing THF (0.05 mL) at 0 °C until the dark-blue color appeared. The cooled solution of the nitrile compound (*ca* 60 mg, 0.25 mmol) and the necessary alcohol (3 equivalents) in anhydrous THF solution (0.5 mL) was added dropwise to the above HMPA solution of solvated electrons. In runs without H-donors, the cooled solution of the nitrile compound (*ca* 60 mg) in dry THF (0.5 mL) were added dropwise to the HMPA solution of solvated electrons and the same procedure as in experiments with H-donors were followed. The blue color disappeared immediately after addition of the nitrile. After stirring the mixture for 4.5 hours at 0 °C, the reaction was quenched with ammonium chloride solution. The decyanated product was extracted into n-hexane. The concentrate was subject to ^{1}H NMR analysis for determining the ratio of **5** and **6**. The pure **5** and **6** were obtained after purification by MPLC (silica gel, elution with n-hexane) as a colorless oil.

For **5**: ^{1}H NMR (300 MHz, $CDCl_3$) δ 7.35-7.12 (series of m, 5H), 2.43 (m, 1H), 1.88 (m, 4H), 1.47 (m, 2H), 1.15 (m, 3H), 0.88 (s, 9H) ; MS (EI) m/z (M^+) 216.

For **6**: ^{1}H NMR (300 MHz, $CDCl_3$) δ 7.42-7.22 (series of m, 5H), 3.03 (m, 1H), 2.23 (m, 2H), 1.78 (m, 2H), 1.55 (m, 2H), 1.17 (m, 3H), 0.79 (s, 9H); MS (EI) m/z (M^+) 216.

Acknowledgment. This work was supported by the Yeungnam University Research Grants in 1996.

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