Re-examination of the Anodic Dimerization of Enamines, 2-Cyano-2-phenylvinylamines, Using the Austin Model 1 Method

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Dimerization of cation radicals derived from 2-cyano-2-phenylvinylamines (1) to produce diphenylmethane derivatives (Ph–CH(CN)–C_6H_4–C(CN)=CH–NR^2R^3, 2) was re-examined by the AM1 (Austin model 1) method. However, dimerization of cation radicals derived from 1 was forbidden by calculation of the total energies of the dimers. An alternative reaction mechanism for the formation of 2 was proposed. Hydrolysis of cation radical (A) derived from *N*,*N*-dimethyl-2-cyano-2-phenylvinylamine (1a) gives a cyanophenylmethyl radical (F), which attacks at 1a to give a radical (G). Following anodic oxidation of G, deprotonation gives phenyl-[4-(1-cyano-2-dimethylaminovinyl)phenyl]acetonitrile (2a) as the final product.

Key words Austin model 1; *β*-cyanoenamine; radical; radical cation; oxidative dimerization

There are few reports concerning the electrochemical oxidation of enamines.[1—4] However, a unique mechanism for an anodic dimerization of 2-cyano-2-phenylvinylamines, R^1–C_6H_4–C(CN)=CH–NR^2R^3 (**1**), to produce diphenylmethane derivatives R^1–C_6H_4–CH(CN)–C_6H_4–C(CN)=CH–NR^2R^3 (**2**) has been reported.[3] The coupling of the cation radicals derived from **1** occurred between the *β*-carbon and the para-position of the phenyl ring to produce **2**. However, the reason why coupling between the para-position and the para-position of phenyl ring of **1** did not occur was not discussed satisfactorily. Dimerization of cation radicals derived from **1** was re-examined using the AM1 (Austin model 1) method in this paper.

Results and Discussion

Masui *et al.* reported that the controlled potential electrolysis of **1** in acetonitrile at a glassy carbon electrode gives **2**, when R^1 is H. The yields of **2** were 52—76%. When R^1 is not H, 2,3-diphenylsuccinonitrile derivatives (**3**) are formed. A mechanism involving the dimerization of radical cations from **1** was proposed.[2,3]

The radical cation mechanism was examined in more detail using *N*,*N*-dimethyl-2-cyano-2-phenylvinylamine (**1a**) as a typical compound. The molecular orbital of the radical cation derived from **1a** was calculated by the AM1 method. A geometry search was carried out by MM+ using various torsion angles before conducting the MO calculations. The results are summarized in Table 1.

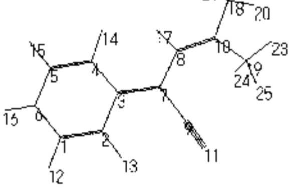
The SOMO (singly occupied molecular orbital) is distributed to the *β* position and the para position on *β*-phenyl ring of A, so the para-*β* coupling is possible as Masui *et al.* predicted. However, the total energy of the para-*β* coupled dimer of A, assumed to be one of the precursors of phenyl-[4-(1-cyano-2-dimethylaminovinyl)phenyl]acetonitrile (**2a**) was calculated as −91208.28 kcal/mol. The total energy of the para-para coupled dimer was estimated as −91213.55 kcal/mol. These values are more than double that of A ($2\times(-45627.03\,\text{kcal/mol})=-91254.06\,\text{kcal/mol}$), and dimerization must reduce the entropy. The difference between the total energy of the para-*β* coupled dimer of A and double that of A, *i.e.* 45.78 kcal/mol, is higher than the resonance energy of benzene *i.e.* 36 kcal/mol. This reaction will be difficult at room temperature. The reaction between A and **1a** was also examined. The total energy of the product that was a cation radical, $(Me)_2N(+)=CH–C(CN)=C_6H_5–C(C_6H_5)(CN)–CH(\cdot)–N(Me)_2$, was −91417.22 kcal/mol, and this value was also higher than the sum of the total energy of A and **1a** (−45795.43 kcal/mol).

Then, we examined the by-products, which are formic acid and 2,3-diphenyl succinonitriles. An alternative mechanism was proposed and is shown in Chart 1.

The reaction of A with a hydroxy anion gives the 1-cyano-2-dimethylamino-2-hydroxy-1-phenylethyl radical (B). The purified acetonitrile contains 5—10 mM water and the bulk solution is alkaline owing to **1**, a basic compound.[5] Therefore, the electrolyte may contain a small amount of hydroxy anions.

The reaction of A with water ($A+2H_2O\rightarrow B+H_3O^+$)

Table 1. Electron Density in Frontier MO of A



Mol. Symbol	Orbital[a] Atom No.	HOMO	LUMO
		Electron density	Electron density
C	1	0.01632	0.00076
C	2	0.13188	0.06151
C	3	0.11313	0.00297
C	4	0.08414	0.08165
C	5	0.03554	0.00084
C	6	0.29663	0.08968
C	7	0.16532	0.17121
C	8	0.03915	0.27075
C	9	0.00058	0.01415
N	11	0.04858	0.14514
N	12	0.02813	0.05364
C	18	0.00139	0.00020
C	19	0.00088	0.00003

a) Only Pz vectors are shown, because other eigenvectors are negligible.

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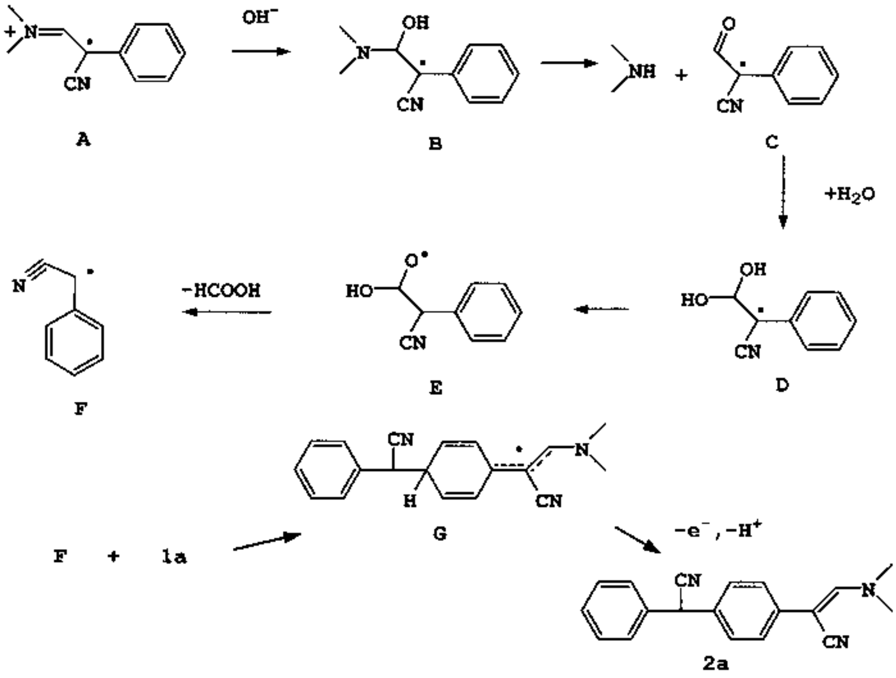
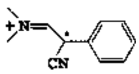


Chart 1

Table 2. Results of Chemical Calculations

Comp.	Total energy (kcal/mol)
Cation radical[a] (A)	−45627.03
Hydroxy anion	−7678.17
1-Cyano-2-dimethylamino-2-hydroxy-1-phenylethyl radical (B)	−53503.78
Dimethylamine	−12904.88
Cyanoformylphenyl radical (C)	−40594.24
1-Cyano-2,2-dihydroxy-1-phenylethyl radical (D)	−48640.47
1-Cyanophenylacetate radical (E)	−48644.39
Cyanophenylmethyl radical (F)	−30260.42
1-Cyano-2-(dimethylamino)-1-(4-(cyanophenylmethyl)cyclohexa-2,5-dienyl)ethyl radical(G)	−76058.94

a)


was also examined. The total energy of the reactants (−61703.47 kcal/mol) was lower than that of the products (−61534.31 kcal/mol) in such a reaction, and this was impossible. C–N bond cleavage of B, accompanying proton migration, gives dimethylamine and the cyanoformylphenylmethyl radical (C). The addition of water to C gives the 1-cyano-2,2-dihydroxy-1-phenylethyl radical (D) and the proton migration in D gives the cyanophenylacetate radical (E). Radical E undergoes breakdown to the cyanophenylmethyl radical (F) and formic acid. The reaction of F with **1a** gives the 1-cyano-2-(dimethylamino)-1-(4-(cyanophenylmethyl)-cyclohexa-2,5-dienyl)ethyl radical (G). Following anodic oxidation of G, deprotonation gives phenyl-[4-(1-cyano-2-dimethylaminovinyl)phenyl]acetonitrile (**2a**) as a final product. The total energy of the reactants and products are summarized in Table 2.

The reaction mechanism shown in Chart 1 is also supported by the fact that the sum of the total energy of the reactants is higher than that of the products.

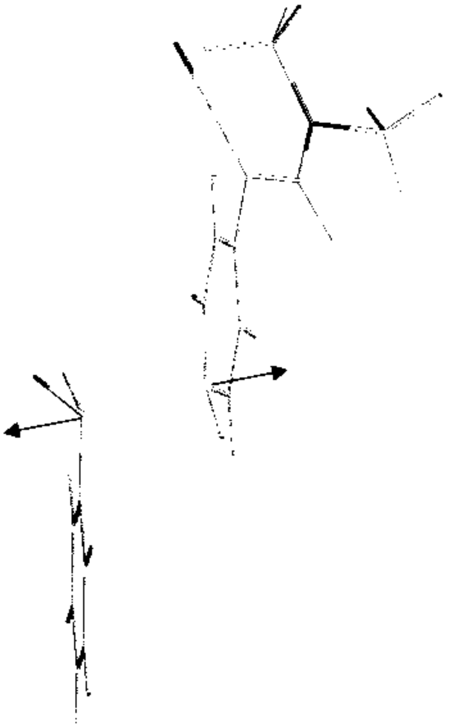


Fig. 1. Transition State of the Reaction between the Cyanophenylmethyl (F) and Cation (A) Radicals

The arrows show the direction of the vibrations.

Dimerization of F may give 2,3-diphenyl succinonitriles. There is also the possibility of a reaction between F and A.

To judge which was more reactive to A, the activation energy, *i.e.*, the energy of the transition structure relative to the reactants, was calculated. The synchronous transit method of transition state searching was applied and, then, the eigenvector follow transition state search was used with a RMS (root-mean-square) gradient termination criterion of 0.01 kcal/(Å mol) to find the structure with maximum energy. Vibrational analysis of the transition states was carried out and it was found that the number of negative eigenvalues was 1. The results are shown in Figs. 1, 2.

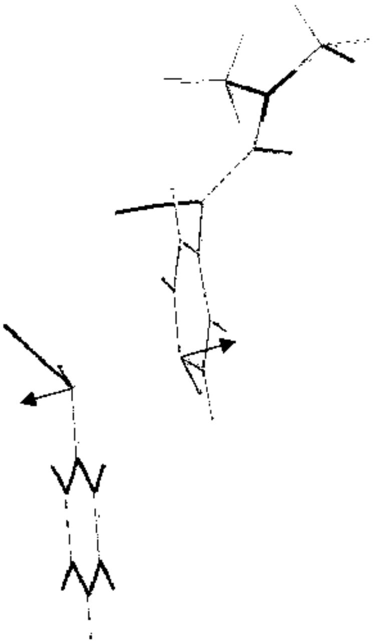


Fig. 2. Transition State of the Reaction between the Cyanophenylmethyl Radical (F) and *N*,*N*-dimethyl-2-cyano-2-phenylvinylamine (**1a**)

The arrows show the direction of the vibrations.

The total energies of the reactants, products, and transition states were calculated and the results are summarized in Table 3.

The activation energy of the reaction of F with **1a** is 9.44 kcal/mol lower than that of the reaction of F with A. This result supports the scheme shown in Chart 1.

Experimental

Apparatus Except for the transition state search, MO calculations were carried out using Dell Dimension XPS D266 and R400 personal computers running HyperChem release 5.01 (Hypercube Inc., U.S.A.).

The transition search was carried out using a Fujitsu FMV-Deskpower SII167 personal computers running WinMOPAC, version 2.0 (Fujitsu Limited, Japan).

Semi-Empirical Calculations AM1 was used. Before single point calculations, geometry optimization was carried out with UHF (spin unrestricted Hartree-Fock) calculations using Polak-Ribiere as the minimization algorithm until the total RMS gradient was reduced to 0.01 kcal/(Å mol).

References

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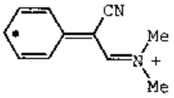
Table 3. Total Energies of Intermediates

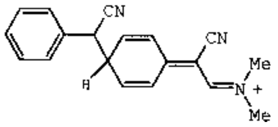
Reactants	(kcal/mol)	Transition state (kcal/mol)	Activation energy[a]	Products (kcal/mol)
Phenylacetonitrile radical	−30260.42			
Cation radical[b]	−45627.03			
Total	−75887.45	−75861.08	26.37 kcal/mol	−75899.17[c]
Phenylacetonitrile radical	−30260.42			
N,*N*-dimethyl-2-cyano-2-phenylvinylamine	−45795.43			
Total	−76055.85	−76038.92	16.93 kcal/mol	−76058.94[d]

[a] The energy of the transition structure relative to reactants.

[b]



[c]



[d]