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ALTERNATIVE MECHANISMS FOR CYANIDE ANION EXCHANGE WITH ACETONITRILE

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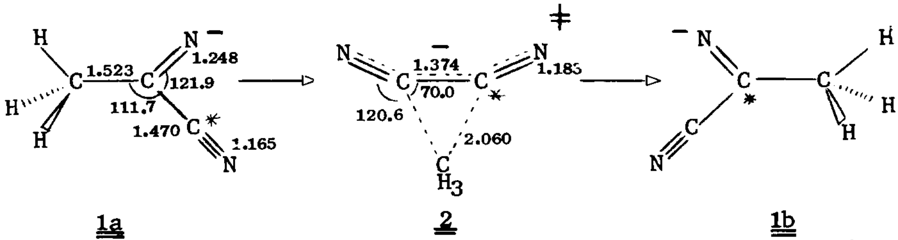
Summary: Mechanisms for the recently observed exchange of cyanide anion in acetonitrile have been investigated by means of semi-empirical MNDO molecular orbital calculations. A prototropic type mechanism via a cyclopropane intermediate is the most likely candidate. The previously proposed concerted migration is indicated to be the least favourable reaction pathway.

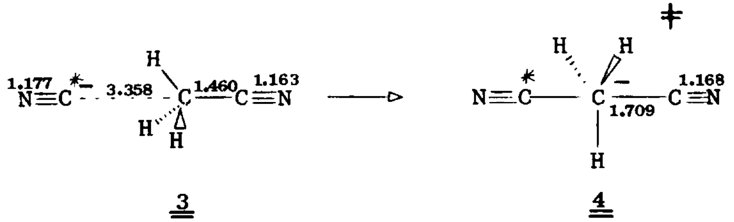
By means of isotopic tracers, Jay, Layton, and Digenis[2] recently demonstrated an exchange between cyanide anion and the nitrile group of acetonitrile (eq 1).

$$CH_3CN + {}^*CN^- \rightleftharpoons CH_3{}^*CN + CN^- \qquad [1]$$

Although cases are known where the reaction of carbon nucleophiles give products resulting from the formal displacement of CN^-,[3] an S_N2 mechanism was considered to be rather unlikely. The preferred reaction pathway was postulated to involve the addition-rearrangement-elimination process depicted in Scheme 1. Thus, the addition product of labelled cyanide anion and acetonitrile, cyanoaldimine anion (1a), was suggested to undergo a benzilic acid-type methyl rearrangement via 2 to give 1b, followed by CN^- loss.

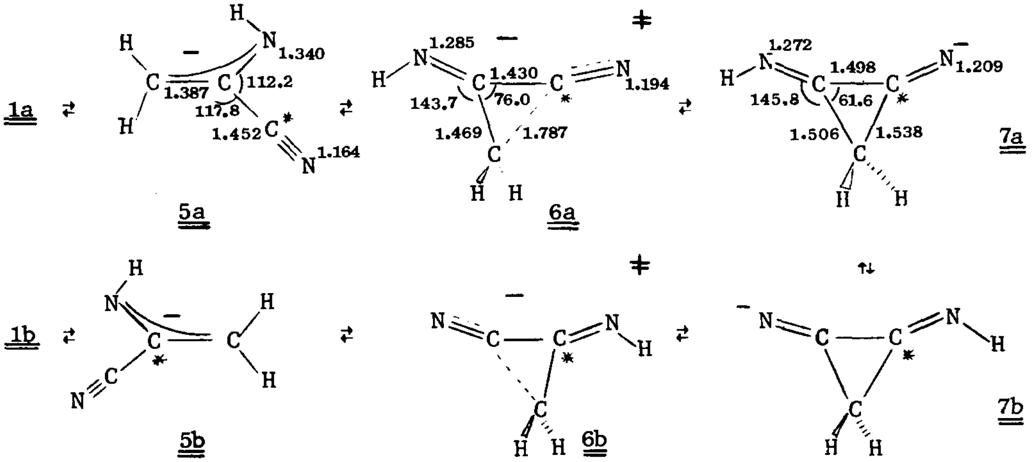


Scheme 1



Scheme 2

It is instructive to examine such mechanistic proposals and their alternatives with readily available and easily applied theoretical methods. The results of our semi-empirical MNDO[4,5] molecular orbital calculations not only suggest that the S_N2 displacement by CN^- (Scheme **2**) may be competitive with the proposed addition-rearrangement-elimination mechanism (Scheme **1**), but also that an even more favourable reaction pathway is likely to be a prototropic type rearrangement (Scheme 3) via the cyclopropanediimine anion intermediate, 7.



Scheme 3

The calculated energy profiles for the three processes are compared in the Figure. The reaction of cyanide anion and acetonitrile to give (1a) is highly exothermic (31 kcal/mol). However, a high barrier of 54 kcal/mol is calculated for the rearrangement of 1a to 1b via the transition state, 2 (Scheme 1). In the S_N2 alternative (Scheme 2), the dipole-stabilised intermediate (3) resulting from back-side approach of CN^- to CH_3CN, is indicated to be 6 kcal/mol more stable than the separated species;[8] the S_N2 barrier via the D_{3h} Walden-type transition state (4) is calculated to lie 27 kcal/mol above (3).[9] The possible transition states, 2 and 4, are thus indicated to have very nearly the same energy (Figure).

Our proposed mechanism (Scheme 3) also involves 1a as the first intermediate. The formation of the acetaldimine anion 5a via a 1,3 hydrogen shift from 1a is calculated to be exothermic by 5.7 kcal/mol. Although such processes are forbidden[10] and have high activation energies[11] in the gas phase, prototropic shifts in solution occur rapidly by stepwise proton transfers.[12] The energy of activation (43.0 kcal/mol from 1a) for the intramolecular cyclization of 5 to the cyclopropane anion intermediate 7 (see Figure) yields an overall reaction barrier almost 15 kcal/mol lower than those for the two alternative mechanisms. Prototropic rearrangement, 7a ⇄ 7b, followed by ring reopening to 1b and subsequent cyanide loss complete the cycle.

Our calculations are not intended to be definitive as they are subject to errors inherent in MNDO and neglect solvation. The most serious error is in the heat of formation of CN^-[13] (calc. 54.9, exp. 16 kcal mol^{-1}). This error distorts the energy profile shown in the Figure. However, as MNDO has been shown to be reliable for a large number of anions larger than CN^-[13] we are more confident that the relative energies of the transition states and intermediates are reliable. The clear energetic preference for the mechanism shown in Scheme 3 at MNDO should, if nothing else, provide a guide for further experiments.

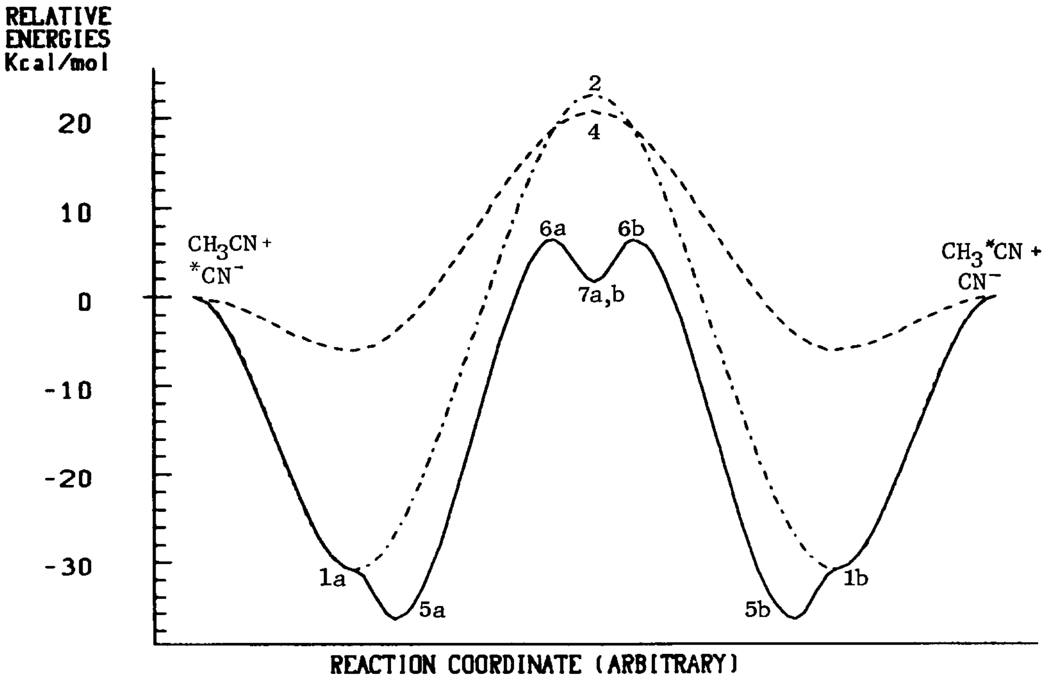


Figure. Comparison of MNDO energy profiles for the three mechanisms: Scheme 1·–·–·, Scheme 2 – – – –, and Scheme 3 ——. The energies relative to CH_3CN + CN^- are given in the Table.

Table. MNDO Heats of Formation and Relative Energies, kcal/mol

Species	Point Group	ΔH_f^o	Energies relative to CH_3 + CN^-	Activation energies[a]
Cyanide anion	$C_{\infty v}$	54.9[b]		
Acetonitrile	C_{3v}	18.9[c]		
Cyanoacetaldimine anion (**1**)	C_s	42.9	-30.9	
Transition state (**2**)	C_1 $(C_s)^d$	96.4	22.6	53.5
Cyanide anion-acetonitrile complex (**3**)	C_{3v}	67.7	-6.1	
S_N2 Transition State (**4**)	D_{3h}	94.5	20.7	26.8
Cyanoacetaldimine anion (**5**)	C_s	37.2	-36.6	
Transition state (**6**)	C_1 $(C_s)^d$	80.2	6.4	43.0
Cyclopropanediimine anion (**7**)	C_s	75.4	1.6	

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[a] The energy differences between the relevant intermediate and the corresponding transition state.

[b] Experimental value, 16 kcal/mol: JANAF Thermochemical Tables, Nat. Stand. Ref. Data Ser., Natl Bur. Stand. (US), 37 (1971).

[c] Experimental value, 20.9 kcal/mol: Natl. Bur. Stand. (US), Techn. Note, 270-3 (1968).

[d] See reference 6.

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References and Notes

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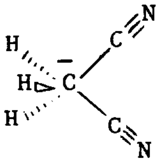
2. M. Jay. W. J. Layton, and G. A. Digenis, *Tetrahedron Lett.*, 2621 (1980).
3. The reactions of aromatic and higher molecular weight aliphatic nitriles with Grignard reagents normally proceed *via* aldimine adducts. However, the first members of the aliphatic series give many anomalous reactions. See: S. I. Ioffe and A. N. Nesmeyanov, *Methods of Elemento-Organic Chemistry*, Vol. 2, p. 356, North Holland, Amsterdam, 1967.
4. M. J. S. Dewar and W. Thiel, *J. Am. Chem. Soc.*, **99**, 4899 (1977); W. Thiel, QCPE, 353, Indiana University.
5. Full geometry optimizations (both with and without symmetry constraints) were carried out. Energies are given in kcal/mol, bond lengths in Ångstroms, and bond angles in degrees. The transition states **2**, **4**, and **6** were characterised rigorously[6] by diagonalising the Hessian (force constant) matrices.[7]
6. Strictly speaking, **2** and **6** were calculated to have C_1 symmetry but the deviations from C_s symmetry were within the error limits inherent in the optimisation.
7. J. N. Murrell and K. J. Laidler, *Trans. Faraday Soc.*, **64**, 371 (1968); M. J. D. Powell, *Comput. J.*, **7**, 303 (1965); D. Poppinger, *Chem. Phys. Lett.*, **35**, 550 (1975); J. W. McIver, *Acc. Chem. Res.*, **7**, 72 (1974).
8. Such adducts involving anions and alkyl halides are well established in the gas phase. The stabilities with respect to the separated species range from 8.6 to 14.4 kcal/mol, R. C. Dougherty, J. Dalton, and J. D. Roberts, *Org. Mass. Spectrometry*, **8**, 77, 81, 85 (1974). Also see W. N. Olmstead and J. I. Brauman, *J. Am. Chem. Soc.*, **99**, 4219 (1977).
9. We also examined the transition state structure (**8**) necessary for front side displacement. The energy was calculated to lie 15 kcal/mol above that of **4**. This is in agreement with other calculations on similar systems. See N. T. Anh and C. Minot, *J. Am. Chem. Soc.*, **102**, 103 (1980) and references cited therein.



[8]

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12. See e.g., J. March, *Advanced Organic Chemistry*, 2nd Ed., p. 533, 962, McGraw Hill, New York, 1977.
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