

hydrate but that both of these are outstripped by the iodine-based catalysts.

The ultimate catalysts for reference for our systems are the zinc-containing enzymes that mediate reactions at phosphorus(V) centers. It remains to be seen whether our systems will improve with the addition of other catalytic groups, mimicking some of the known enzymatic functional groups, or with construction of related di- or polynuclear complexes. In any case, our systems

seem to be good first models of the zinc enzymes that catalyze phosphate ester hydrolysis.

**Registry No.** 1, 41546-66-1; 2, 100946-05-2; 3, 100928-84-5; (ZnHCR)<sub>2</sub>(ClO<sub>4</sub>)<sub>3</sub>(OH), 100946-07-4; (ZnCR)<sub>2</sub>(ClO<sub>4</sub>)<sub>3</sub>(OH), 100946-09-6; DPPA, 838-85-7; PPNPPA, 793-12-4; Zn(ClO<sub>4</sub>)<sub>2</sub>, 13637-61-1; 3,3'-diaminodi-*n*-propylamine, 56-18-8; 2,6-diacetylpyridine, 1129-30-2; 1-iodohexadecane, 40474-98-4; zinc bromide, 7699-45-8; diphenyl *p*-nitrophenyl phosphate, 10359-36-1.

## Facile Heterolysis of a Carbon-Carbon Bond. Arylazodicyanomethanides as the Leaving Group Capable of Generating *tert*-Cumyl Cation and the Hydrogen-Bond-Insusceptible Behavior of the Leaving Group Anions

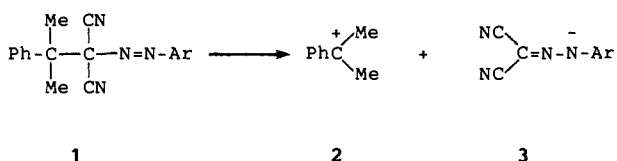
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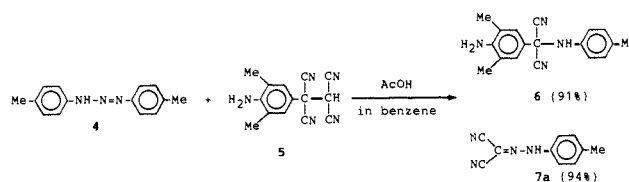
**Abstract:** Decompositions of (*p*-nitrophenyl)azo-*tert*-cumylmalonitrile in polar solvents were found to proceed via the heterolysis of a carbon-carbon bond to generate *tert*-cumyl cation and the conjugate base of (*p*-nitrophenyl)hydrazonomalonitrile. The major products arising from *tert*-cumyl cation are as follows: *tert*-cumyl methyl ether in methanol, the *N*-cumylpyridinium hydrazone in pyridine, and  $\alpha$ -methylstyrene in Me<sub>2</sub>SO and in DMF. The reactions in MeCN and in acetone afford a rearranged product, *N*-(*tert*-cumyl)(*p*-nitrophenyl)hydrazonomalonitrile, which gradually undergoes heterolysis as well. Decompositions of the azo compound and the rearranged product are faster in Me<sub>2</sub>SO than in methanol, being in conflict with the usual trend of solvent-ionizing power. This phenomenon is explained in terms of extensive charge dispersal of the leaving group anion which prevents hydrogen bonding with a protic solvent molecule. It is pointed out that the behavior of the conjugate base of (*p*-nitrophenyl)hydrazonomalonitrile as the leaving group anion is closely connected with the function of FCCP (the *p*-CF<sub>3</sub>O derivative of the hydrazone) as one of the best uncouplers of oxidative phosphorylation in mitochondrial systems.

Studies of the cleavage of carbon-carbon bonds are of primary importance in organic chemistry. One of the fundamental modes of the cleavage is the heterolysis of the bonds to form cationic and anionic species; however, despite the interesting S<sub>N</sub>1 nature of the process, very little is known about this area, the major problem being obviously the lack of efficient leaving groups which terminate in a carbon atom. The data so far reported are limited to those on the ring opening of cyclopropanes,<sup>1</sup> intramolecular rearrangements,<sup>2</sup> and the generation of extremely stable carbocations (cyclopropenium ions<sup>3</sup> and a tropylium ion<sup>4</sup>).

This paper reports the use of arylazodicyanomethanides as the novel leaving group which enables us to generate *tert*-cumyl cation 2, a typical carbocation in solvolysis reactions. The entry into



the study of this heterolysis was made by the observation that the metathesis products, 6 and 7a, were formed from the reaction of 1,3-di-*p*-tolyltriazenes (4) with the TCNE-amine adduct 5<sup>5</sup> in 1:10 (v/v) acetic acid-benzene,<sup>6</sup> which was studied in connection with our previous investigations on the triazene chemistry.<sup>7,8</sup> In the



presence of acetic acid, the triazene 4 behaves as a mild diazonium coupling reagent because of the equilibrium involving the diazonium acetate. The result strongly suggests that the initially formed azo intermediate 8 undergoes carbon-carbon bond heterolysis and the subsequent reaction of the resulting cation 9 with *p*-toluidine leads to the formation of 6. The azo compound 8 could not be isolated. Conceivably, the reason is that both ions 9 and 3a generated from 8 are highly stabilized by delocalization through the electron-donating amino group and through the diazo allylic

(1) (a) Cram, D. J.; Ratajczak, A. *J. Am. Chem. Soc.* **1968**, *90*, 2198. (b) Chmurny, A. B.; Cram, D. J. *J. Am. Chem. Soc.* **1973**, *95*, 4237.  
(2) Wigfield, D. C.; Feiner, S.; Malbacho, G.; Taymaz, K. *Tetrahedron* **1974**, *30*, 2949.

(3) (a) Arnett, E. M.; Troughton, E. B.; McPhail, A. T.; Molter, K. E. *J. Am. Chem. Soc.* **1983**, *105*, 6172. (b) Troughton, E. B.; Molter, K. E.; Arnett, E. M. *J. Am. Chem. Soc.* **1984**, *106*, 6726. (c) Arnett, E. M.; Chawla, B.; Molter, K.; Amarnath, K.; Healy, M. *J. Am. Chem. Soc.* **1985**, *107*, 5288.

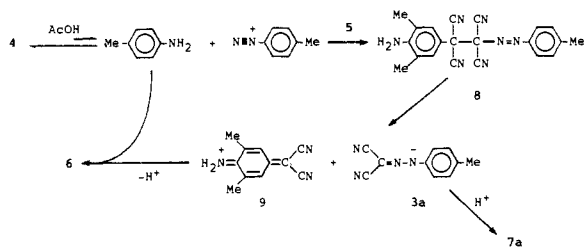
(4) Okamoto, K.; Kitagawa, T.; Takeuchi, K.; Komatsu, K.; Takahashi, K. *J. Chem. Soc., Chem. Commun.* **1985**, 173.

(5) Rappoport, Z.; Shohamy, E. *J. Chem. Soc. B* **1969**, 77.

(6) Mitsuhashi, T. *J. Chem. Soc., Perkin Trans. 2*, in press. See also: Mitsuhashi, T.; Matsumura, C.; Koga, Y. *J. Chem. Soc., Chem. Commun.* **1986**, 257.

(7) Mitsuhashi, T.; Simamura, O. *J. Chem. Soc. B* **1970**, 705.

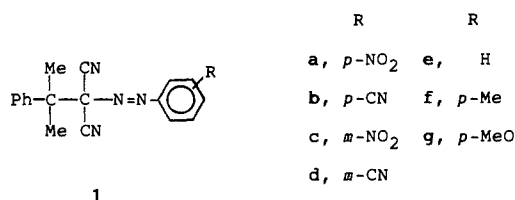
(8) (a) Mitsuhashi, T.; Simamura, O. *Chem. Ind.* **1964**, 578. (b) Mitsuhashi, T.; Osamura, Y.; Simamura, O. *Tetrahedron Lett.* **1965**, 2593.



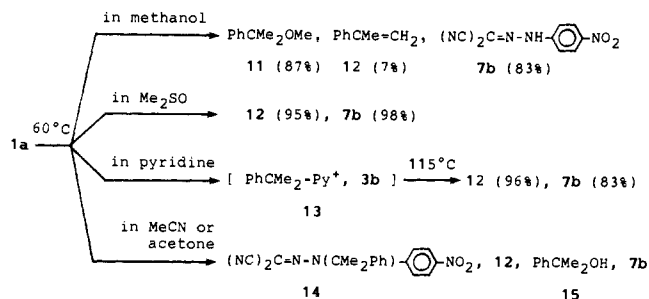
system bearing two electron-withdrawing cyano groups, respectively. The implication is that a careful choice of an alkyl group and an arylazodicyanomethane moiety would give an isolable substrate which may be conducive to the kinetic study of  $S_N1$ -E1 reactions involving the heterolysis of a carbon-carbon bond.

## Results and Discussion

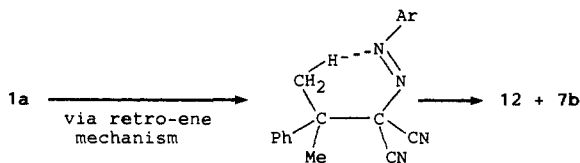
**Decompositions of Arylazo-*tert*-cumylmalononitriles in Polar Solvents. (1) (*p*-Nitrophenyl)azo-*tert*-cumylmalononitrile.** The azo compound **1a**, which was prepared by reaction of *tert*-cumylmalononitrile (**10**)<sup>9</sup> with (*p*-nitrophenyl)diazonium chloride in the presence of sodium acetate in aqueous ethanol at 0 °C, was dissolved in a polar solvent, and the solution was heated at 60 °C for a couple of hours. The substitution product, *tert*-cumyl methyl



ether (**11**), in methanol and the elimination product,  $\alpha$ -methylstyrene (**12**), in Me<sub>2</sub>SO and in dimethylformamide (DMF) were obtained together with the hydrazone **7b**. The possibility of a



retro-ene mechanism for the formation of **12** in Me<sub>2</sub>SO is ruled out, since the intervention of the cation **2** was confirmed by the fact that the addition of a small quantity of methanol-*d*<sub>4</sub> (1.05 M, 9.4 molar equiv) to a solution of **1a** in Me<sub>2</sub>SO-*d*<sub>6</sub> at 31 °C had little effect on the rate ( $k = 30.6 \times 10^{-5} \text{ s}^{-1}$ , cf. footnote c in Table I) but yielded a significant amount of the substitution product **11-d**<sub>3</sub> (39%) at the expense of **12** (57%). The pyridinium

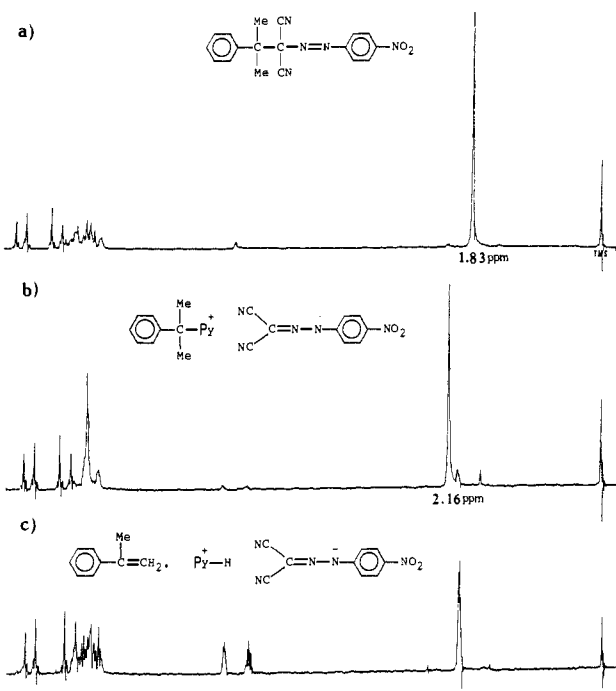


salt **13** was found as the major initial product in pyridine. As shown in Figure 1, the methyl protons of **13** appear 0.33 ppm downfield from those of **1a** in pyridine. The resulting reaction mixture readily yielded **12** when heated at 115 °C for 2 h. The high stability of **13** seems peculiar to the anion **3** because decomposition of *tert*-cumyl chloride (**19**) in pyridine at 60 °C gave only **12** without any detectable accumulation of the possible intermediate pyridinium salt. Decompositions of **1a** in acetonitrile

**Table I. Products and Rates for Decomposition of 1a at 60 °C**

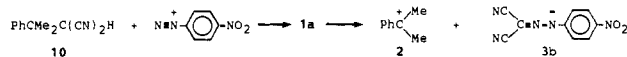
solvent	time, h	product, <sup>a</sup> %	10 <sup>5</sup> <i>k</i> , s <sup>-1</sup>
methanol- <i>d</i> <sub>4</sub>	2	<b>11-d</b> <sub>3</sub> (94), <b>12</b> (4)	97.2 <sup>b</sup>
Me <sub>2</sub> SO- <i>d</i> <sub>6</sub>	2	<b>12</b> (97)	772 <sup>c</sup>
DMF- <i>d</i> <sub>7</sub>	2	<b>12</b> (86), <b>14</b> (3), <b>15</b> (10)	245
pyridine	2	see text	76.8
MeCN- <i>d</i> <sub>3</sub>	3	<b>12</b> (29), <b>14</b> (32), <b>15</b> (35)	57.6
acetone- <i>d</i> <sub>6</sub>	6	<b>12</b> (35), <b>14</b> (29), <b>15</b> (29)	29.6

<sup>a</sup> Products arising from **2**. <sup>b</sup> 10<sup>5</sup>*k*, s<sup>-1</sup> (°C): 30.3 (50), 8.51 (40), 2.67 (31);  $\Delta H^\ddagger = 24.4 \pm 0.4 \text{ kcal/mol}$ ,  $\Delta S^\ddagger = 0.7 \pm 1.4 \text{ eu}$ . <sup>c</sup> 10<sup>5</sup>*k*, s<sup>-1</sup> (°C): 283 (50), 89.8 (40), 32.3 (31);  $\Delta H^\ddagger = 21.5 \pm 0.7 \text{ kcal/mol}$ ,  $\Delta S^\ddagger = -3.8 \pm 2.1 \text{ eu}$ .



**Figure 1.** <sup>1</sup>H NMR spectra of the products from decomposition of (*p*-nitrophenyl)azo-*tert*-cumylmalononitrile in pyridine-*d*<sub>5</sub>: (a) before heating; (b) after heating at 60 °C for 2 h; addition of **7b** at this stage in a separate experiment induced no change in the signals due to the *p*-nitrophenyl group; (c) after heating further at 115 °C for 2 h.

and in acetone gave a rearranged product, *N*-(*tert*-cumyl)(*p*-nitrophenyl)hydrazonomalononitrile (**14**), in addition to **12** and *tert*-cumyl alcohol (**15**).<sup>10</sup> In any case, no products derived from the carbon-nitrogen bond fission were obtained. The results are in line with the  $S_N1$ -E1 mechanism involving carbon-carbon bond heterolysis.



Rates of decomposition of the azo compound **1a** were determined by <sup>1</sup>H NMR spectroscopy (Table I). Good first-order kinetics were observed in all solvents examined. Intriguingly, the rate is increased by a factor of 8 on changing the solvent from methanol to Me<sub>2</sub>SO at 60 °C. Likewise, the reaction is 2.5 times faster in DMF than in methanol. Apparently this trend is in conflict with that expected from the generally accepted solvent-ionizing power.<sup>11</sup> In sharp contrast, *tert*-cumyl chloride (**19**) behaves in accordance with the usual sequence of solvent-ionizing power;<sup>12,13</sup> it is reluctant to decompose in Me<sub>2</sub>SO, while its

(10) **15** would be formed by the reaction of the cation **2** with a very small amount of water present in the solvents owing to the insufficient solvent basicity for the removal of a proton from **2**.

(11) Smith, S. G.; Fainberg, A. H.; Winstein, S. *J. Am. Chem. Soc.* **1961**, *83*, 618.

(12) Okamoto, Y.; Inukai, T.; Brown, H. C. *J. Am. Chem. Soc.* **1958**, *80*, 4976.

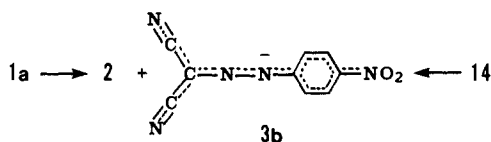
(9) Ohtsuka, Y.; Ohmori, M. *Bull. Chem. Soc. Jpn.* **1967**, *40*, 1734.

Table II. Data for 1b-g at 60 °C

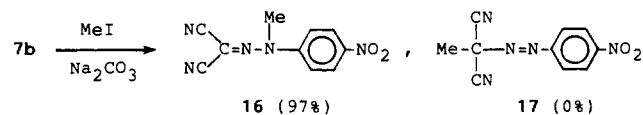
compound	solvent	product, %	$10^5 k, \text{s}^{-1a}$
1b	methanol- <i>d</i> <sub>4</sub>	11- <i>d</i> <sub>3</sub> (85), 12 (5.5), 10 (4)	45.9 (44.1)
	Me <sub>2</sub> SO- <i>d</i> <sub>6</sub>	12 (98), 10 (tr)	276 (276)
1c	methanol- <i>d</i> <sub>4</sub>	11- <i>d</i> <sub>3</sub> (82), 12 (5.5), 10 (6.5)	31.5 (29.5)
	Me <sub>2</sub> SO- <i>d</i> <sub>6</sub>	12 (93), 10 (4.5)	181 (173)
1d	methanol- <i>d</i> <sub>4</sub>	11- <i>d</i> <sub>3</sub> (77), 12 (5.5), 10 (10)	19.2 (17.3)
	Me <sub>2</sub> SO- <i>d</i> <sub>6</sub>	12 (92), 10 (5)	86.9 (82.6)
1e	methanol- <i>d</i> <sub>4</sub>	11- <i>d</i> <sub>3</sub> (13), 10 (70)	6.32
1f	methanol- <i>d</i> <sub>4</sub>	11- <i>d</i> <sub>3</sub> (16), 10 (67)	3.99
1g	methanol- <i>d</i> <sub>4</sub>	11- <i>d</i> <sub>3</sub> (6), 10 (88)	3.03

<sup>a</sup>In parentheses are rates for the C-C bond heterolysis corrected by taking the yield of 10 into account.

methanolysis proceeds very rapidly ( $k = 8.30 \times 10^{-5} \text{ s}^{-1}$  in Me<sub>2</sub>SO-*d*<sub>6</sub> and  $k = 742 \times 10^{-5} \text{ s}^{-1}$  in methanol-*d*<sub>4</sub> at 31 °C). A comparison of these data with those in Table I (see footnotes b and c) reveals that the (*p*-nitrophenyl)azodicyanomethanide moiety departs more easily than chloride in Me<sub>2</sub>SO ( $k_{1a}/k_{19} = 3.9$  in Me<sub>2</sub>SO-*d*<sub>6</sub> at 31 °C), whereas the latter is a much better leaving group in methanol ( $k_{1a}/k_{19} = 0.0036$  in methanol-*d*<sub>4</sub> at 31 °C). An important feature of the present heterolytic reactions is that internal return of the ion pair 2-3b to 1a can be dismissed as the



most unfavorable on kinetic as well as thermodynamic grounds; the nucleophilic reactivity of the carbon terminus of the anion 3b is extremely low as shown by the fact that methylation of the hydrazone 7b with methyl iodide in the presence of sodium carbonate in Me<sub>2</sub>SO affords exclusively 16, i.e., the *N*-methyl de-



rivative of 7b, but not even trace amounts of the corresponding C-methylated azo compound 17,<sup>14</sup> and diazonium coupling to malononitrile immediately leads to the azo-to-hydrazone prototropic rearrangement.<sup>15</sup> In consequence, it is evident that the observed solvent effect on rate directly reflects solvent-ionizing power.

(2) **Substituent Effects on Products and Rates.** The data on the decomposition of other derivatives of the azo compound 1 (1b-g) are summarized in Table II. The formation of *tert*-cumylmalononitrile (10) was detected as a byproduct due to the carbon-nitrogen bond fission, and the yield of 10 increased with decreasing electron-withdrawing power of the substituent in both methanol and Me<sub>2</sub>SO. Compounds without substituents and with electron-donating substituents (1e, 1f, and 1g) gave 10 as the major product. It was proved that 10 was formed via a reversal of diazonium coupling, since 1f afforded the corresponding coupling product in high yield when heated in methanol in the presence of acetylacetone. Such carbon-nitrogen bond heterolysis, however, can be suppressed by introducing an electron-donating substituent into the cumyl group. For instance, the *p*-methoxycumyl derivative of 1e underwent exclusively carbon-carbon bond heterolysis in methanol.<sup>16</sup>

Owing to the formation of 10, the reliable data on the rate of carbon-carbon bond heterolysis are limited to only those for the substrates bearing an electron-withdrawing group (1a-d). It is reasonably expected that the more the charge is developed in the

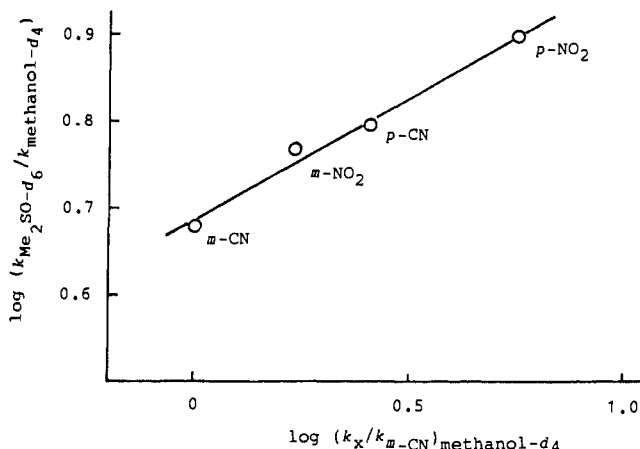


Figure 2. Correlation between substituent and solvent effects on the carbon-carbon bond heterolysis of arylazo-*tert*-cumylmalononitriles.

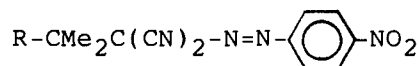
transition state, the more the sensitivity to solvent-ionizing power would be enhanced. A combination of solvent and substituent effects provides such a relationship (Tables I and II). The rates in both Me<sub>2</sub>SO and methanol increase in the order 1d (*m*-CN) < 1c (*m*-NO<sub>2</sub>) < 1b (*p*-CN) < 1a (*p*-NO<sub>2</sub>), suggesting that the charge development is in that order. The following linear correlation between the rates in these two solvents was obtained with the above four substituents ( $R = 0.999$ ),

$$\log(k_{1x})_{\text{Me}_2\text{SO}} = 1.33 \log(k_{1x})_{\text{methanol}} + 1.90$$

It is seen that the quantity  $\log k_{\text{Me}_2\text{SO}}/k_{\text{methanol}}$ , a measure of the sensitivity to a change in solvent-ionizing power, tends to increase in the above rate order (Figure 2).

The rates are only roughly correlated with the Hammett  $\rho$  values ( $\rho = 3.0$  with  $R = 0.88$  in methanol-*d*<sub>4</sub>;  $\rho = 3.9$  with  $R = 0.89$  in Me<sub>2</sub>SO-*d*<sub>6</sub>), because the observed rates for 1c (*m*-NO<sub>2</sub>) are less than those expected by the  $\sigma$  value. An extra-resonance term may be required to obtain a better correlation, though its contribution seems slight.

In order to assess the scope and limitations of the present carbon-carbon bond heterolysis, reactions of the azo compounds 18a-b were examined. 18a (cyclopropyl instead of phenyl in 1a)



18a, R = cyclopropyl

18b, R = Me

gave the corresponding ether (nearly quantitatively) in methanol and 2-cyclopropylpropene (84%) in Me<sub>2</sub>SO, the first-order rate constants at 60 °C being  $70.0 \times 10^{-5} \text{ s}^{-1}$  in methanol-*d*<sub>4</sub> and  $466 \times 10^{-5} \text{ s}^{-1}$  in Me<sub>2</sub>SO-*d*<sub>6</sub>. In the case of 18b (methyl instead of phenyl in 1a), heating at 60 °C in methanol-*d*<sub>4</sub> for 24 h, however, resulted in the decomposition of a half amount of the substrate due to carbon-nitrogen bond fission to give *tert*-butylmalononitrile almost exclusively. Under similar conditions in Me<sub>2</sub>SO-*d*<sub>6</sub>, 20% of 18b disappeared and *tert*-butylmalononitrile was produced in 75% yield based on the decomposed substrate, but no evidence for the carbon-carbon bond heterolysis was obtained. Arylazodicyanomethanides, therefore, may serve as the effective leaving group when the resulting carbocations are not far less stable than *tert*-cumyl cation 2.

**Classification of Polar Unimolecular Reactions.** It is well-known that S<sub>N</sub>1-E1 reactions of uncharged substrates are faster in protic solvents than in dipolar aprotic solvents because of the stabilization of the leaving group anion through hydrogen bonding.<sup>17</sup> However, as has been mentioned above, conflicting results were obtained

(13) Uchida, T.; Marui, S.; Miyagi, Y.; Maruyama, K. *Bull. Chem. Soc. Jpn.* 1974, 47, 1549.

(14) Kerber, R.; Nuyken, O. *Makromol. Chem.* 1973, 164, 200.

(15) Freeman, F. *Synthesis* 1981, 948.

(16) Mitsuhashi, T. *J. Am. Chem. Soc.*, following paper in this issue.

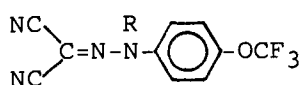
(17) Reichardt, C. *Solvent Effects in Organic Chemistry*; Verlag Chemie: Weinheim, 1979; pp 144-147.

**Table III.** Kinetic Data on  $S_N1$ -E1 Reactions Involving the Heterolysis of Carbon-Heteroatom Bonds

solvent	$10^5 k, s^{-1}$			
	14 (60 °C)	19 (50 °C)	20 (120 °C)	21 (75 °C) <sup>a</sup>
methanol- <i>d</i> <sub>4</sub>	2.53 <sup>b</sup>	6410 <sup>d,e</sup>	1360 <sup>d,g</sup>	130 (166) 133
Me <sub>2</sub> SO- <i>d</i> <sub>6</sub>	8.66 <sup>c</sup>	43.2 <sup>d,f</sup>	43.7 <sup>d,h</sup>	17.2 (18.2)
DMF- <i>d</i> <sub>7</sub>	5.11	3.72 <sup>d,f</sup>	8.71 <sup>d,h</sup>	5.57 (4.96)
pyridine	2.94	0.512	1.05	2.36 (2.14)
MeCN- <i>d</i> <sub>3</sub>	2.04	6.40 <sup>d,f</sup>	6.92 <sup>d,h</sup>	6.65 (6.01)
acetone- <i>d</i> <sub>6</sub>	1.36	0.166 <sup>f</sup>	0.603 <sup>d,h</sup>	0.94 (0.86)

<sup>a</sup>In parentheses are rates measured in undeuterated solvents (ref 11). <sup>b</sup> $10^5 k, s^{-1}$  (°C): 7.93 (70), 24.8 (80), 73.0 (90);  $\Delta H^\ddagger = 26.3 \pm 0.8$  kcal/mol,  $\Delta S^\ddagger = -0.9 \pm 2.3$  eu. <sup>c</sup> $10^5 k, s^{-1}$  (°C): 27.5 (70), 81.9 (80), 230 (90);  $\Delta H^\ddagger = 25.6 \pm 0.1$  kcal/mol,  $\Delta S^\ddagger = -0.5 \pm 0.1$  eu. <sup>d</sup>Undeuterated solvents. <sup>e-f</sup>Calculated from data at other temperatures: *e*, ref 12; *f*, ref 13; *g*, ref 22. <sup>h</sup>Ref 23. <sup>i</sup>Including pyridine in amounts equimolar with 19.

from the present system. In this regard, it was found that the *N*-cumyl-substituted hydrazone 14, when heated in polar solvents for long periods, underwent carbon-nitrogen bond heterolysis to afford substitution and elimination products together with the hydrazone 7b almost quantitatively. While decomposition of 14 proceeds very slowly in the rate ratio  $k_{14}:k_{1a}$  (at 60 °C) ranging from 1:20 to 1:90 depending on the solvent used, its behavior toward differential solvation closely resembles that of decomposition of 1a, indicating that the unprecedented solvent effect has originated from the nature of the leaving group anion 3b but not from that of the bond cleaved (Table III). This finding is particularly important, not only because it ensures a better understanding of solvent-ionizing power, but because from a bioenergetic point of view it is closely associated with the function of the hydrazone 7c (FCCP) as one of the best uncouplers of oxidative phosphorylation in mitochondrial systems.<sup>18</sup> The charge dispersal of the anion 3b is spread over the whole molecule, and furthermore the presence of electron-withdrawing groups lowers base strength of the nitrogen atom. In light of these characteristics, one might imagine the anion to be relatively weakly solvated in protic solvents. Nevertheless, the actual retarding effect of solvent transfer from Me<sub>2</sub>SO to methanol observed in the reactions leading to the anion 3b surpasses our expectations and furnishes evidence supporting the Mitchell postulate on the role of uncouplers,<sup>19</sup> which states that the anionic form of an uncoupler (e.g., 3c or a 3c-7c pair<sup>20</sup>) is lipophilic because of extensive charge delocalization and,



7c, R = H (FCCP)

3c, R = -

in cooperation with 7c, acts as an ionophore carrying protons across the mitochondrial bilayer membrane to dissipate a proton gradient which is generated by respiration and, according to the chemiosmotic theory, is regarded as the driving force for conversion of ADP to ATP.

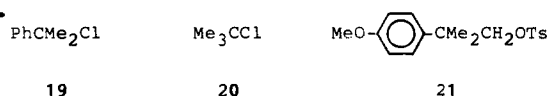
The quantity  $P_s = RT \ln k_{Me_2SO}/k_{methanol}$  (kcal/mol) may serve as a measure of the relative importance of ionizing power between dipolar aprotic and protic solvents in polar unimolecular reac-

**Table IV.** Values of  $P_s$  for  $S_N1$ -E1 Reactions

substrate	$P_s$ , kcal/mol	substrate	$P_s$ , kcal/mol
1a	1.4 (60 °C)	19	-2.7 (31 °C)
1b	1.2 (60 °C)		-2.8 (25 °C) <sup>a,b</sup>
1c	1.2 (60 °C)	20	-2.7 (120 °C) <sup>a,c</sup>
1d	1.0 (60 °C)		
14	0.8 (60 °C)	21	-1.4 (75 °C)
18a	1.3 (60 °C)		-1.5 (75 °C) <sup>a,d</sup>

<sup>a</sup>In undeuterated solvents. <sup>b</sup>References 12 and 13. <sup>c</sup>References 22 and 23. <sup>d</sup>Reference 11.

tions.<sup>21</sup> As listed in Table IV, decompositions of the azo compounds, 1a-d and 18a, and the hydrazone 14 exhibit the positive  $P_s$  values, whereas the values for those of *tert*-cumyl chloride (19),<sup>12,13</sup> *tert*-butyl chloride (20),<sup>22,23</sup> and *p*-methoxyneophyl tosylate (21)<sup>11</sup> are negative.



The polar unimolecular reactions may be classified into two types depending on the sign of  $P_s$  values; one is "hydrogen-bond-susceptible" in which a growing negative charge is stabilized through hydrogen bonding with protic solvents and shows a negative  $P_s$  value, and the other is "hydrogen-bond-insusceptible" which lacks the ability to strengthen hydrogen bonding with protic solvents during charge separation, giving a positive  $P_s$  value. An acceleration due to hydrogen bonding is therefore absent or meager in the latter reactions. However, protic solvents can naturally be similar to dipolar aprotic solvents in the modes of other solvent-solute interactions. In fact, methanol exerts ionizing power approximately as much as pyridine in the decompositions of the azo compound 1a and the hydrazone 14, even though the effect of hydrogen bonding is depressed. Although a number of highly delocalized anions as potent as the hydrazone anions 3 may be envisioned, the quickest way to attain hydrogen-bond-insusceptible reactions would be to generate the conjugate base of efficient uncouplers<sup>18b</sup> or their analogues via the  $S_N1$ -E1 mechanism.

Now there are three examples of hydrogen-bond-susceptible reactions and two of hydrogen-bond-insusceptible reactions available for a comparison of the effects of six representative polar solvents on rate (Tables I and III). The decomposition of the tosylate 21 is taken as the reference reaction. The validity of the deuterated solvents for quantitative treatment has been confirmed by a comparison of the rates for the tosylate 21 between labeled and unlabeled solvents. The rate in methanol shows an appreciable discrepancy ( $k_D/k_H = 0.83$ ), which is yet slight enough to examine the solvent effects for the present purpose (Table III). Figure 3 shows plots of a change in free energy of activation transferred from a solvent to methanol vs.  $W_{ion}$  which is expressed as  $W_{ion} = RT \ln k_{ion}/k_{ion,methanol}$  (kcal/mol),<sup>24</sup> where  $k_{ion}$  is the rate of decomposition of the tosylate 21.<sup>11</sup>

A common feature of the plots is that the points for the following four aprotic solvents define a straight line with an increase in the order acetone < pyridine < DMF < Me<sub>2</sub>SO (termed the APFS line). With the chlorides 19 and 20, the plots including all data points are approximately linear. On the other hand, with the azo compound 1a and the hydrazone 14, the points for methanol exhibit dramatic downward shifts from the APFS line. A similar trend is seen with the MeCN points as well. Presumably, such rate depression in MeCN may be attributed to the electrophilic property of MeCN which allows charge transfer from leaving group anions such as chloride and tosylate ions to the

(18) (a) Heytler, P. G.; Prichard, W. W. *Biochem. Biophys. Res. Commun.* **1962**, *7*, 272. (b) Liberman, E. A.; Topaly, V. P.; Tsolina, L. M.; Jasaitis, A. A.; Skulachev, V. P. *Nature (London)* **1969**, *222*, 1076. (c) Hinkle, P. C.; McCarty, R. E. *Sci. Am.* **1978**, *238*, 104. (d) Nicholls, D. G. *Bioenergetics: An Introduction to the Chemiosmotic Theory*; Academic: New York, 1982. (e) (*m*-Chlorophenyl)hydrazone malononitrile (CCCCP) is also referred to as an efficient uncoupler.

(19) (a) Mitchell, P. *Biochem. J.* **1961**, *81*, 24p. (b) Mitchell, P. *Biochem. Soc. Trans.* **1976**, *4*, 399. (c) Greville, G. D. *Curr. Top. Bioenerg.* **1969**, *3*, 55.

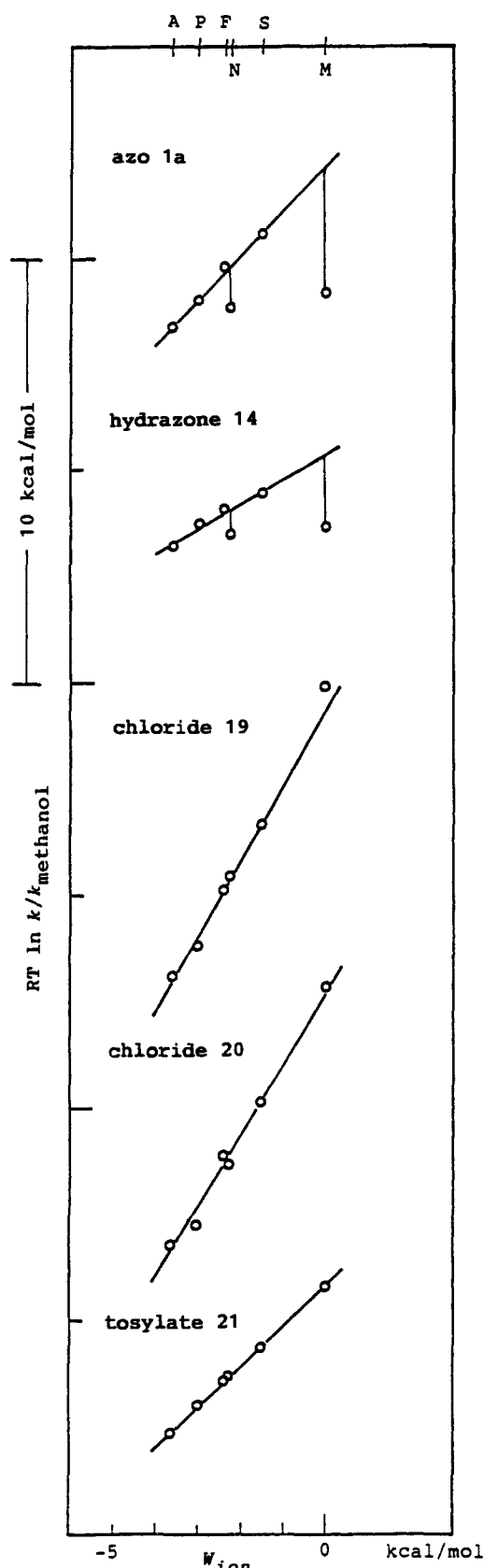
(20) Finkelstein, A. *Biochim. Biophys. Acta* **1970**, *205*, 1.

(21) Ionizing power of dimethyl sulfoxide relative to that of methanol.

(22) Biordi, J.; Moelwyn-Hughes, E. A. *J. Chem. Soc.* **1962**, 4291.

(23) Abraham, M. H.; Abraham, R. J. *J. Chem. Soc., Perkin Trans. 2* **1974**, *47* and references cited therein.

(24) Methanol has generally been used as the reference solvent for the differential solvation between dipolar aprotic and protic solvents (see ref 25). The term  $W_{ion}$  was adopted on Prof. Paul D. Bartlett's suggestion: Bartlett, P. D. *J. Am. Chem. Soc.* **1972**, *94*, 2165.



**Figure 3.** Plots of  $-\Delta\Delta G^*$  vs.  $W_{ion}$  and the APFS line. Solvents: A = acetone; P = pyridine; F = DMF; N = MeCN; S = Me<sub>2</sub>SO; M = methanol. **1a**, 60 °C, slope = 1.04 ( $R = 0.997$ , the correlation coefficient of the APFS line); **14**, 60 °C, slope = 0.57 ( $R = 0.985$ ); **19**, 50 °C, slope = 1.73 ( $R = 0.995$ ); **20**, 120 °C, slope = 1.68 ( $R = 0.981$ ); **21**, 75 °C, slope = 0.95 ( $R = 0.999$ , in deuterated solvents except pyridine).

sterically less-hindered cyano carbon and not from the highly dispersed hydrazone anion **3b**. Considering much greater dispersal of the negative charge during the reactions of **1a** and **14**, the resulting plots are expected to reflect mainly the difference in cation solvation through the specific orientation of solvent molecules around the positively charged center and suggest that such solvation is the most important factor affecting the slope of the APFS line in all the S<sub>N</sub>1-E1 reactions.<sup>25</sup> The importance of cation solvation besides electrostatic interaction has been pointed out by Arnett and his co-workers<sup>3b</sup> who observed enhanced dissociation in the reversible carbon-carbon bond heterolysis of arylcyclopropenylmalononitriles in Me<sub>2</sub>SO. It has been reported that the solvolysis of *tert*-butyl chloride proceeds via a "limiting" mechanism.<sup>26</sup> The fact that the APFS line holds for all the heterolytic reactions including decomposition of *tert*-butyl chloride affords evidence that they are in a similar mechanistic situation and the mode of cation solvation differs from S<sub>N</sub>2-like participation by a solvent molecule.<sup>27</sup>

Although a large number of solvent polarity scales have been proposed, most of them, e.g., Y (Y'), E<sub>T</sub>, Z, etc., embrace all the factors especially including the effect of solvation due to hydrogen bonding as much as  $W_{ion}$  ( $\log k_{ion}$ ). Recently, these scales have been explained by dual-parameter treatments; e.g., AN and DN;<sup>28</sup>  $\alpha$  and  $\pi^*$  (and  $\beta$ );<sup>29</sup>  $A$  and  $B$ ,<sup>30</sup> in which AN,  $\alpha$ , and  $A$  are scales of anion solvation mainly through hydrogen bonding. It is noteworthy that the plots for the hydrogen-bond-insusceptible reactions are analogous to those for the solvent polarity scales DN,  $\pi^*$ ,  $\beta$ , and  $B$  in that both the methanol and MeCN points deviate downward from the line composed of the points for acetone, DMF, and Me<sub>2</sub>SO, while the pyridine points of these scales tend to deviate upward (Figure 4). These scales are supposed to be free from specific electrophilic solvation. At issue is whether  $\pi^*$  is a measure of general solvent power exerted on the whole body of a dipolar solute or mostly a manifestation of basic or nucleophilic properties of solvents, as represented by DN,  $\beta$ , and  $B$ .<sup>29b,30</sup> The fact that the observed values of rates and scales for pyridine are larger than those for acetone, whereas the dielectric constant and dipole moment of pyridine ( $\epsilon$  12.3,  $\mu$  2.2 D) are smaller than those of acetone ( $\epsilon$  20.7,  $\mu$  2.9 D), is incompatible with that expected from general solvent power which should be correlated with  $\epsilon$  and  $\mu$  and may be qualified as evidence for contributions of solvent basicity or nucleophilicity to solvation of dipolar solutes. The differential solvation among polar solvents would be influenced to a great extent by specific solvent-solute interactions which are susceptible to both electronic and steric effects, although the necessity of general solvent power should be emphasized in understanding the differences in solvation especially between less polar and polar solvents. It appears by no means easy to account for the solvent effects on the hydrogen-bond-insusceptible reactions in favor of any treatment that excludes a measure of the specific ability to stabilize cationic species.

### Conclusion

(*p*-Nitrophenyl)azo-*tert*-cumylmalononitrile obtained as one of stable arylazomalononitriles was found to undergo carbon-

(25) It is conceivable that solvation of the leaving group anion **3** due to dispersion forces in polarizable solvents such as Me<sub>2</sub>SO and DMF is more important than that in other solvents, so that relatively small contributions of anion solvation to the slope of the APFS line are properly admissible: Parker, A. J. *Chem. Rev.* **1969**, *69*, 1. See also ref 17, pp 155-159.

(26) (a) Winstein, S.; Grunwald, E.; Jones, H. W. *J. Am. Chem. Soc.* **1951**, *73*, 2700. (b) Raber, D. J.; Bingham, R. C.; Harris, J. M.; Fry, J. L.; Schleyer, P. v. R. *J. Am. Chem. Soc.* **1970**, *92*, 5977.

(27) Although the pyridinium salt **13** has actually been detected as the major product from both **1a** and **14**, no anomalous rate enhancement due to S<sub>N</sub>2-like backside attack by pyridine has been observed (see also ref 16).

(28) (a) Gutmann, V. *The Donor Acceptor Approach to Molecular Interactions*; Plenum: New York, 1978. (b) Parker, A. J.; Mayer, U.; Schmid, R.; Gutmann, V. *J. Org. Chem.* **1978**, *43*, 1843.

(29) (a) Kamlet, M. J.; Abboud, J. L. M.; Taft, R. W. *Prog. Phys. Org. Chem.* **1981**, *13*, 485. (b) Taft, R. W.; Abboud, J. L. M.; Kamlet, M. J. *J. Org. Chem.* **1984**, *49*, 2001.

(30) (a) Swain, C. G.; Swain, M. S.; Powell, A. L.; Alunni, S. *J. Am. Chem. Soc.* **1983**, *105*, 502. (b) Swain, C. G. *J. Org. Chem.* **1984**, *49*, 2005.

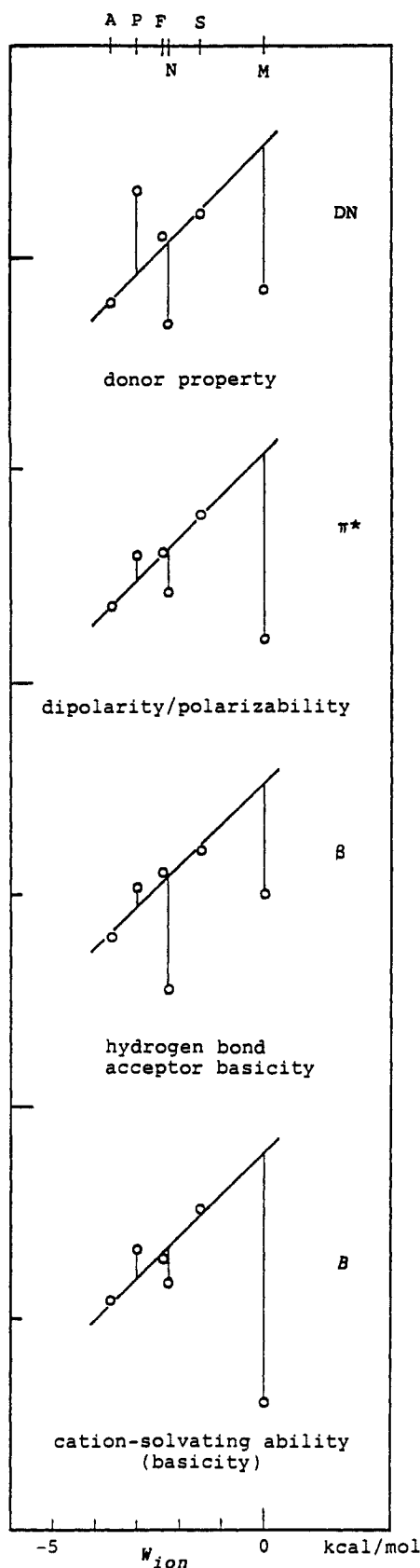


Figure 4. Plots of solvent polarity parameters vs.  $W_{ion}$  and the AFS line. The magnitude between  $Me_2SO$  and acetone is adjusted so that  $\Delta W_{ion} = \Delta DN = \Delta \pi^* = \Delta \beta = \Delta B$ .

carbon bond heterolysis with remarkable ease upon heating in polar solvents. The observed solvent effects on the rate of decompositions of the malononitrile and the rearranged isomer, e.g.,  $k_{Me_2SO} > k_{methanol}$ , are different from those predicted by generally accepted solvent-ionizing power. Assuming that such a difference comes

from the ability of the leaving group anion to hydrogen bond with a protic solvent molecule, polar unimolecular reactions were classified into two types. The validity of the Mitchell postulate on the role of uncouplers can be verified by the hydrogen-bond-insusceptible behavior of the conjugate base of arylhydrazono-malononitriles as the leaving group anion.

### Experimental Section

**General.** Melting points are uncorrected.  $^1H$  NMR spectra were recorded as  $CDCl_3$  solutions, on either a Hitachi R-20B or Varian EM-390 spectrometer. The internal standard was  $Me_4Si$  ( $\delta$  0). Infrared spectra were recorded as KBr disks on a Hitachi 260-30 spectrometer. Elemental analyses were performed by Ms. T. Seki and K. Saeki of the analytical section of the Department. All known compounds were prepared by standard literature procedures.

**Preparation of Arylazo-*tert*-alkylmalononitriles.** *tert*-Cumylmalononitrile (**10**) was prepared according to the literature procedure,<sup>9</sup> which is briefly described. A solution of 25.5 g (0.15 mol) of 1,1-dicyano-2-phenylpropene<sup>31</sup> in 60 mL of benzene was added to a water-cooled solution of 0.17 mol of methylmagnesium iodide in 35 mL of ether under nitrogen. The mixture was stirred at room temperature for 0.5 h and poured onto an aqueous  $NH_4Cl$  solution. The aqueous layer was extracted with benzene, and the combined organic layers were washed with water, dried, and concentrated. The residue was distilled to give 25 g (90%) of **10**, bp 114–116 °C (2 mmHg) as a colorless liquid: NMR  $\delta$  1.69 (s, 6 H), 3.86 (s, 1 H), 7.4 (m, 5 H). Anal. Calcd for  $C_{12}H_{12}N_2$ : C, 78.23; H, 6.57; N, 15.21. Found: C, 78.09; H, 6.28; N, 15.29.

A diazonium solution was prepared by dissolving 1.38 g (0.01 mol) of *p*-nitroaniline in 15 mL of 6 N HCl, cooling to 0 °C, and adding a solution of 0.80 g of sodium nitrite in 2 mL of water with stirring. To the solution, which was filtered once, 10 mL of cold water, 12 g of sodium acetate, and 20 mL of cold ethanol were added successively. To the vigorously stirred solution, a cold solution of 1.66 g (0.009 mol) of **10** in 15 mL of ethanol was added at 0 °C. After 30 min, the resulting mixture was diluted with 50 mL of cold water to give a yellow deposit, which was filtered off, washed with water, and dissolved in benzene (50 mL). The benzene solution was washed with 5%  $Na_2CO_3$  and then with water, dried, treated with 0.5 g of Norit, concentrated to 10 mL under reduced pressure at temperatures below 45 °C, filtered, and diluted with 30 mL of hexane, to give 1.67 g (56%) of **1a** (*p*- $NO_2$ ) as yellow needles: mp 99 °C dec; NMR  $\delta$  1.92 (s, 6 H), 7.2–7.5 (m, 5 H), 7.84 (d,  $J = 9$  Hz, 2 H), 8.36 (d,  $J = 9$  Hz, 2 H); IR ( $cm^{-1}$ ) 2245 (vw, CN), 2200 (vw, CN). Anal. Calcd for  $C_{18}H_{15}N_5O_2$ : C, 64.85; H, 4.54; N, 21.01. Found: C, 64.57; H, 4.26; N, 20.97.

Likewise, **1b–g** were prepared. Crude products were chromatographed on silica gel (eluent: hexane–benzene) and recrystallized repeatedly from hexane–benzene to afford yellow crystals except as noted. **1b** (*p*-CN): mp 91 °C dec; NMR  $\delta$  1.88 (s, 6 H), 7.2–7.5 (m, 5 H), 7.80 (app s, 4 H). Anal. Calcd for  $C_{19}H_{15}N_5$ : C, 72.82; H, 4.83; N, 22.35. Found: C, 72.74; H, 4.77; N, 22.21. **1c** (*m*- $NO_2$ ): mp 100 °C dec; NMR  $\delta$  1.90 (s, 6 H), 7.2–7.6 (m, 5 H), 7.6–8.6 (m, 4 H). Anal. Calcd for  $C_{18}H_{15}N_5O_2$ : C, 64.85; H, 4.54; N, 21.01. Found: C, 65.13; H, 4.39; N, 20.92. **1d** (*m*-CN): mp 99 °C dec; NMR  $\delta$  1.89 (s, 6 H), 7.2–7.6 (m, 5 H), 7.65–8.1 (m, 4 H). Anal. Calcd for  $C_{19}H_{15}N_5$ : C, 72.82; H, 4.83; N, 22.35. Found: C, 73.07; H, 4.96; N, 22.16. **1e** (H): mp 73.5 °C dec; NMR  $\delta$  1.85 (s, 6 H), 7.2–7.85 (m, 10 H). Anal. Calcd for  $C_{18}H_{16}N_4$ : C, 74.97; H, 5.59; N, 19.43. Found: C, 75.02; H, 5.35; N, 19.47. **1f** (*p*-Me, yellowish orange): 82 °C dec; NMR  $\delta$  1.89 (s, 6 H), 2.43 (s, 3 H), 7.29 (d,  $J = 9$  Hz, 2 H), 7.65 (d,  $J = 9$  Hz, 2 H), 7.3–7.6 (m, 5 H). Anal. Calcd for  $C_{19}H_{18}N_4$ : C, 75.47; H, 6.00; N, 18.53. Found: C, 75.55; H, 5.71; N, 18.44. **1g** (*p*-MeO): mp 108 °C dec; NMR  $\delta$  1.84 (s, 6 H), 3.87 (s, 3 H), 6.96 (d,  $J = 9$  Hz, 2 H), 7.74 (d,  $J = 9$  Hz, 2 H), 7.2–7.6 (m, 5 H). Anal. Calcd for  $C_{19}H_{18}N_4O$ : C, 71.67; H, 5.70; N, 17.60. Found: C, 71.94; H, 5.61; N, 17.73. **18a** was similarly prepared as above from diazotized *p*-nitroaniline and  $\alpha,\alpha$ -dimethylcyclopropylmethylmalononitrile which was obtained from 1,1-dicyano-2-cyclopropylpropene<sup>32</sup> and methylmagnesium iodide. **18a**: mp 104 °C dec; NMR  $\delta$  0.2–0.7 (m, 4 H), 0.8–1.2 (m, 1 H), 1.23 (s, 6 H), 7.99 (d,  $J = 9$  Hz, 2 H), 8.41 (d,  $J = 9$  Hz, 2 H). Anal. Calcd for  $C_{15}H_{15}N_5O_2$ : C, 60.60; H, 5.09; N, 23.56. Found: C, 60.72; H, 5.03; N, 23.48. **18b** was prepared from *tert*-butylmalononitrile<sup>33</sup> as above. **18b**: mp 112 °C dec; NMR  $\delta$  1.41 (s, 9 H), 8.00 (d,  $J = 9$  Hz, 2 H), 8.41 (d,  $J = 9$  Hz, 2 H). Anal. Calcd for  $C_{13}H_{13}N_5O_2$ : C, 57.56; H,

(31) Mowry, D. T. *J. Am. Chem. Soc.* **1945**, *67*, 1050.

(32) Opie, J. W.; Seifter, J.; Bruce, W. F.; Mueller, G. U.S. Patent 2538322, 1951; *Chem. Abstr.* **1951**, *45*, 6657.

(33) Wheland, R. C.; Martin, E. L. *J. Org. Chem.* **1975**, *40*, 3101.

4.83; N, 25.82. Found: C, 57.42; H, 4.59; N, 25.60.

**Analyses of Products from Decomposition of Arylazo-*tert*-alkyl-malononitriles.** In cases of the solvents, methanol and Me<sub>2</sub>SO, 0.3 mmol of **1a** was dissolved in 10 mL of a solvent and heated at 60 °C for 2 h. To the solution were added 10 mL of 5% Na<sub>2</sub>CO<sub>3</sub> and 5 mL of CCl<sub>4</sub> containing a measured amount of 9,10-dihydroanthracene as an internal standard. The aqueous layer was extracted twice with 5 mL of CCl<sub>4</sub>. The combined CCl<sub>4</sub> layers were washed with water, dried, carefully concentrated to 3 mL at atmospheric pressure, and subjected to NMR measurements. The aqueous layer was acidified with dilute HCl to yield **7b**, mp 223 °C dec, identical with the authentic sample [lit.<sup>34</sup> mp 215 °C]. With pyridine, the reaction mixture obtained under the same conditions was heated at 115 °C under nitrogen for 2 h prior to product analyses. With other solvents and substrates, the yields of products were determined by NMR measurements of the reaction mixture using a measured amount of an internal standard.

**Isolation of *N*-(*tert*-Cumyl)(*p*-nitrophenyl)hydrazonomalononitrile (14).** A solution of **1a** (1.25 g) in 5 mL of MeCN was heated at 60 °C for 3 h, and after 0.6 g of NaHCO<sub>3</sub> was added, the solvent was evaporated in vacuo. The residue was extracted with benzene and the extract, after it was treated with Norit, was concentrated to 10 mL, which gave a solid mass (0.44 g) upon addition of 10 mL of hexane. Recrystallization of the solid from benzene-hexane gave 0.34 g of **14** (27% yield) as pale-yellow needles; mp 137 °C dec; NMR δ 1.82 (s, 6 H), 6.94 (d, *J* = 9.5 Hz, 2 H), 7.2-7.5 (m, 5 H), 8.18 (d, *J* = 9.5 Hz, 2 H); IR (cm<sup>-1</sup>) 2215 (s, CN), 2195 (m, CN). Anal. Calcd for C<sub>18</sub>H<sub>15</sub>N<sub>5</sub>O<sub>2</sub>: C, 64.85; H, 4.54; N, 21.01. Found: C, 64.93; H, 4.80; N, 21.00.

**Methylation of (*p*-Nitrophenyl)hydrazonomalononitrile (7b).** A mixture of 0.223 g of **7b** and 1 g of Na<sub>2</sub>CO<sub>3</sub> in 10 mL of Me<sub>2</sub>SO was heated at 60 °C for 0.5 h and cooled at room temperature. To the reddish-orange mixture was added 3 mL of methyl iodide and, after the reaction mixture was stirred for 16 h, were added 1 mL of methyl iodide and 0.5 g of Na<sub>2</sub>CO<sub>3</sub>. After stirring for 8 h, the resulting mixture was treated with a mixture of 30 mL of benzene and 10 mL of 5% Na<sub>2</sub>CO<sub>3</sub> and diluted with 50 mL of water. From the aqueous layer, 0.016 g (7%) of

**7b** was recovered. The benzene layer gave 0.214 g (97% based on the unrecovered starting material) of the *N*-methylhydrazone **16** mp 140 °C (from ethanol); NMR δ 4.10 (s, 3 H), 7.53 (d, *J* = 10 Hz, 2 H), 8.30 (d, *J* = 10 Hz, 2 H); IR (cm<sup>-1</sup>) 2220 (s, CN), 2210 (s, CN). Anal. Calcd for C<sub>10</sub>H<sub>7</sub>N<sub>5</sub>O<sub>2</sub>: C, 52.40; H, 3.08; N, 30.56. Found: C, 52.26; H, 3.06; N, 30.78. The absence of the *C*-methylated azo compound **17** was confirmed by direct comparison of NMR and IR spectra of the reaction mixture with those of the authentic sample. **17**: mp 85 °C [lit.<sup>14</sup> mp 87 °C]; NMR δ 2.21 (s, 3 H), 8.00 (d, *J* = 8.00 Hz, 2 H), 8.39 (d, *J* = 8.34 Hz, 2 H); IR (cm<sup>-1</sup>) 2245 (vw, CN), 2200 (vw, CN). Anal. Calcd for C<sub>10</sub>H<sub>7</sub>N<sub>5</sub>O<sub>2</sub>: C, 52.40; H, 3.08; N, 30.56. Found: C, 52.29; H, 3.11; N, 30.60.

**Kinetic Experiments.** The rates of decomposition were determined by monitoring the disappearance of the methyl peak of a substrate relative to a peak of an internal standard in the NMR spectrum as a function of time. Anisole was used as the internal standard except for the following cases: *p*-xylene for **1g** and hexamethylethane for **21** (hexamethyldisiloxane for **21** in methanol-*d*<sub>4</sub>). Commercially available deuterated solvents dried with molecular sieves (3- or 4-Å) and purified pyridine were used in the kinetic measurements. Initial concentrations were ca. 0.08 M. The sealed NMR tube was heated directly in the NMR probe or in a thermostated water bath (±0.01 °C). Measurements were usually taken up to more than 80% reaction. With decompositions of **21** in acetone-*d*<sub>6</sub> and acetonitrile-*d*<sub>3</sub>, the rate constants are initial rates covering 40-45% reaction because of the upward drift as reported.<sup>11</sup> However, in DMF-*d*<sub>7</sub> no reported downward drift was observed up to more than 80% reaction. With **19** in acetone-*d*<sub>6</sub> (including some pyridine), an upward drift was observed for the points of more than 50% reaction.

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**Registry No.** **1a**, 101225-70-1; **1b**, 101225-71-2; **1c**, 101225-72-3; **1d**, 101225-73-4; **1e**, 101225-74-5; **1f**, 101225-75-6; **1g**, 101225-76-7; **10**, 1203-13-0; **11-d**<sub>3</sub>, 101225-77-8; **12**, 98-83-9; **14**, 101225-78-9; **15**, 617-94-7; **16**, 79490-50-9; **18a**, 101225-79-0; **18b**, 101225-80-3.

(34) Hünig, S.; Boes, O. *Liebigs Ann. Chem.* **1953**, 579, 28.

## Azo Cope Rearrangement. A Sigmatropic Change Having a Strong Bias in the Direction of Heterolytic Bond Cleavage

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**Abstract:** The first example of the azo Cope rearrangement is presented. Arylazo( $\alpha,\alpha$ -dimethylallyl)malononitriles are readily rearranged to *N*-( $\gamma,\gamma$ -dimethylallyl)arylhydrazonomalononitriles under mild conditions. The reaction rate increases greatly with increasing electron-withdrawing power of the substituent ( $\log k/k_0 = 1.64\sigma$  in *o*-dichlorobenzene at 60 °C) and with increasing the basicity or nucleophilicity of the solvent, e.g., CCl<sub>4</sub> < acetone < methanol < pyridine < DMF < Me<sub>2</sub>SO, indicating the polar structure of the transition state. A comparison of the kinetic behavior of the rearrangement with that of the carbon-carbon bond heterolysis of phenylazo-*tert*-cumylmalononitriles affords conclusive evidence for a concerted mechanism. The hydrogen-bond-insusceptible nature of polar sigmatropic reactions is discussed.

The electron-deficient azo system as a  $\pi$  component in pericyclic reactions is unique in promoting electron transfer that increases the polar nature of the transition state, as can be seen from intensive work on the Diels-Alder reaction.<sup>1</sup> This paper presents



monoaza Cope; X = Y = C

diaza Cope; X = N, Y = C

azo Cope; X = C, Y = N

the first example of the azo Cope rearrangement, i.e., the [3,3] sigmatropic shift involving an azo-to-hydrazone conversion which is exceedingly sensitive to the polar effects of substituents and solvents. The monoaza and diaza Cope rearrangements<sup>2a-c</sup> and

(1) (a) Gillis, B. T. *1,4-Cycloaddition Reactions*; Hamer, J., Ed.; Academic: New York, 1967; pp 143. (b) Timberlake, J. W.; Stowell, J. C.; Mackenzie, K. *The Chemistry of the Hydrazo, Azo, and Azoxy Groups*; Patai, S., Ed.; Wiley: London, 1975; pp 72, 426. (c) Burrage, M. E.; Cookson, R. C.; Gupta, S. S.; Stevens, I. D. R. *J. Chem. Soc., Perkin Trans. 2* **1975**, 1325. (d) Weinreb, S. M.; Staib, R. R. *Tetrahedron* **1982**, 38, 3121.

(2) (a) Vögtle, F.; Goldschmitt, E. *Chem. Ber.* **1976**, 109, 1. (b) Brombach, D.; Vögtle, F. *Synthesis* **1977**, 800. (c) Rhoads, S. J.; Raulins, N. R. *Org. React.* **1975**, 22, 1. (d) Cope, A. C.; Hardy, E. M. *J. Am. Chem. Soc.* **1940**, 62, 441.