Ring Transformations in Reactions of Heterocyclic Compounds with Nucleophiles.[1] 1,3- and 1,4-Cycloadducts as Intermediates in the Pyrimidine to Pyridine Ring Transformation of 5-Nitropyrimidines by α-Phenylacetamidines[2]

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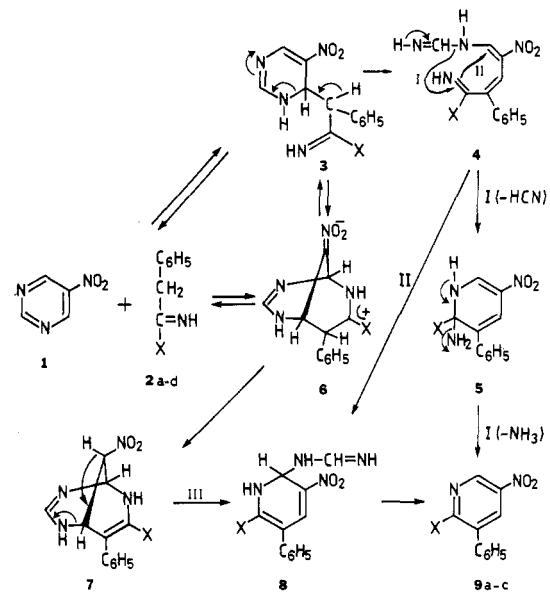
5-Nitropyrimidine reacts with α-phenylacetamidines at −40 °C to form σ adducts at the C-2 position of the ring but gives 2-aminopyridine derivatives at temperatures above 0 °C. Experiments with ^{15}N-labeled α-phenylacetamidine have shown that the reaction proceeds via different reaction pathways with replacement of either the N_1–C_2–N_3 or N_1–C_2 fragment of the pyrimidine ring by the C–C–N or the C–C moiety of the amidine. The role of 1,3- and 1,4-cycloadducts as possible intermediates in the ring-transformation reaction is discussed.

The ability of pyrimidine and its C and N derivatives to undergo ring transformation reactions with ammonia, potassium amide, hydrazine, and other nucleophiles is well-established.[3-5] Also the reactions of pyrimidines with 1,3-ambident nucleophiles such as amidines,[6,7] 1,3-bis-carbanionic reagents,[8-10] α-substituted acetamides,[11,12] guanidine, urea, and thiourea derivatives[6,7,13] have been investigated; these reactions are gaining interest because of their importance as potential new methods for the syntheses of novel heterocyclic compounds. Very recently the reaction of 5-nitropyrimidine (**1**) with CH-active amidines was described.[7] It was found that with α-phenylacetamidine (**2a**) exclusively 2-amino-5-nitro-3-phenylpyridine (**9a**) was formed. It was suggested that the C_4–C_5–C_6 fragment in **9a** originated from the C_4–C_5–C_6 fragment of **1** and that the C_3–C_2–N moiety in **9a** was derived from **2a**[7] (on the basis of earlier results in which it was firmly established that σ adducts formed between pyrimidines and nitrogen-containing nucleophiles easily undergo ring opening.[4,5]). The ring transformation reaction was supposed to occur either via the bicyclic adduct **7a** (**7a** → **8a** → **9a**) and/or via the open-chain product **4a**, that cyclizes according to route II (**4a** → **8a** → **9a**); Scheme I).

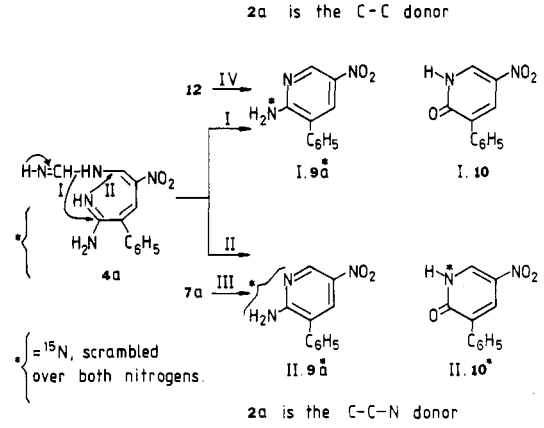
However, it cannot be excluded that the ring closure of **4a** takes place according to pathway I leading to **5a**, which aromatizes to **9a** by loss of ammonia.

In order to differentiate between these two alternative mechanistic pathways I and II in the ring closure of **4**, we investigated the reaction of **1** with ^{15}N-labeled α-phenylacetamidine (**2*a**) at different temperatures. The results obtained induced us to extend the study of the ring transformations by investigating the reaction of **1** with N,N-disubstituted α-phenylacetamidines (**2b** and **2c**) and with ethyl α-phenylacetimidate (**2d**) and of 2-(methylthio)-5-nitropyrimidine with **2a** to obtain by ^1H NMR spectroscopy evidence for the intermediacy of monocyclic σ adducts such as **3** or bicyclic adducts such as **7**.

Scheme I



Scheme II



Results and Discussion

(1) Reaction of 5-Nitropyrimidine (1) with α-Phenylacetamidine (2a). (a) Experiments with ^{15}N-Labeled α-Phenylacetamidine (2*a). When reacting an ethanolic solution of **1** with **2a** at 0 °C for 4 h the pyridine **9a** is obtained in low yield (22%); this yield is increased to about 80% when the temperature is raised to 78 °C and the reaction time is decreased to about 15 min (Table I). Scheme I suggests that in the reaction of **1** with the amidine **2*a** having both nitrogen atoms enriched equally by nitrogen-15, the ring closure of **4a** by pathway II would lead to a pyridine derivative in which nitrogen-15 is equally

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(1) Part 26 in the series. For part 25 see: Swistun, Z.; van der Plas, H. C. *J. Heterocycl. Chem.* **1981**, *18*, 1639.
(2) Part 90 on Pyrimidines. For part 89 see: Hara, H.; van der Plas, H. C., submitted for publication in *J. Heterocycl. Chem.*
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Table I. Reaction of 1 equiv of 5-Nitropyrimidines with 2.2 equiv of α-Phenylacetamidines

pyrimidine	amidine	solvent	reaction temp, °C	reaction time, h	products (% yield)
1	2a	ethanol	0	4	9a (22)
1	2a	ethanol	20	2	9a (57)
1	2a	ethanol	78	0.25	9a (86)
1	2b	ethanol	20	90	9b (36) + 9a (17)
1	2c	methanol	20	20	traces of 9c
1	2c	ethanol	78	5	traces of 9c
1	2c	DMF	20	16	3c (25)
1	2d·HCl + 6 equiv of $N(C_2H_5)_3$	ethanol	20	40	9a (63)
16	2a	ethanol	20	50	9a (43)

Table II. ^{15}N Excess[a] in Products Obtained in the Reaction of 5-Nitropyrimidines 1 and 16 with 2.2 equiv of ^{15}N-Labeled α-Phenylacetamidine (2*a) in Ethanol

pyrimidine	total % ^{15}N in 2*a	reaction temp, °C	% ^{15}N in products: total, 9*a	% ^{15}N in products: in the ring, 10*	ratio of C-C/C-C-N reactivity[c] of 2*a
1	6.9[b] × 2	0	9.8	3.4	0.9
1	11.5[b] × 2	20	17.7	5.8	1.0
1	11.5[b] × 2	20	18.8	6.3	1.0
1	6.9[b] × 2	78	8.5	2.1	2.0
16	6.9[b] × 2	20	12.8	6.2	0.06

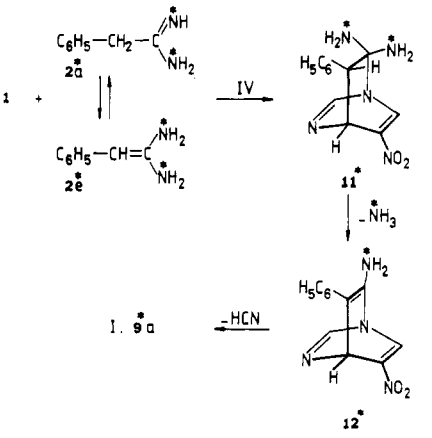
[a] The accuracy of the measurements is ±0.5%. [b] The experimentally derived percentage of ^{15}N labeling of each nitrogen atom. [c] For the calculation of this ratio, we refer to note 22 in ref 4.

scrambled over the ring nitrogen and amino nitrogen in **9a** (=II.9*a). The same product can also result via the bicyclic intermediate **7a** (route III). If the ring closure takes place exclusively according to route I, the ring nitrogen in **9a** is unlabeled, and only the amino nitrogen is labeled (=I.9*a); see Scheme II.

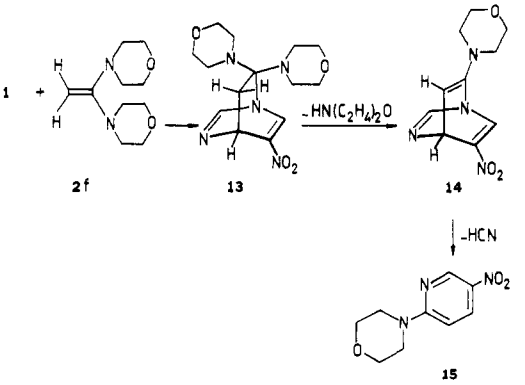
In order to establish the percentage of nitrogen-15 that is present in the pyridine ring, ^{15}N-labeled compound **9*a** was converted into 3-nitro-5-phenyl-2(1*H*)-pyridone. By mass spectrometric determination of the excess of ^{15}N in **9*a** and in the 2-pyridone (II.10*) the contributions of **2a** as a C–C donor and as a C–C–N donor could be calculated. The data of all measurements and calculations are summarized in Table II. From these data it is obvious that in the temperature range 0–20 °C α-phenylacetamidine (**2a**) serves in this ring transformation reaction equally well as the C–C–N donor to replace the N_1–C_2–N_3 moiety and concurrently as the C–C donor to substitute the N_1–C_2 fragment of the pyrimidine ring.

(b) Another Mechanistic Approach To Explain the Ring Transformation of 1 into 9a. On consideration of the results obtained thus far it cannot be excluded that when the amidine **2*a** serves as the C–C donor, the ring transformation of **1** into **9*a** can be explained not only by route I (Scheme I) but also via the formation of the [4 + 2] cycloadduct **11*** provided the amidine **2*a** can react as the tautomeric enediamine **2*e** (route IV, Scheme III).[14] The results of our experiments with ^{15}N-labeled **2*a** are not in conflict with this hypothesis.

Scheme III



Scheme IV



In order to get more substantial evidence for the occurrence of this mechanistic pathway, we carried out the reaction of **1** with *N,N'*-vinylidenedimorpholine (**2f**), Scheme IV). The reaction of **1** with **2f**, having a fixed enediamine function, under the same conditions as used in the reaction of **1** with **2a** (20 °C, ethanol) results in the formation of 2-morpholino-5-nitropyridine (**15**) in good yield. Its formation can be rationalized via the intermediacy of **13** and **14**.

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No indication was found for the formation of 4-morpholino-3-nitropyridine, pointing out that the reaction is highly regioselective. These results indicate that 5-nitropyrimidine is able to undergo cycloaddition reactions and support the idea that the formation of **9a** can occur via [4 + 2] cycloaddition reaction on the 3,6-positions of the pyrimidine ring followed by the retrograde process (**11** → **12** → **9a**, Scheme III). Ring transformations preceded by cycloaddition reactions have been reported to occur in reactions of substituted *s*-tetrazines and 1,2,4-triazines with ketene *N,N*-acetals,[15] enamines,[16,17] and ynamines.[18,19] The ability of the pyrimidine ring system to undergo Diels–Alder cycloadditions with inverse electron demand is also described.[20] 5-Nitropyrimidine, however, has so far not been studied in Diels–Alder cycloaddition reactions resulting in ring transformation prroducts. Investigation of the scope of this reaction is in full progress now.

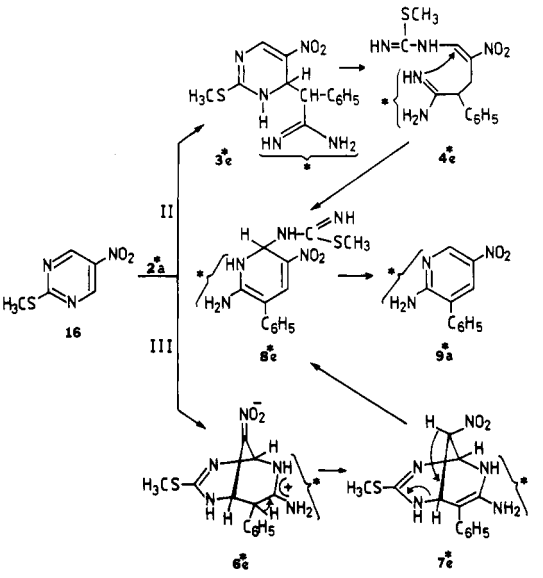
(2) Reaction of 5-Nitropyrimidine with N,N-Disubstituted α-Phenylacetamidines 2b,c and with Ethyl α-Phenylacetimidate (2d). When reacted with *N,N*-dimethyl-α-phenylacetamidine (**2b**) compound **1** was converted into a mixture of **9a** and 2-(dimethylamino)-5-nitro-3-phenylpyridine (**9b**) (see Table I). The formation of both products can be explained by the several mechanisms given in Schemes I and III. Intermediate **4b** can undergo ring closure into **5b** (route I), which by loss of an amino group or the dimethylamino group can be aromatized into **9b** and **9a**, respectively. The formation of **9a** and **9b** can also be explained by route IV via the intermediacy of 1,4-cycloadducts such as **11** and **12** (Scheme III) and the formation of **9b**, either via the bicyclic 1,3-cycloadduct **7b** (route III) or via the ring closure of **4b** into **8b** (route II, Scheme I). Thus, the formation of **9b** can be described by all possible pathways (I–IV) given in Schemes I and III.

The reaction of **1** with *N,N*-diethyl-α-phenylacetamidine (**2c**) occurs very slowly in an alcoholic solution—only traces of 2-(diethylamino)-5-nitro-3-phenylpyridine (**9c**) are formed—but in DMF a moderate yield of **9c** has been obtained (Table I). Since no **9a** is obtained in this reaction, it seems unlikely that **5c** [X = $N(C_2H_5)_2$] is the intermediate, and therefore we propose that **9c** is formed via **8c** (route II or III). A route via 1,4-cycloadducts as **11** and **12** (route IV) is disfavored, since besides **9c** also **9a** should have been obtained.

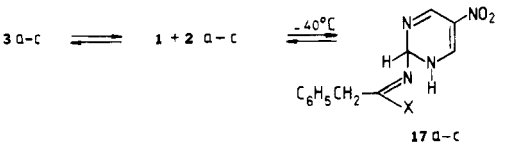
The reaction of **1** with **2d** has been found to give **9a** under mild conditions. This product formation can be explained by route I (**4d** → **5d** → **9a**) and also via cycloadducts such as **11** and **12** (route IV, Scheme III). Routes II and/or III (Scheme I) can be excluded.

(3) Reaction of 2-(Methylthio)-5-nitropyrimidine (16) with α-Phenylacetamidines 2a and 2*a. The reaction of **16** with **2a** has been found to result in **9a** (Table I), and the experiment with ^{15}N-labeled **2*a** has shown that the amidine **2a** serves in this reaction almost exclusively (94 ± 7%) as the C–C–N donor (Table II). It means that the formation of **9a** can be only explained by route II and/or route III (Scheme V).

Scheme V



Scheme VI



The data of the ^1H NMR examination discussed below show, however, that the reaction is likely to proceed via bicyclic intermediates **6e** and **7e** (Scheme V).

(4) NMR Study. It follows from the structure of compounds **9a–c** that the active methylene grouping of **2a–d** has to be attached to C-6 (C-4) of **1** (**16**). Therefore, as far as σ adducts are concerned, only C adducts **3** or cycloadducts **6** and **7** can be considered as possible intermediates from which the rearrangement occurs. However, it is known that both the C-2 and C-6(4) positions of **1** are vulnerable to a nucleophilic attack by the methoxide ion,[21] ammonia,[22] and carbanions.[23] It was not plausible to expect, therefore, that 5-nitropyrimidine (**1**) would be attacked by 1,3-ambident amidines **2** exclusively as C nucleophiles and only at C-6(4). In order to investigate this rather complex reaction, we undertook an ^1H NMR examination of reaction mixtures at different temperatures to detect possible intermediates of this ring transformation.

The σ adduct **17a**, resulting from the reaction of **1** with unsubstituted amidine **2a** (Scheme VI), showed at −40 °C two singlets at δ 5.87 and 8.43 with integral intensities of 1:2; **17a**, however, proved to be unstable even at −40 °C and gave a complex mixture. The σ adducts **17b,c** resulting from the pyrimidine **1** and N,N-disubstituted amidines **2b,c**, showed the same chemical shifts for the ring hydrogens (5.87 and 8.43 ppm); they are quite stable at −40 °C. The high-field singlet is characteristic for the resonance of a proton attached to an sp^3-hybridized carbon atom in σ adducts of 5-nitropyrimidines, and the chemical shift δ 5.86 indicates that the N-addition rather than the C-addition has taken place.[22,23] That the spectrum cor-

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Table III. Melting Points, Mass Spectral, ^{1}H NMR Spectral, and Elemental Analytical Data

compd	mp, °C	M$^+$ in mass spectrum, *m/e*	solvent: NMR,[a] δ (*J*, Hz)	analyses: calcd C	calcd H	found C	found H
9a	178–179 (lit.[7] 177)	215	$CDCl_3$: 8.95 (d, H-6), 8.13 (d, H-4, $J_{4,6}$ = 2.8), 7.45 (s, 5 H), 5.50 (br s, 2 H)	61.39	4.21	61.55	3.94
9b	115–116	243	$CDCl_3$: 8.98 (d, H-6), 8.12 (d, H-4, $J_{4,6}$ = 2.6), 7.44 (s, 5 H), 2.95 (s, 6 H)	64.18	5.39	64.09	5.52
9c	oil	271	$(CD_3)_2CO$: 8.95 (d, H-6), 7.98 (d, H-4, $J_{4,6}$ = 2.6), 7.47 (s, 5 H), 3.38 (q, 4 H), 0.98 (t, 6 H)	66.40	6.32	66.60	6.41
10	236–238	216	$(CD_3)_2SO$: 8.66 (d, H-6), 8.20 (d, H-4, $J_{4,6}$ = 2.8), 7.9–7.2 (m, 5 H)	61.11	3.73	60.95	3.66
15	143 (lit.[32] 142–143)	209	$CDCl_3$: 9.03 (d, H-6), 8.21 (dd, H-4, $J_{4,6}$ = 2.8, $J_{4,3}$ = 9.6), 6.55 (d, H-3), 3.80 (s, 8 H)	51.67	5.30	51.94	5.21

[a] The assignment of signals is based on calculated chemical shifts obtained with use of shielding parameters of substituents in the pyridine ring.[26]

responds to the addition of **2c** at C-2 of the pyrimidine ring to form **17c** has been confirmed by the experiment with 4,6-D_2-labeled 5-nitropyrimidine and by the ^{13}C NMR spectrum of the reaction mixture in methanol-d_4 at −40 °C as well. The resonance signals of **17c**, found at δ 96.2 (C-2, $^1J_{CH}$ = 172.1 Hz) and 153.7 (C-4,6) are in full agreement with the structure. For comparison, the C-2 adduct formed from **1** with ammonia has resonance signals at δ 80.8 (C-2) and 151.3 (C-4,6).[22]

The formation of **17b,c** has been shown to be a reversible reaction affected by temperature. Increasing the temperature to 0 °C resulted in gradual disappearance of signals at 5.86–5.87 and 8.44 ppm. If the temperature is decreased below −30 °C, however, σ adducts **17b,c** are formed again. It is evident that the formation of σ adducts **17a–c** at low temperature is kinetically favored, but it has no relation to the ring transformation reaction to give **9a–c**. This is also substantiated by the reaction of **16** with **2a** to form **9a** in spite of the C-2 position being blocked by the methylthio group, and no indications of σ adduct formation were present in ^{1}H NMR spectra at −40 to −10 °C.

The ring transformation reaction of **1** and **16** into **9a–c** has been established to occur with a perceptible rate only at 0 °C and above. The formation of **9a–c** is indicated by the appearance of two doublets of protons of the pyridine ring, H-6 and H-4, in the range of 7.9–9.0 ppm (Table III). In addition, ^{1}H NMR spectra of **1** with **2a–c** in CD_3OD at 0 °C display a number of signals in the range between 4.0 and 6.0 ppm. This region of the spectra is too complicated to be interpreted accurately. More simple ^{1}H NMR spectra are observed in the reaction of **16** with **2a** (Figure 1).

The ^{1}H NMR spectrum of the mixture of **16** with **2a** in CD_3OD at −40 to −20 °C displays only signals of starting materials. Two doublets appear at 4.70 and 5.71 ppm (J = 2 Hz) at −10 °C (Figure 1a), and another couple of doublets with chemical shifts at 4.26 and 5.30 ppm (J = 2 Hz) appear at 0 °C (Figure 1b). Signals at 4.70 and 5.71 ppm are gradually decreasing while doublets at 4.26 and 5.30 ppm are increasing. When reagents **16** and **2a** are mixed at 30 °C only doublets at 4.26 and 5.30 ppm are present in this region of the NMR spectrum (Figure 1c). Allowing the reagents to stand at 30 °C resulted in the appearance and the growth of the ring transformation product **9a** (doublets at 8.05 and 8.85 ppm) with simultaneous decreasing of signals at 4.26 and 5.30 ppm (Figure 1c). To assign signals in the range of 4.2–5.8 ppm one has

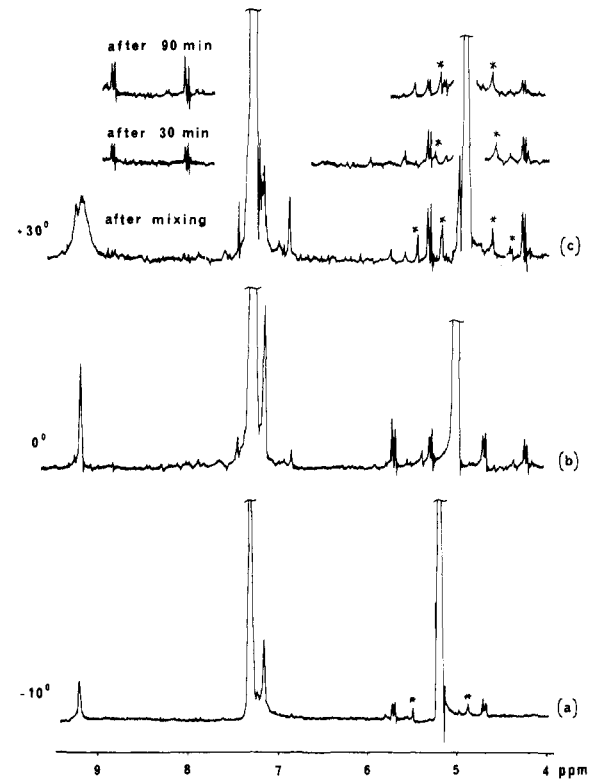

Figure 1. ^{1}H NMR spectra of the **16**–**2a** 1:1 reaction mixture in CD_3OD at (a) −10 °C, (b) 0 °C, and (c) +30 °C. An asterisk indicates side bands.

to take into account the following: (a) all signals belong to protons originated from the pyrimidine **16**, because protons of the active methylene group are exchanged with CD_3OD; (b) chemical shifts and coupling constants are in accordance either with the diaddition at C-4 and C-6 of the pyrimidine ring or with the formation of cycloadducts;[24,25] (c) the difference in chemical shifts between doublets of equal intensity (about 1 ppm in both cases) reflects a different character of substituents at C-4 and C-6 of the ring. These data suggest that signals at 4.70 and

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5.71 ppm may be ascribed to bridgehead protons of the cycloadduct **6e**, and doublets at 4.26 and 5.30 ppm correspond to those of the $C_{4,6}$ cycloadduct **7e** (Scheme V).

^1H NMR data obtained support strongly the 1,3-cyclization mechanism of the ring transformation of **16** into **9a** via bicyclic adducts **6e** and **7e** (route III, Scheme V). This mechanism is also in nice agreement with the ^{15}N-labeling experiment.

Conclusion

The ability of the pyrimidine ring to form 1,3- and 1,4-cycloadducts demonstrated above makes it at least reasonable to postulate their formation as intermediates in ring transformations of pyrimidines by action of 1,3-ambident nucleophiles and electron-rich dienophiles. A recently published paper[24] on the pyrimidine to benzene ring transformation proceeding via the 5-nitro-2(1*H*)-pyrimidone–acetone bicyclic adduct supports the conclusion of the importance of cycloadduct formation in ring transformations of pyrimidines.

Experimental Section

Melting points are uncorrected. The ^1H NMR spectra were recorded on a Hitachi Perkin-Elmer R-24B and a Varian EM-390 spectrometer equipped with a Varian EM-3940 variable-temperature controller. Tetramethylsilane was used both for the lock signals and as the internal standard (δ 0). IR spectra were recorded on a Hitachi EPG-3 spectrometer.

Mass spectra and ^{15}N contents were determined on an AEI MS-902 mass spectrometer. The percentage of excess ^{15}N in compounds **2*a** and **10*** was determined by measuring the ratio $(m + 1)/m \times 100$, where m is the intensity of the molecular ion and $(m + 1)$ the intensity of its isotope peak. This value was corrected by the one measured for the pure unlabeled reference compound. Because α-phenylacetamidine **2a** is not stable enough due to loss of ammonia, the peak of benzyl cyanide with m/e 117 and the isotope peak with m/e 118 were used for measurements. These peaks were identified by means of exact mass measurements as those of benzyl cyanide resulting from **2a** through thermal elimination of ammonia in the hot (200 °C) inlet system of the mass spectrometer. Particularly, the peak with m/e 118 of **2*a** has been shown to correspond to two species of benzyl cyanide molecules: $C_8H_7\,^{15}N$ (found m/e 118.0551, calcd 118.0549) and $^{13}C^{12}C_7H_7N$ (found m/e 118.0608, calcd 118.0612). The measured excess of ^{15}N in benzyl cyanide was then doubled to calculate the percent of ^{15}N in **2*a**. The total percentage of ^{15}N in **9*a** was determined by measurements of the M + 1 and M + 2 peaks and comparison with those of the unlabeled compound **9a**. Data of all measurements are summarized in Table II.

Starting Materials. 5-Nitropyrimidine,[27] 2-(methylthio)-5-nitropyrimidine,[28] 4,4′-vinylidenedimorpholine,[29] ethyl α-phenylacetimidate, and *N*,*N*-dimethyl-α-phenylacetamidine[30] were prepared according to procedures given in the literature.

^{15}N-Labeled α-phenylacetamidine was prepared by modification of the described procedure.[31] Dry ^{15}N-labeled ammonia (5 mL, obtained by heating of $^{15}NH_4NO_3$ with 12 N solution of KOH) was condensed, and 10 mL of absolute methanol was added through a dry ice–acetone condenser. This solution was added to the suspension of ethyl α-phenylacetimidate[30] hydrochloride (2 g, 10 mmol) in 10 mL of absolute methanol, and the reaction mixture was stirred for 2 h under the dry ice–acetone condenser. The solvent was distilled off (a washing bottle with 65% nitric acid was used to trap unreacted ^{15}N ammonia), and the residue was treated with a solution of sodium 0.23 g (10 mmol) in 30 mL of absolute ethanol. After filtration from sodium chloride and evaporation of ethanol, the residue was recrystallized from benzene to give α-phenylacetamidine as white leaflets: 0.75 g (56%); mp 96–98 °C; **1H** NMR ($CDCl_3$) δ 7.32 (s, 5 H), 5.78 (s, 3 H), 3.60 (s, 2 H). Anal. Calcd for $C_8H_{10}N_2$: C, 71.61; H, 7.51. Found (unlabeled compound): C, 71.31; H, 7.35.

Reactions of Pyrimidines 1 and 16 with Amidines 2a–d. The procedure[7] for the reaction of 1 with α-phenylacetamidine was simplified since the free amidine was used instead of the hydrochloric salt.[7] 5-Nitropyrimidine (1; 125 mg, 1 mmol) and α-phenylacetamidine (**2a**; 300 mg, 2.2 mmol) were dissolved in 3 mL of ethanol, and the reaction mixture was stirred under conditions given in table I. A precipitate was obtained which was filtered off, recrystallized from ethanol, and identified by melting point and mass and NMR spectral data as 2-amino-5-nitro-3-phenylpyridine (**9a**) (see Tables I and III).

The same procedure was used for the reaction of 1 with **2*a**, with N,N-disubstituted amidines **2b,c**, and with ethyl α-phenylacetimidate **2d** and for that of **16** with **2a**.

The mixture of products **9a,b** resulting from the reaction of 1 with **2b** was separated by TLC (silica gel; chloroform–ethyl acetate, 1:1). Compound **9c** was isolated by column chromatography on silica gel as an oil and purified by repeated TLC (silica gel plates, chloroform–ethyl acetate 1:1) (see Tables I and III).

Conversion of 2-Amino-5-nitro-3-phenylpyridine (9a) into 5-Nitro-3-phenyl-2-pyridone (10). Sodium nitrite (35 mg, 0.5 mmol) was added to sulfuric acid (0.8 mL, d = 1.84) with shaking and gentle heating to complete the dissolution. The solution was cooled to 30 °C, and 2-amino-5-nitro-3-phenylpyridine (52 mg, 0.5 mmol) was added in small amounts with stirring. The mixture was stirred for an additional 2 h, cooled to 10 °C, diluted with water (1 mL), held at 10 °C for 30 min, and then treated with a solution of sodium hydroxide (0.8 g) in water (1.5 mL). After the mixture had been shaken for 30 min at 30 °C, the solid was collected and recrystallized from ethanol, giving 5-nitro-3-phenyl-2-pyridone (**10**): 42 mg (80%); mp 236–238 °C (Table III). The same procedure was used to convert **9*a** into **10***.

Reaction of 1 with 4,4′-Vinylidenedimorpholine (2f). 5-Nitropyrimidine (1; 125 mg, 1 mmol) and 4,4′-vinylidenedimorpholine (**2f**; 400 mg, 2 mmol) were dissolved in 3 mL of ethanol, and the reaction mixture was stirred at room temperature for 2 h. The yellow precipitate was filtered off and recrystallized from ethanol to give 120 mg (57%) of 2-morpholino-5-nitropyridine (**15**), mp 143 °C (Table IV) (lit.[32] mp 142–143 °C).

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Registry No. 1, 14080-32-1; **2a**, 5504-24-5; **2*a**, 86014-47-3; **2b**, 56776-16-0; **2c**, 14277-12-4; **2d**, 4971-77-1; **2d**·HCl, 5442-34-2; **2f**, 14212-87-4; **9a**, 79899-29-9; **I.9*a**, 86014-48-4; **II.9*a**, 86014-49-5; **9b**, 86014-50-8; **9c**, 86014-51-9; **10**, 86014-52-0; **10***, 86014-53-1; **15**, 26820-62-2; **16**, 14001-70-8; $^{15}NH_3$, 13767-16-3.

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