Elimination Reactions of (*Z*)-Thiophene- and (*Z*)-Furan-2-carbaldehyde *O*-Benzoyloximes. Effect of *β*-Aryl Group upon the Nitrile-Forming Anti Transition State

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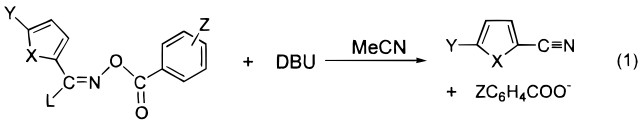
Elimination reactions of (*Z*)-thiophene- and (*Z*)-furan-2-carbaldehyde *O*-benzoyloximes **1** and **2** with DBU in MeCN have been investigated kinetically. The reactions are second order and exhibit substantial values of Hammett ρ and k_H/k_D values, and an E2 mechanism is evident. The relative rates of elimination from (*Z*)-ArCH=NOC(O)C_6H_4Y are 1/1.1/0.6 for Ar = phenyl/thienyl/furyl, respectively. For reactions of **1** with DBU in MeCN, $k_H/k_D = 8.2 \pm 0.1$, Hammett $\rho = 1.22 \pm 0.19$, $\beta_{1g} = -0.43 \pm 0.01$, $\Delta H^{\ddagger} = 5.9 \pm 0.1$ kcal/mol, and $\Delta S^{\ddagger} = -28.5 \pm 0.3$ eu have been determined. The corresponding values for **2** are $k_H/k_D = 8.8 \pm 0.2$, $\rho = 1.87 \pm 0.05$, $\beta_{1g} = -0.55 \pm 0.10$, $\Delta H^{\ddagger} = 6.5 \pm 0.1$ kcal/mol, and $\Delta S^{\ddagger} = -29.0 \pm 1.5$ eu. The k_H/k_D, Hammett ρ, and $|\beta_{1g}|$ values increase as the *β*-aryl group is changed in the order phenyl < thienyl < furyl. The results indicate that the transition state structure for the nitrile-forming elimination changes slightly toward product-like with the change of the *β*-aryl group.

Extensive studies of structure−reactivity relationships in the nitrile-forming syn elimination reactions have led to a qualitative understanding of the relationship between the reactant structure and the E2 transition state.[1−9] In contrast, much less is known about the effects of the reactant structure on the corresponding anti elimination reactions.[10,11]

Very recently, we reported that elimination reactions of (*E*)- and (*Z*)-benzaldehyde *O*-benzoyloximes with 1,8-diazabicyclo[5.4.0]undec-7-ene (DBU) in MeCN proceeded by an E2 mechanism.[11] The anti elimination from the (*Z*)-isomer proceeded at a rate approximately 36 000-fold faster via a more symmetrical transition state with smaller degrees of proton transfer and N_α-OC(O)Ar bond cleavage and less negative charge development at the *β*-carbon than the corresponding syn elimination from the (*E*)-isomer.

In this work, we have studied the anti elimination reactions of (Z)-thiophene- and (*Z*)-furan-2-carbaldehyde *O*-benzoyloximes promoted by 1,8-diazabicyclo[5.4.0]-undec-7-ene (DBU) in MeCN (eq 1). We were interested in determining the effect of the *β*-aryl group upon the nitrile-forming anti transition state. Since the aromatic resonance energies of thiophene and furan are much smaller than that of benzene, they could provide different stabilization of the respective transition states.[12] To assess the effect of the *β*-aryl group upon the nitrile-forming anti elimination transition state, we have determined the k_H/k_D, Hammett ρ, and β_{1g} values for eliminations from **1** and **2** and compared the results with those obtained for the elimination reactions from (*Z*)-benzaldehyde *O*-benzoyloximes under the same conditions.



(1)

X = S (**1**); X = O (**2**); L = H, D

Y = H (**a**), Me (**b**), MeO (**c**), Br (**d**), NO_2 (**e**); Z = H (**a'**), *m*-Br (**b'**), *p*-NO_2 (**c'**)

Results

(*Z*)-Thiophene-2-carbaldehyde *O*-benzoyloximes were prepared in reasonable yields by reacting the (*Z*)-thiophene-2-carbaldehyde oximes with substituted benzoyl chlorides in pyridine at −35 °C.[13−15] The deuterated compounds **1aa′-*d*$_1$**, **1ab′-*d*$_1$**, **1ac′-*d*$_1$**, and **1ea′-*d*$_1$** were prepared from (*Z*)-thiophene-2-carbaldehyde-d_1 and (*Z*)-5-nitrothiophene-2-carbaldehyde-d_1 by the same procedure.[16−19]

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Table 1. Rate Constants for Nitrile-Forming Eliminations from *(Z)*-5-YC$_4$H$_2$(S)CL=NOC(O)C$_6$H$_4$Z[a] Promoted by DBU[b,c] in MeCN at 25.0 °C

Y	Z	L	$10^{-2}k_2$, M^{-1} s^{-1}
MeO	H	H	1.65 ± 0.01
H	H	H	1.90 ± 0.02[d,e]
H	H	D	0.232 ± 0.002
H	*m*-Br	H	6.20 ± 0.01
H	*m*-Br	D	0.780 ± 0.01
H	*p*-NO$_2$	H	13.6 ± 0.01
H	*p*-NO$_2$	D	1.81 ± 0.05
Br	H	H	6.36 ± 0.02
NO$_2$	H	H	26.0 ± 0.01
NO$_2$	H	D	3.38 ± 0.02
NO$_2$	*m*-Br	H	68.1 ± 1.4
NO$_2$	*p*-NO$_2$	H	143 ± 1

[a] [Substrate] = 5.0×10^{-5} M. [b] DBU = diazabicyclo[5.4.0]undec-7-ene. [c] [DBU] = $(0.255-2.55) \times 10^{-3}$ M. [d] $10^{-2}k_2 = 1.82$ and 1.77 M^{-1} s^{-1} when [DBU] = 0.0145 and 0.00255 M, respectively. [e] $10^{-3}k_2 = 0.129$, 0.267, and 0.375 M^{-1} s^{-1} at 15.0, 35.0, and 45.0 °C, respectively.

Table 2. Rate Constants for Nitrile-Forming Eliminations from *(Z)*-5-YC$_4$H$_2$(O)CL=NOC(O)C$_6$H$_4$Z[a] Promoted by DBU[b,c] in MeCN at 25.0 °C

Y	Z	L	$10^{-2}k_2$, M^{-1} s^{-1} [c]
MeO	H	H	0.301 ± 0.05
CH$_3$	H	H	0.531[d,e] ± 0.01
CH$_3$	H	D	0.0601 ± 0.001
CH$_3$	*m*-Br	H	1.58 ± 0.04
CH$_3$	*m*-Br	D	0.201 ± 0.005
CH$_3$	*p*-NO$_2$	H	7.04 ± 0.06
CH$_3$	*p*-NO$_2$	D	0.922 ± 0.017
Br	H	H	2.35 ± 0.05
NO$_2$	H	H	30.0 ± 0.09
NO$_2$	H	D	3.90 ± 0.01
NO$_2$	*m*-Br	H	80.1 ± 1.2
NO$_2$	*p*-NO$_2$	H	168 ± 1

[a] [Substrate] = 2.0×10^{-5} M. [b] DBU = diazabicyclo[5.4.0]undec-7-ene. [c] [DBU] = $(2.00-10.0) \times 10^{-3}$ M. [d] $10^{-2}k_2 = 0.0523$ and 0.0552 M^{-1} s^{-1} when [DBU] = 0.0213 and 0.00310 M, respectively. [e] $10^{-2}k_2 = 0.341$ and 0.752 M^{-1} s^{-1} at 15.0 and 35.0 °C, respectively.

(*Z*)-Furan-2-carbaldehyde *O*-benzoyloximes **2** and their deuterated compounds were also prepared by a similar method.[16−23]

The reaction of **1aa′** with DBU produced thiophene-2-carbonitrile and benzoates. The GC yield of the thiophene-2-carbonitrile was 94%. No trace of (*Z*)-thiophene-2-carbaldehyde oxime could be detected by either GC or TLC. Similarly, the reaction of **2ba′** with DBU produced 5-methylfuran-2-carbonitrile and benzoate as the only products.

Reactions of (*Z*)-thiophene- and (*Z*)-furan-2-carbaldehyde *O*-benzoyloximes with DBU in MeCN were followed by monitoring the change in the absorption with the reaction time. For all reactions, the UV absorption of the reactants decreased and that of the products increased with time. Except for the reactions of **1aa′**, **1aa′-*d*$_1$**, **2bc′**, **2bc′-*d*$_1$**, and **2ca′** clean isosbestic points were observed at 262−332 nm. Rates of elimination from **1** and **2** were followed by monitoring the increase in the absorption at 265−350 nm with a UV−vis or stopped-flow spectrophotometer as described previously.[9−11] Excellent pseudo-first-order kinetic plots that covered at least two half-lives were obtained. The rate constants for DBU-promoted eliminations from **1** and **2** are listed in Tables 1 and 2. The k_2 values were constant for 10-fold variation in base concentration.

From the rate coefficients for eliminations from **1aa′**, **1ab′**, **1ac′**, **1ea′**, **2ba′**, **2bb′**, **2bc′**, **2ea′**, and their deuterated analogues, the primary isotope effect values were calculated. The k_H/k_D values are listed in Table 3. The k_H/k_D values decrease as the leaving is made less basic and as the electron-withdrawing ability of the 5-thienyl and 5-furyl substituents increases.

The influence of the β-aryl substituents upon the elimination rates gave excellent correlations with σ values (Figure 1). The ρ values for the substituted benzoyl leaving groups (Z = Br, NO$_2$) were calculated with the data for Y = H, NO$_2$ and Y = Me, NO$_2$ for **1** and **2**, respectively, because of the difficulty in the synthesis of other derivatives. Hammett ρ values are summarized in Table 4. For all reactions, the ρ values decrease as the leaving group is made less basic.

Table 3. Primary Isotope Effect Values for Eliminations from *(Z)*-YArCL=NOC(O)C$_6$H$_4$Z Promoted by DBU in MeCN at 25.0 °C

		k_H/k_D	
Y[a]	Z	Ar = thienyl	Ar = furyl
H	H	8.2 ± 0.1	8.8 ± 0.2[b]
H	*m*-Br	7.9 ± 0.1	7.9 ± 0.2[b]
H	*p*-NO$_2$	7.5 ± 0.3	7.6 ± 0.2[b]
NO$_2$	H	7.7 ± 0.1	7.7 ± 0.1

[a] Substituents at 4- and 5-positions for the phenyl and heterocyclic compounds, respectively, unless otherwise noted. [b] Y = 5-CH$_3$.

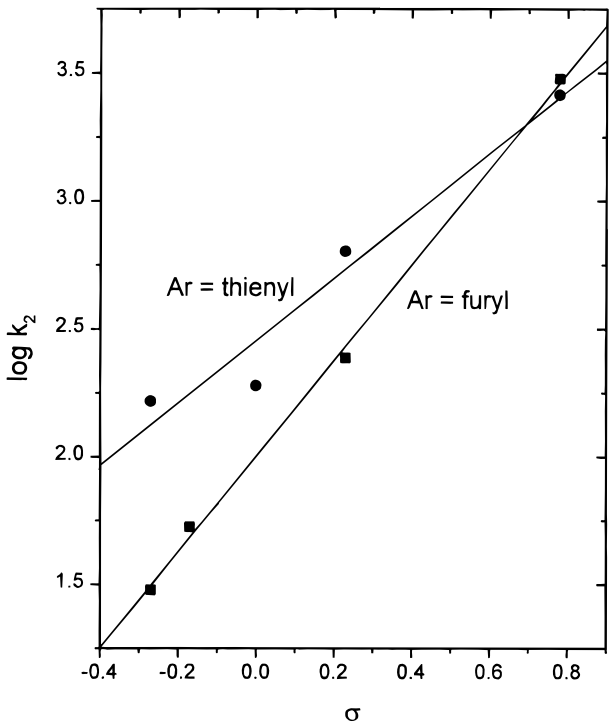

Figure 1. Hammett plots for eliminations from (*Z*)-ArCH=NOC(O)C$_6$H$_5$ promoted by DBU in MeCN at 25.0 °C.

The k_2 values showed excellent correlation with the pK_a of the leaving group on the Brönsted plot (Figure 2). The

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Table 4. Hammett ρ Values for Eliminations from *(Z)*-ArCL=NOC(O)C_6H_4Z Promoted by DBU in MeCN at 25.0 °C

	ρ	
Z	Ar = thienyl	Ar = furyl
H	1.22 ± 0.19 (1.46[a])	1.87 ± 0.05 (1.84[b])
m-Br	1.33[a]	1.79[b]
p-NO_2	1.31[a]	1.45[b]

[a] Calculated from the data for Y = H and 5-NO_2. [b] Calculated from the data for Y = 5-Me and 5-NO_2.

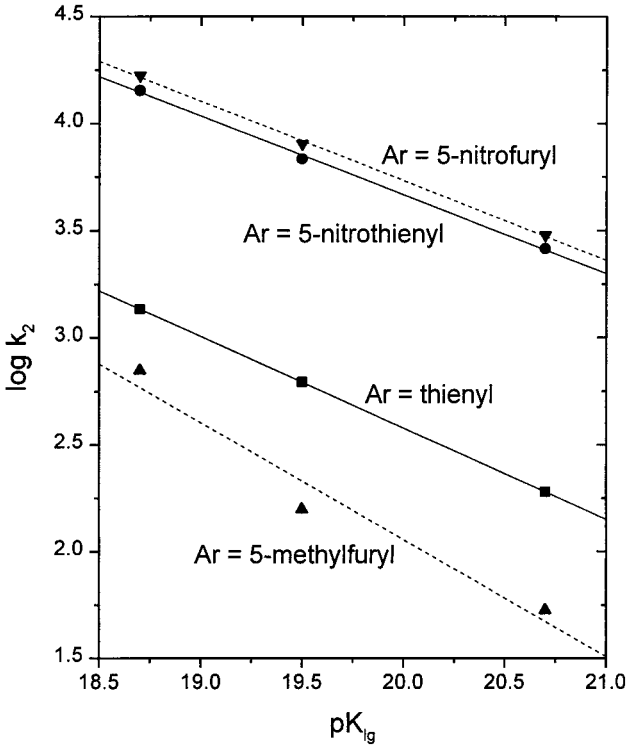

Figure 2. Plots of log k_2 vs pK_{1g} values for eliminations from (*Z*)-ArCH=NOC(O)C_6H_4 Z promoted by DBU in MeCN at 25.0 °C.

Table 5. Values of β_{1g} for Eliminations from *(Z)*-YArCL=NOC(O)C_6H_4Z Promoted by DBU in MeCN at 25.0 °C

	β_{1g}	
Y[a]	Ar = thienyl	Ar = furyl
H	−0.43 ± 0.01	−0.55 ± 0.10[b]
NO_2	−0.37 ± 0.01	−0.37 ± 0.01[b]

[a] Substituents at 4- and 5-positions for the phenyl and heterocyclic compounds, respectively, unless otherwise noted. [b] Y = 5-CH_3.

$|\beta_{1g}|$ value decreases as the electron-withdrawing ability of the β-substituent increases (Table 5).

Rates of elimination from **1** and **2** promoted by DBU−MeCN were measured at four temperatures spanning 30 °C. Arrehnius plots exhibited excellent linearity (plots not shown). Calculated enthalpies and entropies of activation are summarized in Table 6.

Discussion

Mechanism of Elimination from 1 and 2 Promoted by DBU in MeCN. Results of the kinetic investigations and product studies clearly establish that the reactions of (*Z*)-thiophene- and (*Z*)-thiophene-2-carbaldehyde *O*-benzoyloximes **1** and **2** with DBU in MeCN proceed via the E2 mechanism. Since the reactions produced only elimination products and exhibited second-order kinetics, all but bimolecular pathways can be ruled out. In addition, an E1cb mechanism is negated by the substantial values of k_H/k_D and $|\beta_{1g}|$.[24,25]

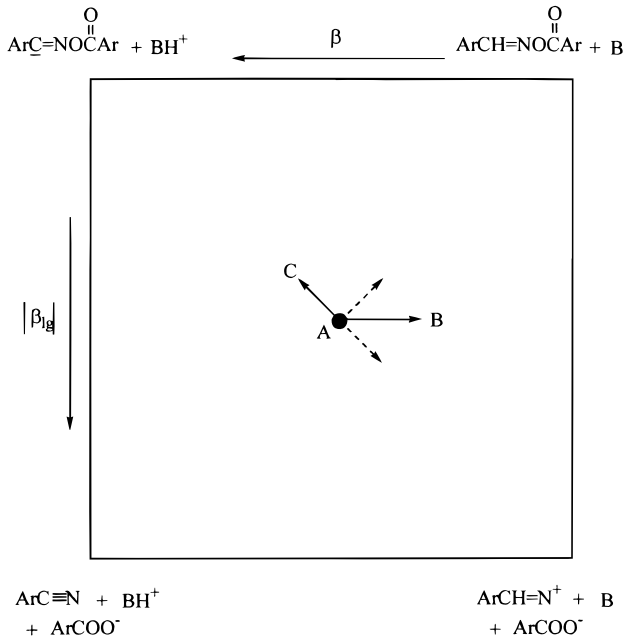

Figure 3. Reaction coordinate diagram for nitrile-forming eliminations. The effects of the change to a better leaving group and a stronger electron-withdrawing β-aryl substituent are shown by the shift of the transition state from A to B and A to C, respectively.

This conclusion is supported by the interaction coefficients. Table 3 shows that the k_H/k_D values for **1** and **2** decrease slightly as the leaving groups are made less basic. In view of the prediction that the k_H/k_D increases until it reaches a maximum value and then decreases as the extent of proton transfer increases, the decrease in the k_H/k_D value may be interpreted as either an increase or a decrease in the extent of proton transfer in the transition state.[26] However, the latter interpretation is more compatible with the smaller ρ values observed for the better leaving groups (Table 4). The result can be described by a positive p_{xy} interaction coefficient, $p_{xy} = \partial\beta/\partial pK_{1g}$, that describes the interaction between the base catalyst and the leaving group.[25,27] On the More−O'Ferall−Jencks energy diagram in Figure 3, a change to a better leaving group will raise the energy of the top edge of the diagram. The transition state on the vertical reaction coordinate will then move slightly toward the right as depicted by a shift from A to B on the energy diagram, resulting in a small decrease in k_H/k_D (vide supra).[28,29] The positive p_{xy} coefficients provide additional support for the concerted E2 mechanism.[25,27]

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For both reactions, the k_H/k_D values decrease as the electron-withdrawing ability of the β-aryl substituents is increased (Table 3). Although this result can also be interpreted with either an increase or a decrease in the extent of proton transfer in the transition state (vide supra), the former interpretation is more consistent with the smaller $|\beta_{1g}|$ values. This effect can be described by a positive $p_{xy'}$ interaction coefficient, $p_{xy'} = \partial\beta/\partial\sigma > 0$, which describes the interaction between the base catalyst and the β-aryl substituent.[25,27] Positive $p_{xy'}$ coefficients are in good agreement with an E2 mechanism and the reaction coordinate that has large components of proton transfer and N_α-OC(O)Ar bond cleavage.[25,27] These changes in the k_H/k_D values can be described on the More−O'Ferall−Jencks energy diagram (Figure 3).[28,29] An electron-withdrawing β-aryl substituent will lower the energy of the carbanion intermediate in the upper left corner of the diagram. The transition state will then move slightly toward the upper left corner, with more proton transfer and a smaller k_H/k_D, as depicted by the shift from A to C on the energy diagram.

As shown in Table 4, there is a progressive decrease in the Hammett ρ values as the leaving group is made less basic. This result can be described by a negative $p_{yy'}$ interaction coefficients, $p_{yy'} = -\partial\rho/\partial pK_{1g} = -\partial\beta_{1g}/\partial\sigma < 0$, that describes the interaction between the leaving group and the β-aryl substituent.[25,27] The decrease in the $|\beta_{1g}|$ values with a stronger electron-withdrawing β-aryl substituent provides additional evidence for this effect, i.e., $p_{yy'} = -\partial\beta_{1g}/\partial\sigma < 0$ (Table 5). The negative $p_{yy'}$ coefficients observed in these reactions are consistent with an E2 mechanism and the reaction coordinates that have large components of proton transfer and N_α-OC(O)-Ar bond cleavage, so that a better leaving group would shift the transition state from A to B in Figure 3 to decrease the extent of negative charge development and the ρ values. In addition, an electron-withdrawing substituent would shift the transition state from A to C for both **1** and **2** in Figure 3 in the direction of decreased N_α-OC(O)Ar bond cleavage and smaller $|\beta_{1g}|$ values.[28,29] All of these results are very similar to those for closely related eliminations from (*Z*)-benzaldehyde *O*-benzoyloximes.[11]

Effect of the β-Aryl Group on the Nitrile-Forming Transition State. Table 6 shows that the relative rate and transition state parameters for DBU-promoted eliminations from (*Z*)-benzaldehyde *O*-pivaloyloximes, **1** and **2**, are similar. This reveals that the transition state structures are similar for all of the elimination reactions, despite the large difference in the aromatic resonance energy of the β-aryl group. Similar values of $\Delta H^\ddagger$ and $\Delta S^\ddagger$ provide additional evidence for this conclusion. However, a closer examination of the data reveals that there is small, but clear, trend in the transition state parameters. The k_H/k_D, Hammett ρ, and $|\beta_{1g}|$ values increase gradually as the β-substituent is changed in the order phenyl < thienyl < furyl. The transition state appears to change slightly toward product-like with a larger degree of proton transfer, more negative charge development at the β-carbon, and a greater extent of leaving group departure in the same order. The trend cannot be explained by the aromatic resonance energy of the β-aryl group. An ab initio calculation reveals that all of the three reactants are nearly planar (Table S1). Hence, if the planarity is retained in the transition state, the π orbitals of the β-aryl groups should be nearly orthogonal to the developing negative charge at the β-carbon and the partial triple bond character in the transition state. This would predict that the aromatic resonance energy of the β-substituent should have little influence on the transition state structure.

Table 6. Relative Rate, k_H/k_D, Hammett ρ, and β_{1g} Values for Eliminations from (*Z*)-YArCL=NOC(O)C_6H_4Z Promoted by DBU in MeCN at 25.0 °C

	Ar = phenyl[a]	Ar = thienyl	Ar = furyl
relative rate[b]	1	1.1	0.6
k_H/k_D[b]	7.3 ± 0.2	8.2 ± 0.1	8.8 ± 0.2[c]
ρ[d]	1.21 ± 0.05	1.22 ± 0.19	1.87 ± 0.05
β_{1g}[d]	−0.40 ± 0.01	−0.43 ± 0.01	−0.55 ± 0.10[c]
$\Delta H^\ddagger$, kcal/mol[b]	6.8 ± 0.5	5.9 ± 0.1	6.5 ± 0.1[c]
$\Delta S^\ddagger$, eu[b]	−25.8 ± 1.9	−28.5 ± 0.3	−29.0 ± 1.5[c]

[a] Reference 11. [b] Y = H, Z = H, unless otherwise noted. [c] Y= 5-Me. [d] Z = H.

On the other hand, the result can readily be attributed to an increased inductive effect of the β-substituent. Since the 5-thienyl and 5-furyl substituents are closer to the β-carbon than the phenyl substituents, the electronic effect of the former would be more efficiently transmitted to the reaction site.[30] Hence the negative charge density at the β-carbon and the partial triple bond character in the former transition states would be better stabilized by the electron-withdrawing substituents, which would in turn change the transition state structures toward more product-like.

In conclusion, the nitrile-forming anti eliminations from **1** and **2** proceed by the E2 mechanism via symmetrical transition states. The structures of the transition states appear to change slightly toward more product-like with a larger degree of proton transfer, more negative charge development at the β-carbon, and a greater extent of the leaving group departure as the β-substituent is changed from phenyl to thienyl to furyl. Noteworthy is the negligible influence of the aromatic resonance energy of the β-substituent upon the nitrile-forming transition state.

Experimental Section

Materials. (*Z*)-Thiophene-2-carbaldehyde oximes were prepared by the reactions of substituted thiophene-2-carboxaldehyde (20 mmol) with 2 equiv of NH_2OH in H_2O−EtOH by the literature procedure.[13−15] Most of the (*Z*)-thiophene-2-carbaldehyde *O*-benzoyloximes were synthesized in reasonable yields by slowly adding the substituted (*Z*)-thiophene-2-carbaldehyde oxime (2.0 mmol) in 0.5 mL of pyridine to a solution containing the substituted benzoyl chloride (2.2 mmol) in 7.0 mL of pyridine at −35 °C. The solution was stirred for 10 min and poured into 70 mL of ice water with vigorous stirring. The product was filtered with Büchner funnel and washed thoroughly with cold water until all of the pyridine was removed. The product was dissolved in a minimum amount of $CHCl_3$ and was added to a larger amount of methanol. The product precipitated as white solid.

(*Z*)-5-Nitrothiophene-2-carbaldehyde *O*-4-nitrobenzoyloxime (**1dd′**) was synthesized by slowly adding (*Z*)-5-nitrothiophene-2-carbaldehyde oxime (0.5 mmol) in 0.06 mL of pyridine to a solution containing 4-nitrobenzoyl chloride (0.5 mmol) in 3.0

(30) The distances between the β-carbon and the para and meta positions of the phenyl group and those between the β-carbon and C-5 of the thienyl and furyl groups can be calculated from the geometrical parameters shown in Table S1 of the Supporting Information. The values are 4.247, 3.840, 3.959, and 3.603 Å, respectively. This indicates that the average distance between the β-carbon and the aryl substituents decreases as the β-aryl group is changed in the order phenyl > thienyl > furyl.

mL of THF at −78 °C. The solution was stirred for 10 min. To this solution was added 30 mL of MeOH, which was cooled below −30 °C. The precipitated product was filtered and washed with cold methanol. The deuterated compounds **1aa′-*d*$_1$**, **1ac′-*d*$_1$**, **1ad′-*d*$_1$**, and **1ea′-*d*$_1$** were prepared by the same procedure using the thiophene-2-carboxaldehyde-d_1 and 4-nitrothiophene-2-carboxaldehyde-d_1, respectively.[16−19] In most cases, the products were analytically pure and used without further purification. The spectral and analytical data of the compounds were consistent with the proposed structures. The yield (%), melting point (°C), IR (KBr, C=O, cm^{-1}), NMR ($CDCl_3$), and combustion analysis data for the new compounds are as follows (all *J* values are in Hz).

(*Z*)-C$_4$H$_3$(S)CH=NOC(O)C$_6$H$_5$ (1aa′): yield 50%; mp 68−70 °C; IR 1744; NMR δ 8.32−8.25 (m, 2H), 8.16 (s, 1H), 7.76−7.62 (m, 2H), 7.58−7.48 (m, 3H), 7.21−7.16 (m, 1H). Anal. Calcd for $C_{12}H_9NO_2S$: C, 62.32; H, 3.92; N, 6.06; S, 13.86. Found: C, 62.44; H, 4.10; N, 6.12; S, 13.90.

(*Z*)-C$_4$H$_3$(S)CD=NOC(O)C$_6$H$_5$ (1aa-*d*$_1$): yield 65%; mp 68−70 °C; IR 2239 (C−D), 1742; NMR δ 8.32−8.26 (m, 2H), 7.76−7.60 (m, 2H), 7.58−7.48 (m, 3H), 7.20−7.16 (m, 1H). Anal. Calcd for $C_{12}H_8DNO_2S$: C, 62.05; H, 4.34; N, 6.03; S, 13.80. Found: C, 62.30; H, 4.15; N, 5.92; S, 13.59.

(*Z*)-C$_4$H$_3$(S)CH=NOC(O)C$_6$H$_4$-*m*-Br (1ab′): yield 52%; mp 94−95 °C; IR 1757; NMR δ 8.42 (s, 1H), 8.22 (d, 1H, *J* = 8.0), 8.17 (s, 1H), 7.81−7.75 (m, 2H), 7.55 (d, 1H, *J* = 4.0), 7.43 (t, 1H, *J* = 8.0), 7.21 (t, 1H, *J* = 4.0). Anal. Calcd for $C_{12}H_8NO_2SBr$: C, 46.47; H, 2.60; N, 4.52; S, 10.34. Found: C, 46.57; H, 2.69; N, 4.52; S, 10.20.

(*Z*)-C$_4$H$_3$(S)CH=NOC(O)C$_6$H$_4$-*m*-Br (1ab′-*d*$_1$): yield 42%; mp 94−95 °C; IR 2235 (C−D), 1759; NMR δ 8.43 (s, 1H), 8.22 (d, 1H, *J* = 8.0), 7.80−7.75 (m, 2H), 7.56 (d, 1H, *J* = 4.0), 7.43 (t, 1H, *J* = 8.0), 7.21 (t, 1H, *J* = 4.0). Anal. Calcd for $C_{12}H_7DNO_2SBr$: C, 46.32; H, 2.92; N, 4.50; S, 10.32. Found: C, 46.56; H, 2.65; N, 4.41; S, 10.32.

(*Z*)-C$_4$H$_3$(S)CH=NOC(O)C$_6$H$_4$-*p*-NO$_2$ (1ac′): yield 62%; mp 146−147 °C; IR 1749; NMR δ 8.46 (d, 2H, *J* = 8.4), 8.40 (d, 2H, *J* = 8.4), 8.20 (s, 1H), 7.78 (d, 1H, *J* = 4.2), 7.58 (d, 1H, *J* = 4.2), 7.22 (t, 1H, *J* = 4.2). Anal. Calcd for $C_{12}H_8N_2O_4S$: C, 52.17; H, 2.92; N, 10.14; S, 11.60. Found: C, 51.87; H, 3.03; N, 10.16; S, 11.88.

(*Z*)-C$_4$H$_3$(S)CD=NOC(O)C$_6$H$_4$-*p*-NO$_2$ (1ac′-*d*$_1$): yield 79%; mp 147−148 °C; IR 2239 (C−D), 1759; NMR δ 8.44 (d, 2H, *J* = 8.4), 8.38 (d, 2H, *J* = 8.4), 7.79 (d, 1H, *J* = 4.2), 7.58 (d, 1H, *J* = 4.2), 7.22 (t, 1H, *J* = 4.2). Anal. Calcd for $C_{12}H_7DN_2O_4S$: C, 51.98; H, 2.65; N, 10.10; S, 11.56. Found: C, 52.02; H, 2.98; N, 10.07; S, 11.47.

(*Z*)-5-MeOC$_4$H$_2$(S)CH=NOC(O)C$_6$H$_5$ (1ca′): yield 61%; mp 89−91 °C; IR 1736; NMR δ 8.25 (d, 2H, *J* = 8.0), 7.93 (s, 1H), 7.69−7.50 (m, 3H), 7.24 (d, 1H, *J* = 4.0), 6.30 (d, 1H, *J* = 4.0), 3.99 (s, 3H). Anal. Calcd for $C_{13}H_{11}NO_2S$: C, 59.76; H, 4.24; N, 5.36; S, 12.27. Found: C, 59.61; H, 4.36; N, 5.35; S, 12.00.

(*Z*)-5-BrC$_4$H$_2$(S)CH=NOC(O)C$_6$H$_5$ (1da′): yield 40%; mp 83−85 °C; IR 1757; NMR δ 8.25 (d, 2H, *J* = 8.0), 8.04 (s, 1H), 7.72−7.53 (m, 3H), 7.29 (d, 1H, *J* = 4.0), 7.17 (d, 1H, *J* = 4.0). Anal. Calcd for $C_{12}H_8NO_2SBr$: C, 46.47; H, 2.60; N, 4.52; S, 10.34. Found: C, 46.37; H, 2.65; N, 4.46; S, 10.14.

(*Z*)-5-O$_2$NC$_4$H$_2$(S)CH=NOC(O)C$_6$H$_5$ (1ea′): yield 51%; mp 105−107 °C; IR 1752; NMR δ 8.24 (d, 2H, *J* = 8.0), 8.18 (s, 1H), 7.97 (d, 1H, *J* = 4.2), 7.75−7.56 (m, 3H), 7.45 (d, 1H, *J* = 4.2). Anal. Calcd for $C_{12}H_8N_2O_4S$: C, 52.17; H, 2.92; N, 10.14; S, 11.60. Found: C, 52.21; H, 3.04; N, 10.25; S, 11.57.

(*Z*)-5-O$_2$NC$_4$H$_2$(S)CH=NOC(O)C$_6$H$_5$ (1ea′-*d*$_1$): yield 79%; mp 106−107 °C; IR 2258 (C−D), 1751; NMR δ 8.24 (d, 2H, *J* = 8.0), 8.18 (s, 1H), 7.97 (d, 1H, *J* = 4.2), 7.75−7.56 (m, 3H), 7.45 (d, 1H, *J* = 4.2). Anal. Calcd for $C_{12}H_8N_2O_4S$: C, 52.17; H, 2.92; N, 10.14; S, 11.60. Found: C, 52.21; H, 3.04; N, 10.25; S, 11.57.

(*Z*)-5-O$_2$NC$_4$H$_2$(S)CH=NOC(O)C$_6$H$_4$-*m*-Br (1eb′): yield 56%; mp 123−125 °C; IR 1751; NMR δ 8.40 (s, 1H), 8.19 (s, 1H), 8.18 (d, 1H, *J* = 8.0), 7.97 (d, 1H, *J* = 4.2), 7.84 (d, 1H, *J* = 8.0), 7.49 (t, 1H, *J* = 8.0), 7.47 (d, 1H, *J* = 4.2). Anal. Calcd for $C_{12}H_7N_2O_4SBr$: C, 40.58; H, 1.99; N, 7.89; S, 9.03. Found: C, 40.51; H, 1.96; N, 7.77; S, 8.89.

(*Z*)-5-O$_2$NC$_4$H$_2$(S)CH=NOC(O)C$_6$H$_4$-*p*-NO$_2$ (1ec′): yield 50%; mp 134−135 °C; IR 1757; NMR δ 8.45 (d, 2H, *J* = 8.0), 8.38 (d, 2H, *J* = 8.0), 8.23 (s, 1H), 7.99 (d, 1H, *J* = 4.2), 7.49 (d, 1H, *J* = 4.2). Anal. Calcd for $C_{12}H_7N_3O_6S$: C, 44.86; H, 2.20; N, 13.08; S, 9.98. Found: C, 45.12; H, 2.14; N, 13.09; S, 9.63.

(*Z*)-Furan-2-carbaldehyde oximes were prepared by refluxing a solution of the substituted furan-2-carbaldehyde (20 mmol) and an excess amount of NH_2OH in MeOH by the literature procedure.[20−25] All of the (*Z*)-furan-2-carbaldehyde *O*-benzoyloximes were synthesized by the same procedure as employed for the synthesis of (*Z*)-thiophene-2-carbaldehyde *O*-benzoyloximes except that the reaction temperature was lowered to −50 °C. The products were obtained as white or yellow solids. The deuterated compounds **2ba′-*d*$_1$**, **2bc′-*d*$_1$**, **2bd′-*d*$_1$**, and **2ea′-*d*$_1$** were prepared by the same procedure from the 5-methylfuran-2-carbaldehyde-d_1 and 5-nitrofuran-2-carbaldehyde-d_1, respectively.[16−19] The spectral and analytical data of the compounds were consistent with the proposed structures. The yield (%), melting point (°C), IR(KBr, C=O, cm^{-1}), NMR ($CDCl_3$), and combustion analysis data for the new compounds are as follows.

(*Z*)-5-MeC$_4$H$_2$(O)CH=NOC(O)C$_6$H$_5$ (2ba′): yield 50%; mp 77−78 °C; IR 1794; NMR δ 8.16 (d, 2H, *J* = 7.3), 7.82 (s, 1H), 7.62−7.50(m, 3H), 7.21(d, 1H, *J* = 3.0), 6.23 (d, 1H, *J* = 3.0), 2.39 (s, 3H). Anal. Calcd for $C_{13}H_{11}NO_3$: C, 68.11; H, 4.84; N, 6.11. Found: C, 68.44; H, 4.50; N, 6.12.

(*Z*)-5-MeC$_4$H$_2$(O)CD=NOC(O)C$_6$H$_5$ (2ba′-*d*$_1$): yield 55%; mp 77−78 °C; IR 2239 (C−D), 1793; NMR δ 8.19 (d, 2H, *J* = 7.3), 7.68−7.45 (m, 3H), 7.21 (d, 1H, *J* = 3.0), 6.23 (d, 1H, *J* = 3.0), 2.43 (s, 3H). Anal. Calcd for $C_{13}H_{10}DNO_3$: C, 67.82; H, 5.25; N, 6.08. Found: C, 67.47; H, 4.95; N, 5.87.

(*Z*)-5-MeC$_4$H$_2$(O)CH=NOC(O)C$_6$H$_4$-*m*-Br (2bb′): yield 51%; mp 99 °C; IR 1747; NMR δ 8.36 (s, 1H), 8.11 (d, 1H, *J* = 5.4), 7.78 (s, 1H), 7.75 (d, 1H, *J* = 5.4), 7.40 (t, 1H, *J* = 5.4), 7.11 (d, 1H, *J* = 2.0), 6.23 (d, 1H *J* = 2.0), 2.49 (s, 3H). Anal. Calcd for $C_{13}H_{10}BrNO_3$: C, 50.67; H, 3.27; N, 4.55. Found: C, 50.57; H, 3.59; N, 4.52.

(*Z*)-5-MeC$_4$H$_2$(O)CD=NOC(O)C$_6$H$_4$-*m*-Br (2bb′-*d*$_1$): yield 41%; mp 99 °C; IR 2236 (C−D), 1748; NMR δ 8.36 (s, 1H), 8.11 (d, 1H, *J* = 5.4), 7.75 (d, 1H, *J* = 5.4), 7.40 (t, 1H, *J* = 5.4), 7.11 (d, 1H, *J* = 2.0), 6.24 (d, 1H *J* = 2.0), 2.49 (s, 3H).

(*Z*)-5-MeC$_4$H$_2$(O)CH=NOC(O)C$_6$H$_4$-*p*-NO$_2$ (2bc′): yield 21%; mp 135−136 °C; IR 1748; NMR δ 8.44−8.32 (m, 4H), 7.84 (s, 1H), 7.13 (d, 1H, *J* = 3.0), 6.27 (d, 1H, *J* = 3.0), 2.44 (s, 3H). Anal. Calcd for $C_{13}H_{10}N_2O_5$: C, 56.94; H, 3.68; N, 10.22. Found: C, 56.87; H, 3.53; N, 10.16.

(*Z*)-5-MeC$_4$H$_2$(O)CH=NOC(O)C$_6$H$_4$-*p*-NO$_2$ (2bc′-*d*$_1$): yield 53%; mp 135 °C; IR 2239 (C−D), 1748; NMR δ 8.45−8.29 (m, 4H), 7.17 (d, 1H, *J* = 3.0), 6.25 (d, 1H, *J* = 3.0), 2.42 (s, 3H).

(*Z*)-5-MeOC$_4$H$_2$(O)CH=NOC(O)C$_6$H$_5$ (2ca′): yield 25%; mp 81−82 °C; IR 1736; NMR δ 8.16 (d, 2H, *J* = 7.2), 7.70 (s, 1H), 7.64−7.48 (m, 3H), 7.24 (d, 1H, *J* = 3.6), 5.46 (d, 1H, *J* = 3.6), 3.90 (s, 3H).

(*Z*)-5-BrC$_4$H$_2$(O)CH=NOC(O)C$_6$H$_5$ (2da′): yield 40%; mp 97−98 °C; IR 1757; NMR δ 8.44−8.32 (m, 4H), 7.84 (s, 1H), 7.13 (d, 1H, *J* = 3.0), 6.27 (d, 1H, *J* = 3.0), 2.44 (s, 3H). Anal. Calcd for $C_{12}H_8BrNO_3$: C, 48.91; H, 2.93; N, 4.75. Found: C, 49.29; H, 2.93; N, 4.57.

(*Z*)-5-O$_2$NC$_4$H$_2$(O)CH=NOC(O)C$_6$H$_5$ (2ea′): yield 51%; mp 110−111 °C; IR 1752; NMR δ 8.22 (d, 2H, *J* = 7.2), 7.80 (s, 1H), 7.70−7.52 (m, 3H), 7.43 (d, 1H, *J* = 3.6), 7.38 (d, 1H, *J* = 3.6). Anal. Calcd for $C_{12}H_8N_2O_5$: C, 55.38; H, 3.10; N, 10.77. Found: C, 55.56; H, 3.09; N, 10.60.

(*Z*)-5-O$_2$NC$_4$H$_2$(O)CD=NOC(O)C$_6$H$_5$ (2ea′-*d*$_1$): yield 45%; mp 111−113 °C; IR 2239 (C−D), 1752; NMR δ 8.23 (d, 2H, *J* = 7.2), 7.70−7.50 (m, 3H), 7.43 (d, 1H, *J* = 3.6), 7.39 (d, 1H, *J* = 3.6).

(*Z*)-5-O$_2$NC$_4$H$_2$(O)CH=NOC(O)C$_6$H$_4$-*m*-Br (2eb′): yield 30%; mp 123−125 °C; IR 1747; NMR δ 8.33 (s, 1H), 8.20 (d, 1H, *J* = 8.0), 7.97 (s, 1H), 7.83 (d, 1H, *J* = 7.4), 7.51−7.47 (m, 1H), 7.46 (d, 1H, *J* = 3.8), 7.31 (d, 1H, *J* = 3.8). Anal. Calcd for $C_{12}H_7BrN_2O_5$: C, 42.50; H, 2.08; N, 8.26. Found: C, 42.51; H, 2.10; N, 8.31.

(*Z*)-5-$O_2NC_4H_2$(O)CH=NOC(O)C_6H_4-*p*-NO_2 (2ec′): yield 35%; mp 120−122 °C; IR 1768; NMR δ 8.55−8.25 (m, 4H), 7.97 (s, 1H), 7.47 (d, 1H, J = 4.0), 7.37 (d, 1H, J = 4.0).

1,8-Diazabicyclo[5.4.0]undec-7-ene (DBU) was redistilled in vacuo prior to use, and acetonitrile was purified as described previously.[10,11]

Product Studies. The products of the reaction between **1aa′** and DBU in MeCN were identified by TLC and GC−MS as described previously.[10,11] The products were thiophene-2-carbonitrile and benzoate. The yield of thiophene-2-carbonitrile from the reactions of **1aa′** with DBU were determined by GC as described previously.[9−11] The yield was 94%. To identify the products of the reaction between **2ba′** and DBU in MeCN, a solution containing **2ba′** (50 mg, 0.22 mmol) and DBU (90 mg, 0.60 mmol) in 2 mL of CD_3CN was added to an NMR tube, and the spectrum was recorded after 5 min. The NMR spectrum indicated that furan-2-carbonitrile and benzoate were the only products.

Kinetic Studies. Reactions of (*Z*)-thiophene- and (*Z*)-furan-2-carbaldehyde *O*-benzoyloximes with DBU in MeCN were followed by monitoring the change in the UV absorption with the reaction time using a UV−vis or a stopped-flow spectrophotometer as described before.[10,11] For all reactions, the UV absorption of the reactants decreased and that of the products increased with time. Except for the reactions of **1aa′** and **1aa′-*d*$_1$**, clean isosbestic points were observed at 262−332 nm. Freshly prepared solutions were used for all kinetic runs.

Control Experiments. The stability of **1**, **2**, and their solutions were determined by measuring the melting point and periodical scanning of the solutions with the UV spectrophotometer.[9,10] No change in melting point or UV spectrum was detected for either compound in the solid state for at least 1 month at −10 °C. However, the solutions of **1** and **2** in MeCN decomposed completely within 20 h.

Calculation. Structures of the (*Z*)-thiophene- and (*Z*)-furan-2-carbaldehyde *O*-benzoyloximes were calculated on a Silicon Graphics workstation using the Gaussian 94, Revision A.1, quantum mechanical package developed by Pole and coworkers.[31] All structures were fully optimized using a 6-311G basis set.

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Supporting Information Available: Structures of (*Z*)-ArCH=NOC(O)C_6H_5 (Ar = phenyl, thienyl, furyl) calculated by the Gaussian 94, Revision A.1 with a 6-311G basis set (1 page). This information is contained in libraries on microfiche, immediately follows this article in the microfilm version of the journal, and can be ordered from the ACS; see any current masthead page for ordering information.

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