Reactions of 1,3-Diaryl-2-chloropropane-1,3-diones with Nucleophiles − Cyanide-Induced Retro-Claisen−Claisen Condensation

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Treatment of some 1,3-diaryl-2-chloropropane-1,3-diones, acyclic chloro-substituted enaminones and β-oxo esters with nucleophiles was shown to proceed easily with the formation, at least in the first stage, of formal nucleophilic substitution products. Treatment of enaminones and β-oxo esters with azide and cyanide ions proceeds with the preservation of the skeleton, whereas chloro-substituted diaroylmethanes undergo retro-Claisen–Claisen condensation reactions in the course of the reaction with cyanide. Dibenzoylchloromethane reacts with azide and cyanide ions with fragmentation of the molecule and subsequent reassembly, resulting in benzoylated benzaldehyde cyanohydrin and a 1,3-oxathiol derivative, respectively.

Introduction

α-Halo-substituted carbonyl compounds are well-known active substrates for nucleophilic substitution reactions. The reason for the high reactivity of these compounds seems to be the operation of a specific reaction mechanism, involving initial attack of the nucleophile at the carbonyl carbon atom with subsequent epoxide ring-closure. The epoxide is opened by the action of one more nucleophile equivalent with the product of reaction formation.[1] At the same time there are very few data in the literature about the reactivity of halo-substituted enaminones, with the halogen atom at the enamine carbon atom,[2] except for our previous papers,[3−7] in which we reported that substitution in this system proceeds easily at least in the case of cyanide and azide ions. This reaction was shown also to proceed through the intermediate epoxide formation.[6]

It was also shown that related substrates, such as halo-substituted nitroenamines and enaminones, with disubstituted nitrogen atoms are unreactive under the same conditions because of the impossibility of the operation of such a mechanism.[6,7] It might thus be speculated that substitution reactions in similar systems might proceed easily, if at all, only according to the suggested scheme. To our surprise we failed to find any data concerning the reactivity of simple acyclic halo-substituted enaminones and of β-dicarbonyl compounds with nucleophiles such as cyanide and azide ions. Data on the reactivity of 1,3-dicarbonyl-2-halo compounds with other nucleophiles are also not numerous (see, for example, refs.[8−12]) The aim of this paper is therefore to investigate the scope of the suggested reaction scheme and the possibilities of its operation in the case of the simplest analogues − acyclic 2-chloroenaminones and 1,3-diketones.

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Results and Discussion

Previously we had found that reactions between chloro-substituted enaminones of imidazolidine nitroxides **1** and NaCN proceed with formation of the corresponding nitrile **2**. This transformation, formally a nucleophilic substitution, proceeds through the intermediate formation of epoxide **3** as a result of initial nucleophilic addition at the carbonyl carbon atom and subsequent intramolecular nucleophilic substitution of the chlorine atom.[6] Reactions between **1** and sodium azide proceed in a similar manner with the intermediate formation of corresponding azides **4**, which are unstable and spontaneously convert into α-imino ketones **5** (Scheme 1).[7] The catalytic effect of cyanide ion was recently shown to allow the involvement of other nucleophiles in this reaction.[13] The reaction between the enaminone **6** and NaCN in DMSO was shown to proceed easily (room temp., 2 h) with the formation of a nitrile **7** (Scheme 2).

Treatment of the chloro-substituted enaminones **6** with NaN_3 affords the dimer **8** of an expected diimino ketone (cf. ref.[7]). The dimeric structure of **8** in the crystalline state was indicated by the IR spectra (KBr), in which no car-

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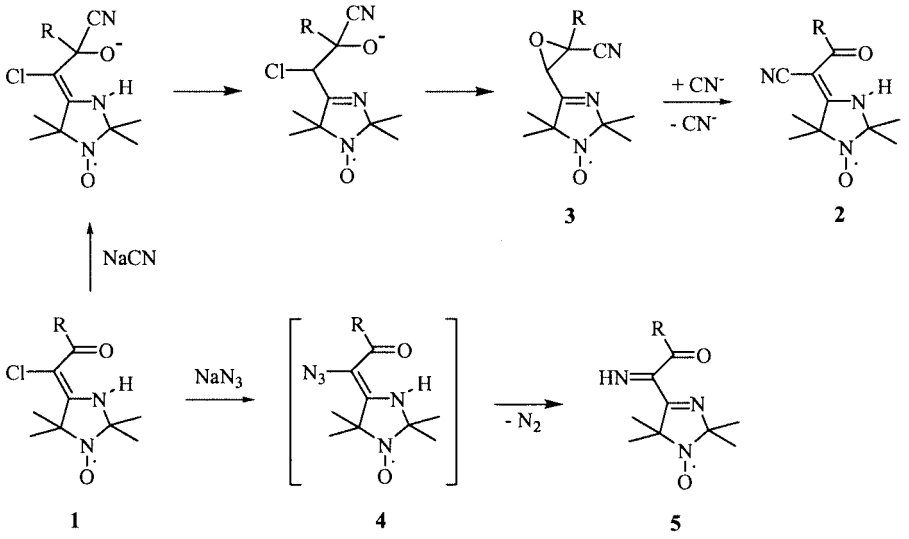
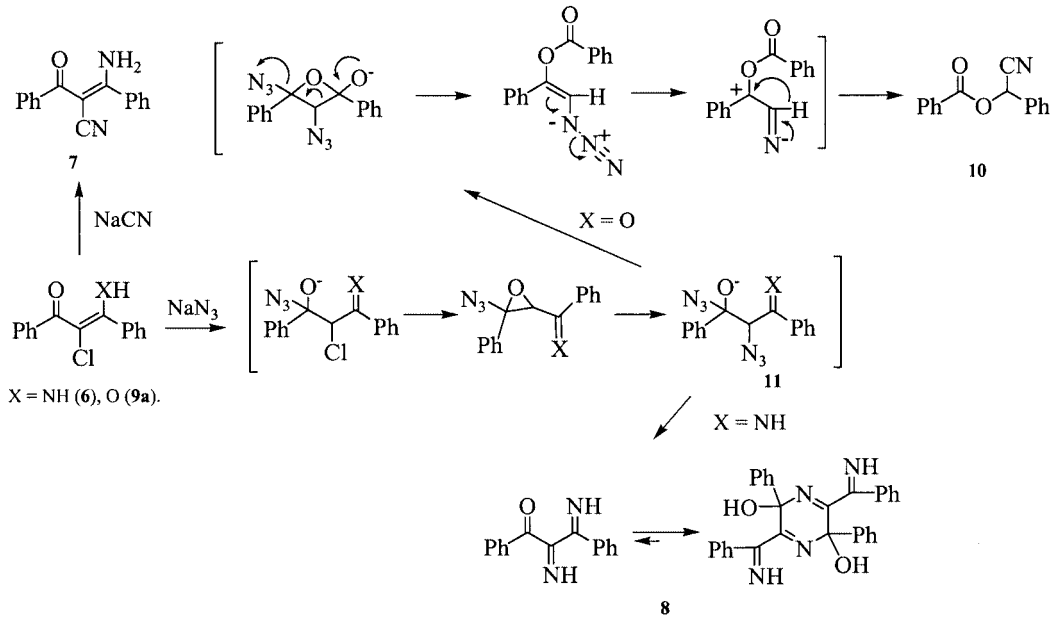


Scheme 1



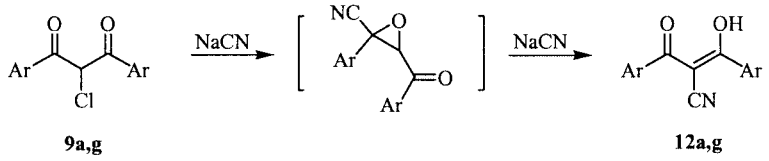
Scheme 2

bonyl bond adsorption was observed. It should be noted that the UV spectrum of **8** in ethanol (λ = 336 nm) is essentially different from that in KBr (λ = 263 nm), which may be due to **8** existing in the dimer form in the crystalline state but in an equilibrium with the monomer form in ethanol solution. The molecular ion of **8** in its mass spectra corresponds to a monomer.

In contrast, treatment of the β-diketone 2-chloro-1,3-diphenylpropane-1,3-dione (**9a**) with sodium azide under the same conditions gave benzoylated benzaldehyde cyanohydrin **10** in a high yield. This could be accountable for by the increased electronegativity of the oxygen atom in the diketone **9a** molecule in relation to the nitrogen atom in the enaminone **6** molecule. As a result, intramolecular nucleophilic attack within the intermediate **11** presumably proceeds at the carbonyl group with intermediate formation of a four-membered ring. Subsequent cleavage of this ring finally results in the formation of product **10**.

Treatment of the 2-chloropropane-1,3-diones **9a** and **9g** with NaCN under the same conditions gave the expected nitriles: 2-benzoyl-3-oxo-3-phenylpropanenitrile (**12a**) and 2-(4-methoxybenzoyl)-3-(4-methoxyphenyl)-3-oxopropanenitrile (**12g**) (Scheme 3). It should be noted that according to its ^{1}H NMR spectrum nitrile **12a** exists in $CDCl_3$ solution as its enol (absence of a signal for the proton at the cyano-substituted carbon atom and presence of a low-field signal at δ = 17.80 ppm for an enol hydrogen atom bonded by very strong intramolecular hydrogen bonding).

Despite the apparent simplicity of the described transformation and the fact that 2-benzoyl-3-oxo-3-phenylpro-



Scheme 3

panenitrile (**12a**) is a well-known substance,[14] the reactions between halogenated propane-1,3-diones, including **9a**, and cyanide and other simple nucleophiles (except for methoxide anion[2]) had not been studied previously. A series of 2-chloropropane-1,3-diones was therefore synthesized and their reactions with NaCN were studied. Unexpectedly, it was found that treatment of the diketone **9b** with NaCN resulted in the formation of a mixture of two nitriles − **12a** and **12b**, in a ratio of 4:1. The reactions of other diketones **9c**−**f** proceed in a similar way, giving mixtures of products (Scheme 4), the ratios of which, by GC-MS, are summarized in Table 1. In some cases nitriles of 3-aryl-3-oxopropanenitriles **13D** and **13E** were isolated from the reaction mixture, but usually the formation of these products was only observed by GC-MS (Table 2).

If the formation of the nitriles **13** in the course of the reactions between compounds **9** and NaCN is taken into account, the reaction according to Scheme 5 could be suggested. The first step is the formation of the corresponding substitution products, unsymmetrical nitriles **12B**, which presumably proceeds consistently with the scheme described above.

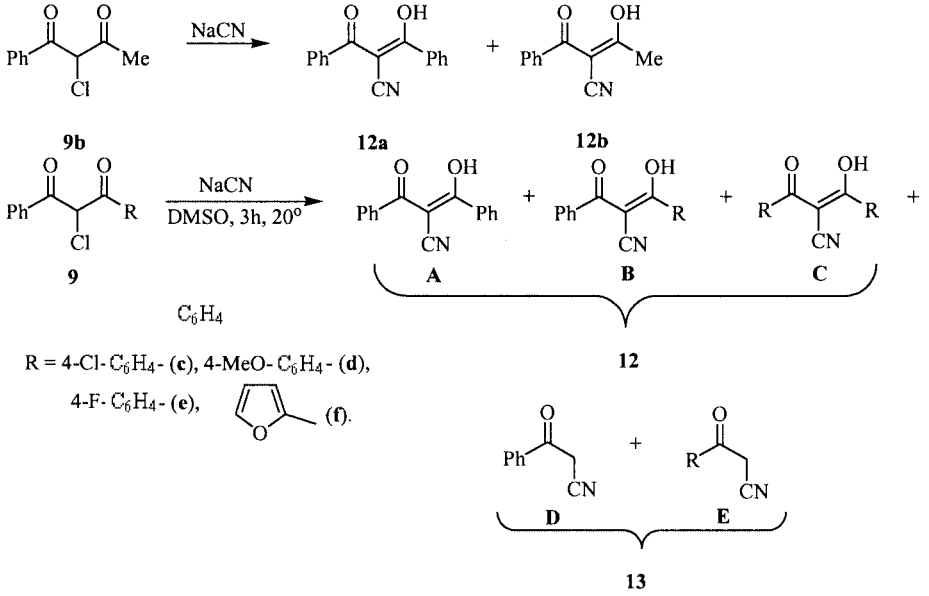
The next step is the nucleophilic attack of the cyanide ion at one of the carbonyl groups of nitrile **12B**, followed by cleavage of the C−C bond, affording the nitriles **14A** or **14B** and the relatively stable anions **15B** and **15A**. Subsequent interaction between anions **15** and the nitriles **14** forms asymmetric (**12B**) or symmetric (**12A** and **12C**) nitriles. Furthermore, it is not ruled out that anions **15** may

Table 1. The compositions of reaction mixture of diaroylchloromethanes **9** with NaCN

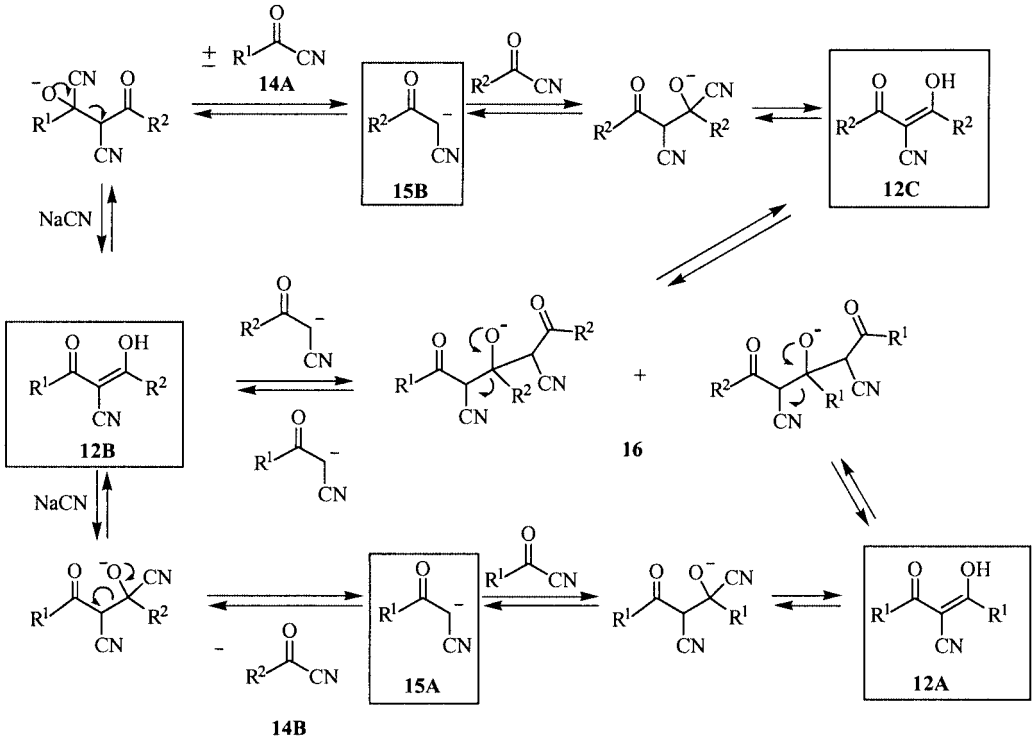
№	R	Ratio (%) A	B	C	Total yield (%)	Reaction time [h]
	4-Cl-C_6H_4	29.6	60.9	9.5	48.9	3
9c	4-Cl-C_6H_4	27.7	51.8	20.6	97.6	24
	4-Cl-C_6H_4	17.4	56.2	26.4	34.5	168
	4-MeO-C_6H_4	14.4	74.4	11.2	52.8	3
9d	4-MeO-C_6H_4	6.6	61.9	31.6	38.9	24
	4-MeO-C_6H_4	3.4	50.8	45.8	67.8	168
9e	4-F-C_6H_4	22.9	55.1	21.9	11.8	3
9f	α-furyl	3	95.7	1.3	27.1	3

Table 2. Ratios of aroylacetonitriles **13** in reaction mixtures of diaroylchloromethanes **9** and NaCN

R	Ratio (%) D	E	Total yield (%)	Reaction time [h]
4-Cl-C_6H_4	36.2	63.8	9.7	3
4-F-C_6H_4	28.4	71.6	0.1	3
α-furyl	3.2	96.8	4.1	3



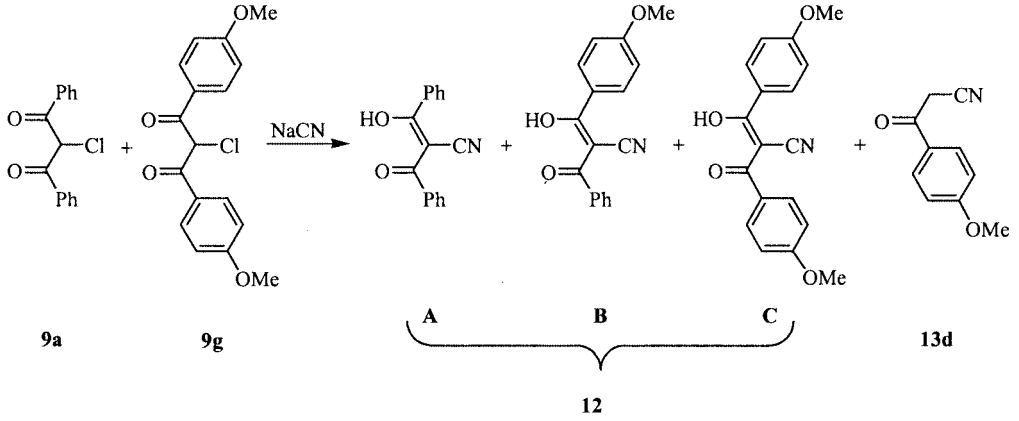
Scheme 4



Scheme 5

interact with the nitriles **12**, forming intermediates of type **16**. All the reaction steps seem to be reversible, because the relative contents of nitriles **12** depend on the reaction time. Thus, the mixture of nitriles **12** obtained after diketones **9c** (Scheme 6) and **9d** had been kept for 3 h with excess NaCN was isolated and analysed quantitatively. After that, the mixture was allowed to react with NaCN for 24 h. Repeated analysis of the mixture showed that the isomer content changed noticeably (Table 1). Data on the products ratio in the cross reaction of diketones **9a** and **9g** with NaCN (Scheme 6) are summarized in Table 3. In this case, both types of product (symmetrical and unsymmetrical) are formed.

One might suppose that the relative content of products should be dictated by the stability of the aroylacetonitrile anion **15**, one of the key intermediates in the process, the stability of which should in turn correlate with the acidity of the corresponding arenecarboxylic acid (the electronic structures of anions **15** are almost the same as those of the subsequent carboxylate anions). In this case, the product ratios in the reactions of 2-chloro-1-(2-furyl)-3-phenylpropane-1,3-dione (**9f**) and 2-chloro-1-(4-chlorophenyl)-3-phenylpropane-1,3-dione (**9c**) with NaCN should be almost the same ($pK_a = 3.45 \cdot 10^{-4}$ for 2-furoic acid and $1.03 \cdot 10^{-4}$ for 4-chlorobenzoic acid), but the product contents in the reaction mixtures are in fact rather different (Table 1). Prediction of the results of the reaction is complicated by the ambiguity of the reaction scheme and by the lack of evidence that we have a thermodynamically equilibrated mixture of products in each particular case because, as mentioned



Scheme 6

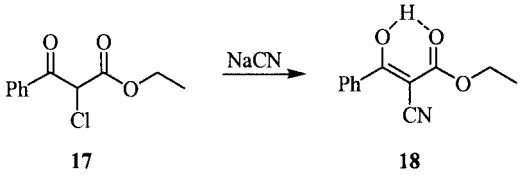
Table 3. The compositions of cross-reaction mixtures of diaroylchloromethanes **9a** and **9g** with NaCN

Ratio (%) A	B	C	Total yield of nitriles **12** (%)	Yield of **13d** (%)	Reaction time [h]
28.2	46.5	25.3	79.9	0.4	3
13.7	44.1	42.2	79.4	0.2	168

above, the product ratios change with reaction time. One can assume that for longer reaction times and equal stabilities of products, the product ratio is simply statistical.

It was of interest to examine whether the reaction of 2-chloro-1,3-diphenylpropane-1,3-dione (**9a**) occurs with preservation of the skeleton or not. For this purpose, 2-chloro-2-(monodeuteriobenzoyl)-1,3-diphenylpropane-1,3-dione was synthesized, and its reaction behaviour with NaCN was examined. Mass spectrometry of the resulting product mixture showed that the intensities of the lines corresponding to [M + 2] and [M + 3] changed dramatically {intensity (%): 1.39/8.54 for [M + 2] and 0/3.87 for [M + 3] for non-deuterated 2-benzoyl-3-oxo-3-phenylpropanenitrile and the mixture of 2-(monodeuteriobenzoyl)- and 2-benzoyl-3-oxo-3-phenylpropanenitriles, respectively}. These data are interpreted as substantial cleavage of the skeleton in the reaction of dibenzoylchloromethane and subsequent reconstruction of the molecule.

It should be noted that, unlike β-diketones but similarly to the enaminone **6**, the only isolated product in the reaction between ethyl 2-chloro-3-oxo-3-phenylpropanoate − β-oxo ester **17** − and NaCN was the nitrile **18** (Scheme 7). The reason for the absence of a retro-Claisen reaction in this case seems to be the reduced electrophilicity of the ester and enamine carbon atom in relation to the carbonyl group.



17 **18**

Scheme 7

In continuation of the study of the reactions of 1,3-diaryl-2-chloropropane-1,3-diones, 2-chloro-1,3-diphenylpropane-1,3-dione (**9a**) was involved in a reaction with potassium thiocyanate. Two isomeric products, **19a** and **19b**, were isolated in this reaction, both with elemental analysis data consistent with the expected substitution product. One might suppose these substances to be thiocyanate and isothiocyanate, but according to ^{13}C NMR these products possess more complex, probably dimeric, structures. We succeeded in obtaining one of the products, **19a**, as a single crystal suitable for X-ray analysis. The structure of **19a** is shown at Figure 1. The structure of compound **19b** was not determined. The structure of 1,3-oxathiol derivative **19a** was unexpected, and one possible scheme for its formation is depicted in Scheme 8.

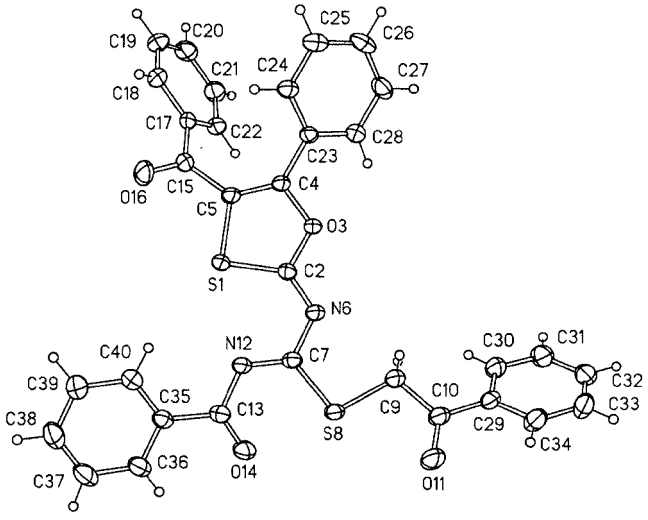
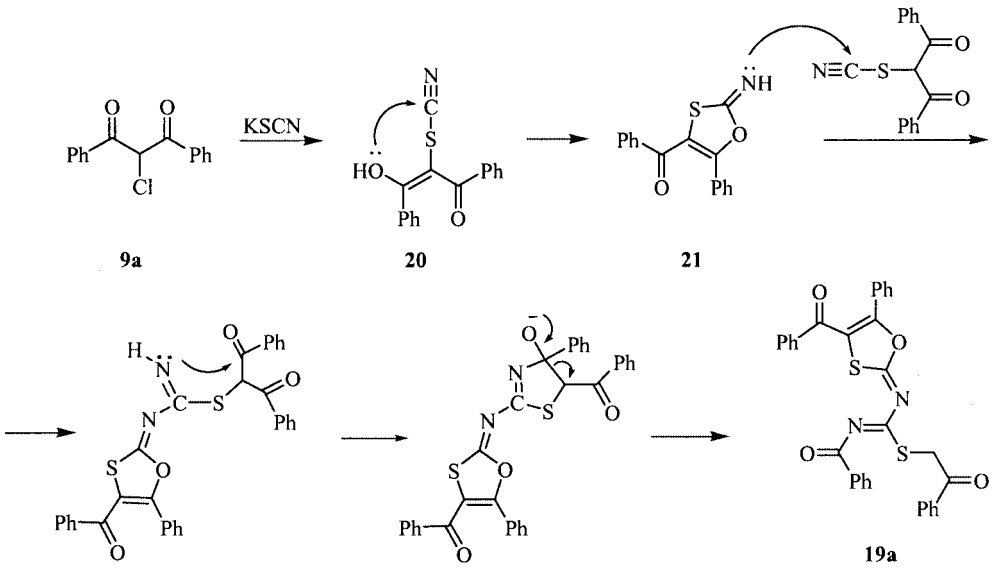


Figure 1. Crystal structure of 2-oxo-2-phenylethyl *N*′-benzoyl-*N*-(4-benzoyl-5-phenyl-1,3-oxathiol-2-ylidene)imidothiocarbamate (**19a**; CCDC-197567)

The first step is the formation of the thiocyanate **20**, which is capable of intramolecular heterocyclization, occurring through nucleophilic addition of the enol hydroxy group at the thiocyanate group and forming the 1,3-oxathiol derivative **21**. Subsequent steps are deduced to be the nucleophilic addition of the imino group of the 1,3-oxathiol **21** to the thiocyanate group of another molecule **20** and formation of the thiazoline cycle, promoting C−C bond cleavage to give the final product **19a**. It is not ruled out, however, that fragmentation of the diketone molecule **20** may proceed independently.

Conclusion

Treatment of some acyclic chloro-substituted enaminones, 1,3-diaryl-2-chloropropane-1,3-diones and β-oxo esters with nucleophiles − azide, cyanide and thiocyanate − was shown to proceed easily with the formation, at least in the first stage, of formal nucleophilic substitution products. The final results of these transformations could be quite ambiguous, however: treatment of enaminones and β-oxo esters with azide and cyanide ions proceeds with the preservation of the skeleton, whereas 1,3-diaryl-2-chloropropane-



Scheme 8

1,3-diones undergo retro-Claisen−Claisen reaction in the course of the reaction with cyanide, with carbon−carbon bond cleavage and subsequent reassembly of the initial skeleton from fragments.

Experimental Section

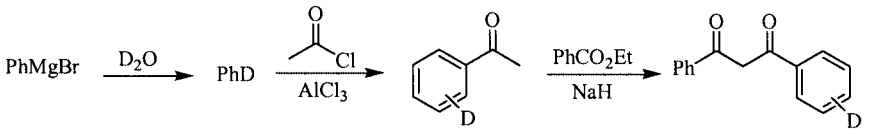
General: IR spectra were recorded with a Bruker IFS 66 spectrometer as KBr pellets (concentration 0.25%, thickness of a pellet 1 mm). UV spectra were measured with a Specord M-40 spectrophotometer in EtOH. NMR spectra were recorded with Bruker WP 200 SY, Bruker AC 200 and Bruker AM 400 spectrometers on 5% solutions in $CDCl_3$, CCl_4 and [D_6]DMSO with HMDS or solvent as the internal standard. The data on the content of reaction mixtures were obtained with a GC-mass spectrometer (HP G18801A). High-resolution mass spectra were recorded with a Finnigan MAT 8200 mass spectrometer with direct sample injection with a resolution of 10000. Melting points were measured with a "Boetius" plate and are uncorrected. Thin layer chromatography monitoring was carried out with the use of Silufol UV-254 plates with chloroform and chloroform/methanol (30:1 or 20:1) as eluent. DMSO was dried with NaOH and distilled in vacuo from BaO. In all cases solvent evaporation was carried out under reduced pressure.

3-Amino-2-chloro-1,3-diphenylprop-2-en-1-one (6): A mixture of dibenzoylmethane (2 g, 8.9 mmol) and NH_4OAc (2 g, 27 mmol) in methanol was heated at reflux for 8 h. The resulting solvents were evaporated, and the residue was diluted with water (15 mL) and extracted with diethyl ether (3 × 15 mL). The combined extracts were dried with $MgSO_4$, the solution was then concentrated, and the residue was crystallized with hexane. The yield of 3-amino-1,3-diphenylprop-2-en-1-one was 1.8 g (90%), m.p. 85−86 °C (from ethanol) (ref.[15] 86 °C). A solution of 3-amino-1,3-diphenylprop-2-en-1-one (2.11 g, 9.5 mmol) and *N*-chlorosuccinimide (NCS; 1.39 g, 10.0 mmol) in $CHCl_3$ (20 mL) was stirred at room temp. for 2 h. The precipitate formed was filtered off, dried in air and dissolved in anhydrous DMSO (20 mL). The solution was poured into saturated brine (30 mL) and the precipitate of enaminones **6** was filtered off, washed with brine and water and then dried in air, the yield being 1.95 g (80%), m.p. 143−144 °C. $C_{15}H_{12}C1NO$ (257.1): calcd. C 69.9, H 4.7, N 5.4; found C 69.9, H 4.7, N 5.4. ^{1}H NMR (CCl_4, 200.13 MHz): δ = 5.06 (s, 2 H, NH_2), 7.01−7.47 (m, 10 H, Ph_2) ppm. IR (KBr): $\tilde{\nu}$ = 3394, 3301 (NH), 1618, 1586, 1571, 1524 (O=C−C=C−N, Ph) cm^{-1}. UV (ethanol): $\lambda_{max.}$ (lg ε) = 233 (3.94), 349 nm (4.06).

3-Amino-2-benzoyl-3-phenylacrylonitrile (7): Enaminone **6** (0.72 g, 2.8 mmol) was added to a solution of KCN (0.36 g, 5.5 mmol) in anhydrous DMSO (20 mL). The mixture was stirred at room temp. for 2.5 h, and then cooled to 0 °C and poured into saturated cold brine (40 mL). The precipitate was filtered off, washed with brine and water, dried and washed with ethyl acetate to give **7** (0.35 g, 50%) as a white, fluffy solid, m.p. 215−218 °C (ethyl acetate). $C_{16}H_{12}N_2O$ (248.1): calcd. C 77.4, H 4.9, N 11.3; found C 77.6, H 4.8, N 11.3. ^{1}H NMR ($CDCl_3$, 200.13 MHz): δ = 6.10 (br. s, 1 H, NH), 7.39−8.09 (m, 10 H, Ph_2), 11.27 (br. s, 1 H, NH) ppm. IR (KBr): $\tilde{\nu}$ = 3395, 3330, 3193, 3137 (N−H), 2204 (CN), 1608, 1570, (O=C−C=C−N, Ph) cm^{-1}. UV (ethanol): $\lambda_{max.}$ (lg ε) = 242 (4.04), 324 nm (4.17).

3,6-Bis[imino(phenyl)methyl]-2,5-diphenyl-2,5-dihydropyrazine-2,5-diol (8): Enaminone **6** (0.96 g, 3.7 mmol) was added to a solution of NaN_3 (0.48 g, 9.8 mmol) in DMSO (25 mL). The mixture was stirred at room temperature for 20 h , cooled to 0 °C and poured into cold brine (30 mL). The mixture was extracted with $CHCl_3$ (3 × 20 mL); the combined extracts were washed with brine and water, and then dried with $MgSO_4$. Treatment with a hexane/ethyl acetate mixture after evaporation of solvent crystallized the residue. The precipitate of **8** was filtered off and washed with a small amount of ethyl acetate, the yield being 0.44 g (50%), m.p. 134−137 °C (ethyl acetate). IR (KBr): $\tilde{\nu}$ = 3440, 3382 (NH, OH), 1623, 1594, 1566 (C=N, Ph) cm^{-1}. UV (ethanol): $\lambda_{max.}$ (lg ε) = 291 (3.94), 337 nm (3.96). MS: calcd. for $C_{15}H_{12}NO$ *m/z* = 236.0960, found 236.0979.

2-Chloro-1,3-diphenylpropane-1,3-dione (9a): A mixture of dibenzoylmethane (1 g, 4.5 mmol) and NCS (0.6 g, 4.5 mmol) in CCl_4 (10 mL) was heated at reflux for 2 h. After cooling, the precipitate of succinimide was filtered off and the solution was concentrated to dryness. The residue was recrystallized from methanol to give β-



Scheme 9

diketone **9a** with a yield of 1.05 g (90%), m.p. 87−88 °C (ref.[16] 87−88 °C). In the same manner, 2-chloro-1-(monodeuteriophenyl)-3-phenylpropane-1,3-dione was obtained from 1-(monodeuteriophenyl)-3-phenylpropane-1,3-dione with a yield of 98%. The full scheme for the synthesis of deuterated dibenzoylmethane is shown in Scheme 9.

2-Chloro-1-phenylbutane-1,3-dione (9b): A mixture of benzoylacetone (1 g, 6.2 mmol) and NCS (0.82 g, 6.2 mmol) in CCl_4 (15 mL) was heated at reflux for 0.5 h. After cooling, the precipitate of succinimide was filtered off and the solution was concentrated to dryness. The residue, β-diketone **9b**, became a colourless, crystalline solid on cooling, the yield being 1.1 g (90%), m.p. 38−40 °C (ref.[17] 40−43 °C). ^{1}H NMR (CCl_4, 200.13 MHz): δ = 2.28 (s, 3 H, CH_3), 5.47 (s, 3 H, CHCl), 7.35−7.54 (m, 3 H), 7.88−7.93 (m, 2 H, C_6H_5) ppm (cf. ref.[18]). The chloro-substituted diketones **9c**−**g** and the chlorinated β-oxo ester **17**[19] were synthesized under the same conditions.

Compound 9c: Reaction time 12 h, yield 35%; m.p. 100−104 °C (hexane/ethyl acetate mixture), ^{1}H NMR (CCl_4, 200.13 MHz): δ = 6.08 (s, 1 H, CHCl), 7.37−7.54 (m, 4 H, C_6H_5, C_6H_4), 7.91−7.98 (m, 5 H) ppm. IR (CCl_4): $\tilde{\nu}$ = 1698, 1679, 1588 (C=O, C=C) cm^{-1}. UV (ethanol): $\lambda_{max.}$ (lg ε) = 259 nm (4.42). $C_{15}H_{10}Cl_2O_2$ (292.0): calcd. C 61.5, H 3.4; found C 61.3, H 3.7.

Compound 9d: Reaction time 20 h, yield 96%, m.p. 89−93 °C (hexane/ethyl acetate mixture). ^{1}H NMR ($CDCl_3$, 200.13 MHz): δ = 3.87 (s, 3 H, OCH_3), 6.26 (s, 1 H, CHCl), 6.91 (d, $J_{A\text{-}B}$ = 9.9 Hz, 2 H, 3,3-H 4-$CH_3OC_6H_4$), 7.45−7.57 (m, 3 H, 3,3,4-H Ph), 7.97−8.03 (m, 4 H, 2,2,2′2′-H Ph). IR (KBr): $\tilde{\nu}$ = 2841 (OMe), 1698, 1672, 1602, 1574 (C=O, C=C). UV (ethanol): $\lambda_{max.}$ (lg ε) = 225 (3.41), 255 (3.48), 290 nm (3.56). $C_{16}H_{13}ClO_3$ (288.1): calcd. C 66.6, H 4.5; found C 66.5, H 4.5. MS: calcd. for $C_{16}H_{13}ClO_3$ *m*/*z* = 288.0553, found 288.0552.

Compound 9e: Reaction time 0.5 h, yield 93%, m.p. 119−122 °C (hexane/ethyl acetate mixture). ^{1}H NMR (CCl_4, 200.13 MHz): δ = 6.17 (s, 1 H, C*H*Cl), 7.05 (dd, 2 H, $J_{A\text{-}B}$ = $J_{H,F}$ = 8.5, 3,3-H, 4-F-C_6H_4), 7.35−7.81 (m, 3 H, 3,3,4-H Ph), 7.92−8.04 (m, 4 H, 2,2,2′2′-H Ph). IR (KBr): $\tilde{\nu}$ = 1714, 1669, 1595 (C=O, C=C) cm^{-1}. UV (ethanol): $\lambda_{max.}$ (lg ε) = 254 nm (4.27). $C_{15}H_{10}ClFO_2$ (276.0): calcd. C 65.1, H 3.6; found C 65.3, H 3.8.

Compound 9f: Reaction time 1 h, yield 88% (colourless oil). ^{1}H NMR (CCl_4, 200.13 MHz): δ = 5.99 (s, 1 H, CHCl), 6.51 (dd, *J* = 4, 2 Hz, 1 H, 4-H furyl), 7.31 (dd, *J* = 4, 0.5 Hz, 1 H, 3-H furyl), 7.43−7.51 (m, 4 H), 7.95−8.00 (m, 2 H, C_6H_5, 5-H furyl), IR (CCl_4): $\tilde{\nu}$ = 1712, 1695, 1678 (C=O, C=C) cm^{-1}. UV (ethanol): $\lambda_{max.}$ (lg ε) = 281 (4.14), 256 nm (4.13). MS: calcd. for $C_{13}H_{19}ClO_3$ *m*/*z* = 248.0240, found 248.0242.

Compound 9g: Reaction time 2 h, yield 99% (colorless oil). IR (CCl_4): $\tilde{\nu}$ = 1699, 1665, 1600, 1572 (C=O, C=C). MS: calcd. for $C_{17}H_{15}ClO_4$ *m*/*z* = 318.0659, found 318.0666. The yield of β-oxo ester **17** being 50% (oil). ^{1}H NMR (CCl_4, 200.13 MHz): δ = 1.19 (t, *J* = 8 Hz, 3 H, CH_3CH_2O), 4.18 (q, *J* = 8 Hz, 2 H, CH_3CH_2O), 5.54 (s, 1 H, CHCl), 7.42−7.46 (m, 3 H), 7.91−7.95 (m, 2 H, C_6H_5) ppm (cf. ref.[20]).

Cyano(phenyl)methyl Benzoate (10): The β-diketone **9a** (0.5 g, 1.9 mmol) was added to a solution of NaN_3 (0.25 g, 3.8 mmol) in anhydrous DMSO (25 mL), and the resulting mixture was stirred at room temp. for 30 min. The mixture was cooled to 0 °C, poured into cold brine (30 mL) and extracted with $CHCl_3$ (2 × 20 mL). The combined extracts were washed with brine and water and then dried with $MgSO_4$. The residue after evaporation of solvent was compound **10**, the yield being 0.25 g (50%), m.p. 57 °C (ref.[21] 61 °C). ^{1}H NMR ($CDCl_3$, 200.13 MHz): δ = 6.65 (s, 1 H, CHCN), 7.40−7.48 (m, 5 H, Ph), 7.56−7.63 (m, 3 H, Ph), 8.04−8.08 (m, 2 H, Ph) ppm. ^{13}C NMR ($CDCl_3$, 50.32 MHz): δ = 63.2 (*C*HCN), 116.0 (CN), 127.6, 128.0, 129.0, 129.4, 129.6, 130.2, 131.8, 134.0 (Ph), 164.4 (C=O) ppm. IR (KBr): $\tilde{\nu}$ = 1727 (C=O), 2245 (CN) cm^{-1}. UV (ethanol): $\lambda_{max.}$ (lg ε) = 232 nm (4.21).

2-Benzoyl-3-hydroxy-3-phenylacrylonitrile (12a): Dibenzoylchloromethane (**9a**) (0.27 g, 1.1 mmol) was added to a solution of NaCN (0.21 g, 3.2 mmol) in anhydrous DMSO (25 mL). The reaction mixture was stirred at room temp. for 3 h, cooled to 0 °C and then poured into cold brine (40 mL). The resulting solution was acidified to pH = 5 with diluted hydrochloric acid. The precipitate of dibenzoylacetonitrile (**12a**) was filtered off, washed with brine and water and dried. Recrystallization of the crude product from ethyl acetate gave pure **12a** (0.22 g, 80%), m.p. 157−159 °C (ref.[14] 159−161 °C). ^{1}H NMR ($CDCl_3$, 200.13 MHz): δ = 7.48−7.66 (m, 6 H), 8.01−8.08 (m, 4 H, Ph), 17.8 (s, 1 H, OH) ppm. IR (KBr): $\tilde{\nu}$ = 3440 (OH), 2216 (CN), 1600, 1519 (C=C, C=O) cm^{-1}. UV (ethanol): $\lambda_{max.}$ (lg ε) = 254 (3.91), 329 nm (4.32). $C_{16}H_{11}NO_2$ (249.1): calcd. C 77.1, H 4.5, N 5.6; found C 76.9, H 4.2, N 5.6. MS: calcd. for $C_{16}H_{11}NO_2$ *m*/*z* = 249.7900, found 249.0775. The data of mass spectra for dibenzoylacetonitrile (**12a**) and its deuterated analogue **[D]-12a** are: *m*/*z* (%) = 249 (42.89), 250 (8.59), 251 (1.39) (**12a**); 249 (31.67), 250 (21.05), 251 (8.54), 252 (3.87), 253 (0.54) (**[D]-12a**). The nitriles **12g** and **18** were obtained in the same manner.

Compound 12g: Yield 80%, m.p. 172−175 °C (ethyl acetate). ^{1}H NMR ($CDCl_3$, 200.13 MHz): δ = 3.89 (s, 3 H, OCH_3), 6.97 (d, *J* = 9 Hz, 2 H), 8.11 (d, *J* = 9 Hz, 2 H, C_6H_4) ppm. IR (KBr): $\tilde{\nu}$ = 3450 (OH), 2212 (CN), 1607, 1535 (C=O, C=N), 1160 (C−O) cm^{-1}. UV (ethanol): $\lambda_{max.}$ (lg ε) = 237 (3.86), 275 (3.65), 359 nm (4.26). $C_{18}H_{15}NO_4$ (309.1): calcd. C 69.9, H 4.9, N 4.5; found C 69.9, H 4.9, N 4.8.

Compound 18: Yield 35%, m.p. 38−40 °C (from hexane; ref.[22] 40.5−41 °C). ^{1}H NMR ($CDCl_3$, 200.13 MHz): δ = 1.60 (t, *J* = 7 Hz, 3 H, CH_3), 4.56 (q, *J* = 7 Hz, 2 H, CH_2CH_3), 7.65−7.70 (m, 3 H), 8.15−8.19 (m, 2 H, Ph), 14.38 (s, 1 H, OH) ppm. IR (KBr): $\tilde{\nu}$ = 2670 (OH), 2220 (CN), 1663, 1597, 1565 (C=O, C=C), 1285

(C−O) cm^{-1}. A cross reaction involving equimolar amounts of the β-diketones **9a** and **9g** and NaCN and subsequent isolation of a mixture of respective nitriles was carried out in the same manner. Treatment of the β-diketones **9d**−**f** with NaCN was carried out in the same way, with the formation of mixtures of the nitriles **12A**−**C**. The reaction mixture obtained after treatment of the β-diketone **9c** with NaCN was treated somewhat differently: after having been poured into brine, the mixture was acidified with diluted hydrochloric acid to pH = 6. The resulting solution was extracted with $CHCl_3$ (2 × 20 mL), and the combined extracts were washed with brine and water and dried with $MgSO_4$. The water solution and organic extract were treated separately. The obtained organic extracts contained mixtures of the corresponding aroylacetonitriles **13** with the diaroylacetonitriles **12**. These mixtures were separated on silica gel columns. Aroylacetonitriles **13** were eluted with chloroform and then with chloroform/methanol mixtures (5:1), diaroylacetonitriles **12** were eluted in the form of their sodium salts. To obtain free diaroylacetonitriles **12** they were suspended in water/ether mixtures (1:1; 20 mL) and the aqueous phases were acidified with diluted hydrochloric acid to pH = 2 with shaking. The diethyl ether phases were separated and dried with $MgSO_4$, and the solvents were evaporated to give mixtures of free diaroylacetonitriles **12**. Aqueous solutions obtained on the first step of treatment, containing the main proportions of diaroylacetonitriles **12,** were acidified to pH = 2 with diluted hydrochloric acid and extracted with diethyl ether (2 × 20 mL). The combined extracts were washed with brine and water, and dried with $MgSO_4$. Concentration of these extracts yielded mixtures of diaroylacetonitriles **12.**

Mixture of Aroylacetonitriles 13 (R = 4-ClC$_6$H$_4$): ^{1}H NMR ($CDCl_3$, 200.13 MHz): δ = 4.06 (s, 2 H, CH_2CN), 4.09 (s, 2 H, CH_2CN), 7.83−7.93 (m, 3 H, C_6H_5), 7.47−7.55 (m, 2 H, C_6H_5), 7.83−7.93 (m, 3 H, C_6H_5) ppm. IR (KBr): $\tilde{\nu}_{max.}$ = 2952, 2922 (CH), 2264, 2195 (CN), 1689 (C=O) cm^{-1}. MS: calcd. for C_9H_6ClNO *m*/*z* = 179.01379, found 179.0136.

13 (R = Ph): MS: calcd. for C_9H_7NO *m*/*z* = 145.0528, found 145.0525.

Mixture of Diaroylacetonitriles 12 (R = 4-ClC$_6$H$_4$): ^{1}H NMR ($CDCl_3$, 200.13 MHz): δ = 7.33−7.77 (m, 6 H), 7.99−8.15 (m, 5 H), 18.25 (s, 1 H, OH) ppm. IR (KBr): $\tilde{\nu}$ = 2217 (CN), 1594, 1537 (C=O, C=C) cm^{-1}. **12B:** MS: calcd. for $C_{16}H_{10}ClNO_2$ *m*/*z* = 283.0400, found 283.0392. **12C:** MS: calcd. for $C_{16}H_9Cl_2NO_2$ *m*/*z* = 317.0010, found 317.0006.

12 (R = *p*-CH$_3$OC$_6$H$_4$): ^{1}H NMR ($CDCl_3$, 200.13 MHz): δ = 3.88 (s, 3 H, OCH_3), 6.96−7.01 (m, 2 H), 7.47−7.64 (m, 2 H), 8.00−8.16 (m, 4 H), 18.50 (s, 1 H, OH) ppm. IR (KBr): $\tilde{\nu}$ = 2840 (OCH_3), 2214 (CN), 1603, 1585, 1513 (C=O, C=C), 1254 (C−O) cm^{-1}. UV (ethanol): $\lambda_{max.}$ (lg ε) = 238 (3.76), 351 (4.17). **12B:** MS: calcd. for $C_{17}H_{13}NO_3$ *m*/*z* = 279.0895, found 279.08997. **12C:** MS: calcd. for $C_{18}H_{15}NO_4$, 309.1001, found 309.0995.

Compound 12 (R = CH$_3$): ^{1}H NMR ($CDCl_3$, 200.13 MHz): δ = 2.51 (s, 3 H, CH_3), 7.44−7.64 (m, 3 H), 7.98−8.06 (m, 2 H, C_6H_5) ppm. IR (KBr): $\tilde{\nu}$ = 3060, 2918 (CH aromatic and aliphatic) 2261 (CN), 1601, 1547 (C=O, C=C) cm^{-1}.

Compound 12 (R = *p*-FC$_6$H$_4$): ^{1}H NMR ($CDCl_3$, 200.13 MHz): δ = 7.08−7.23 (m, 3 H), 7.41−7.62 (m, 3 H), 8.03−8.15 (m, 4 H) ppm. **12B:** MS: calcd. for $C_{16}H_{10}FNO_2$ *m*/*z* = 267.0696, found 267.0697. **12C:** MS: calcd. for $C_{16}H_9F_2NO_2$ *m*/*z* = 285.0601, found 285.06059.

Compound 12 (R = 2-furyl): ^{1}H NMR ($CDCl_3$, 200.13 MHz): δ = 6.65 (d, *J* = 4 Hz, 1 H, β-furyl), 7.50−7.56 (m, 3 H), 7.77 (m, 1 H), 7.86 (*J* = 4 Hz, 1 H, β-furyl), 7.99−8.03 (m, 2 H) ppm. IR (KBr): $\tilde{\nu}$ = 2213 (CN), 1601, 1585, 1523 (C=O, C=N) cm^{-1}. **12B:** MS: calcd. for $C_{14}H_9NO_3$ *m*/*z* = 239.0582, found 239.0581. Treatment of diaroylacetonitrile (**12A**−**C**) mixtures − obtained under the conditions indicated for the synthesis of dibenzoylacetonitriles − with NaCN was carried out under the same conditions but for 24 h. After having been poured into brine, the solution was acidified to pH = 5 and the precipitate formed was filtered off or extracted with $CHCl_3$, with subsequent treatment as indicated above. In the case of the 168 h reaction duration a threefold excess of NaCN was used. Reaction products were isolated as described above, from aqueous solution acidified to pH = 3.

2-Oxo-2-phenylethyl *N*-[(2*Z*)-4-Benzoyl-5-phenyl-1,3-oxathiol-2-ylidene]-*N*′-benzoylimidothiocarbamate (19a): Dibenzoylchloromethane (**9a**, 1 g, 3.9 mmol) was added to a solution of KSCN (0.75 g, 7.7 mmol) in anhydrous DMSO (30 mL) and the resulting mixture was stirred at room temp. for 5 h. The reaction mixture was then cooled to 0 °C and poured into cold brine (40 mL). The solution was extracted with $CHCl_3$ (3 × 15 mL) and the combined extracts were washed with brine and water and then dried with $MgSO_4$. Subsequent concentration of the obtained solution yielded a red, crystalline mixture of two products **19a** and **19b** (the weight was 0.7 g), the separation of which was achieved by multiple fractional recrystallization from ethyl acetate.

Compound 19a: Red, crystalline solid, more soluble in ethyl acetate, m.p. 229−232 °C (ethyl acetate). ^{1}H NMR ([D$_6$]DMSO, 400.14 MHz): δ = 4.77 (s, 2 H, CH_2), 7.26−7.33 (m, 5 H, Ph), 7.38−7.41 (m, 1 H), 7.48−7.58 (m, 5 H, Ph), 7.63−7.66 (m, 3 H), 7.67−7.73 (m, 2 H), 8.01−8.12 (m, 2 H), 8.16−8.19 (m, 2 H) ppm. ^{13}C NMR ([D$_6$]DMSO, 100.64 MHz): δ = 59.6 (t, CH_2), 118,8 (s), 126.2 (s), 128.2 (d), 128.6 (d), 128.9 (d), 129.2 (d), 129.5 (d), 131.0 (d), 132.9 (d), 133.1 (d), 133.5 (d), 134.7 (s), 135.0 (s), 151.5 (s), 169.9 (s), 171.2 (s), 175.2 (s), 187.4 (s), 194.4 (s) ppm. IR (KBr): $\tilde{\nu}$ = (KBr) 1677, 1640, 1631 1609, 1597, 1540 (O=C−C=C, C=C, C=N) cm^{-1}. UV (ethanol): $\lambda_{max.}$ (lg ε) = 249 (4.24), 354 nm (3.93). $C_{32}H_{22}N_2O_4S_2$ (562.1): calcd. C 68.3, H 3.9, N 5.0, S 11.4; found C 68.6, H 3.8, N 4.9, S 11.2.

Compound 19b: Red, crystalline solid, less soluble in ethyl acetate, m.p. 227−229 °C (ethyl acetate). ^{1}H NMR ([D$_6$]DMSO, 400.14 MHz): δ = 7.51−7.60 (m, 10 H), 7.63−7.67 (m, 4 H), 7.77−8.05 (m, 5 H), 8.09−8.14 (m, 1 H, 4Ph), 13.08 (1 H, OH) ppm. ^{13}C NMR ([D$_6$]DMSO, 100.64 MHz): 56.6 (d), 118.9 (s), 127.1 (d), 127.2 (d), 127.9 (d), 128.0 (d), 128.4 (d), 131.5 (s), 132.4 (d), 133.4 (d), 134.1 (s), 154.0 (s), 163.2 (s), 165.5 (s), 185.1 (s), 191.4 (s) ppm. IR (KBr): $\tilde{\nu}$ = 3379 (OH), 1674, 1597, 1578, 1526 (C=O, C=N, C=C), 1257 (C−O) cm^{-1}. UV (ethanol): $\lambda_{max.}$ (lg ε) = 251 (4.22), 279 (4.15), 362 nm (3.91). $C_{32}H_{22}N_2O_4S_2$ (562.1): calcd. C 68.3, H 3.9, N 5.0, S 11.4; found C 68.3, H 3.9, N 5.0, S 11.1.

X-ray Crystallography: Single crystals of **19a** were obtained by recrystallization from ethyl acetate, mounted and transferred to a Bruker P4 diffractometer. Crystal data: $C_{32}H_{22}N_2O_4S_2$, *M* = 562.64, triclinic system, space group $P\bar{1}$, *a* = 8.2201(7), *b* = 12.558(1), *c* = 13.874(1) Å, α = 101.506(7), β = 99.904(7), γ = 99.341(7)°, *V* = 1353.5(2) Å^3, *Z* = 2, $d_{calcd.}$ = 1.381 Mg/m^3. Data collection: Bruker P4 diffractometer, graphite-monochromated Mo-K_α radiation, crystal size 2.8 × 0.2 × 0.08 mm, ω-scans, Θ < 25°, −9 < *h* < 9, −14 < *k* < 14, −16 < *l* < 16, 5105 reflections measured, 4756 reflections independent, R_{int} = 0.0188, absorption correction by integration method (μ = 0.239 mm^{-1}, transmission 0.949−0.981). The structure was solved by direct methods

(SHELXS-97) and refined by full-matrix least squares in anisotropic-isotropic (for H atoms) approximation on all F^2 (SHELXL-97). Final indexes: goodness of fit 1.036, 450 parameters, $wR2$ = 0.1064, $R1$ = 0.0495 for all data and $wR2$ = 0.0945, $R1$ = 0.0365 for 3705 $I > 2\sigma(I)$.

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