New rearrangement of azofuroxans in an oxidising medium

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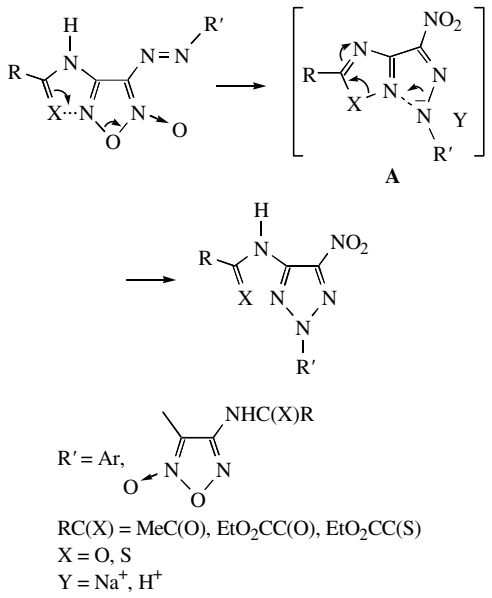
3,3′-(R)-Disubstituted 4,4′-azo-1,2,5-oxadiazole 2-oxides (furoxans) have been found to undergo a new rearrangement into 2-(furoxan-4-yl)-4-nitro-5-R-2*H*-1,2,3-triazole 1-oxides on heating in pertrifluoroacetic or peracetic acids.

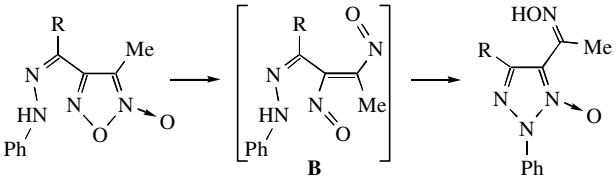
Rearrangements are extensively studied as alternative methods for the preparation of new heterocyclic systems.[1] Only a few examples of such studies in the series of uncondensed furoxan derivatives have been published.[2(a),(b)] In the last few years, new rearrangements in the series of uncondensed furoxan derivatives,[3–7] including azofuroxans[3–6] have been found. Among them are the thermally induced rearrangement of 3,3′-azo-4,4′-bis(acetylamino)furoxans[3] and the base-induced rearrangement of 4-acetylamino-3-arylazofuroxans[4] into corresponding 4-acetylamino-2-(furoxanyl)aryl-5-nitro-2*H*-1,2,3-triazoles, as well as the thermally and base induced rearrangement of 3-arylazo-4-(3-ethoxycarbonylureido)furoxans into 4-amino-2-aryl-5-nitro-2*H*-1,2,3-triazoles.[5] The above reactions were assumed



Scheme 1

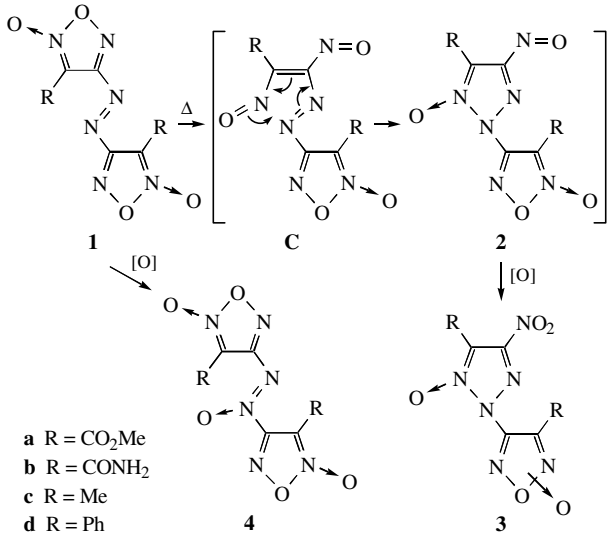
to include two consecutive (cascade) rearrangements: a 1,2,4-oxadiazole ring (intermediate A, X = O, Y = Na^+ or H^+) is formed at the first step, which is then transformed into a 1,2,3-triazole ring with the participation of an azo group. This assumption was supported more recently using the thermally induced rearrangement of 3-arylazo-4-(3-ethoxycarbonylthioureido)furoxans as an example: intermediate 1,2,4-thiadiazol-3-ylnitroformaldehyde arylhydrazones were isolated (compound **A**, X = S, Y = H^+)[6] (Scheme 1).

It can be seen in Scheme 1 that a nucleophilic attack of the oxygen or sulfur atom of a corresponding substituent on the furoxan N(5) atom followed by O(1)–N(5) bond cleavage and the formation of a new heterocyclic ring is the driving force of rearrangements in all of the above reactions. However, as distinct from other azoles, a furoxan ring is capable of thermal O(1)–N(2) bond cleavage with the formation of a short-lived dinitrosoethylene intermediate.[8] In particular, we chemically trapped this intermediate (**B**) in the thermally induced rearrangement of 4-acetyl(benzoyl)-3-methylfuroxan phenylhydrazones with the formation of 5-acetyl-4-phenyl(methyl)-2-phenyl-2*H*-1,2,3-triazole 1-oxide oximes[7] (Scheme 2).



Scheme 2

In this work, we examined the possibility of thermal rearrangements of 3,3′-(R)-disubstituted 4,4′-azofuroxans **1a–d** which could combine the rearrangements on Schemes 1 and 2. The test compounds contained no substituents capable of undergoing a classical rearrangement. We believed that one of the furoxan rings is opened to form dinitrosoethylene intermediate **C** followed by the condensation of one of the nitroso groups with the azo group to form 2-(furoxan-4-yl)-4-nitroso-5-R-2*H*-1,2,3-triazole 1-oxides **2** (Scheme 3).



Scheme 3 *Reagents and conditions*: CF_3CO_2H, 85% H_2O_2, reflux 0.5 h, R = CO_2Me, $CONH_2$, Me; or $MeCO_2H$, Ac_2O, 30% H_2O_2, reflux 48 h, R = Ph.

The initial study was performed with the use of azofuroxan **1a** as an example. We found that the refluxing of **1a** in ethyl acetate, toluene or xylene resulted in complete (or partial) decomposition of the parent compound depending on the boiling temperature of the solvent, or it was recovered unchanged from the reaction mixture. Only the refluxing of compound **1a** in trifluoroperacetic acid was successful. 5-Methoxycarbonyl-2-(furoxan-4-yl)-4-nitro-2*H*-1,2,3-triazole 1-oxide **3a** was isolated

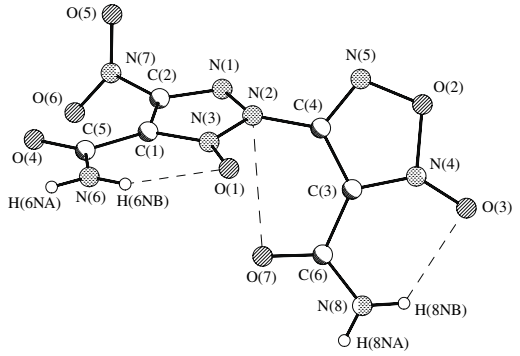


Figure 1 The general view of **3b**. Selected bond lengths (Å) (the second value in square brackets was obtained within the B3LYP/6-31G* calculation): N(1)–N(2) 1.340(2) [1.343], N(2)–N(3) 1.373(2) [1.387], N(3)–C(1) 1.353(2) [1.354], N(1)–C(2) 1.309(2) [1.314], C(1)–C(2) 1.395(2) [1.413], O(1)–N(3) 1.254(2) [1.253], O(2)–N(5) 1.356(2) [1.352], O(2)–N(4) 1.481(2) [1.473], O(3)–N(4) 1.208(2) [1.220], C(3)–C(4) 1.408(2) [1.423], N(4)–C(3) 1.330(2) [1.331], N(5)–C(4) 1.295(2) [1.305]. Selected bond angles (°): N(1)N(2)N(3) 112.5(1) [112.3], N(1)N(2)C(4) 124.0(1) [124.9], N(3)N(2)C(4) 122.1(1) [120.6].

as the reaction product. It is evident that under these conditions the nitroso group in intermediate nitroso compound **2a** was oxidised to the nitro group with the formation of nitro derivative **3a** (Scheme 3).

The conditions found were used for the rearrangement of azofuroxans **1b–d**. We found that, in addition to the expected rearrangement with the formation of furoxanyltriazole 1-oxides **3**, the direct oxidation of the azo group in the parent azofuroxan to azoxy derivative **4** occurred in a number of cases; the character of substituent R affected the amount of this derivative. Thus, in the case of compound **1c** (R = Me), the formation of azoxy derivative **4c** became the predominant reaction path. In the other cases, compounds **4** were formed in insignificant amounts; only compound **4b** was isolated. Use of peracetic acid was more appropriate for the conversion of diphenylazofuroxan **1d**. In this case, two isomers **3d** and **3′d** were isolated, which were different only in the position of the N-oxide oxygen atom in the furoxan ring: it was arranged on the side of the Ph fragment or the triazole ring in isomer **3d** or **3′d**, respectively. Evidently, the furoxan ring in the resulting compounds underwent isomerization under reaction conditions; this isomerization is well known[8] to occur through a dinitrosoethylene intermediate.

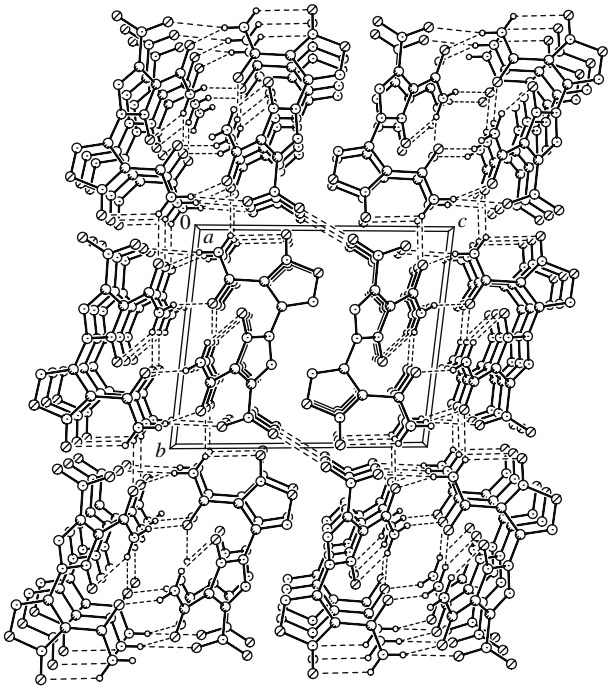


Figure 2 The section of crystal packing in **1** parallel to the crystallographic plane *bc*.

The structures of the compounds obtained were determined using elemental analysis, NMR spectroscopy and mass spectrometry.† In these compounds, the molecular ion increased by 16 units because of the introduction of an additional oxygen atom. ^{14}N NMR spectroscopy played an important role: the chemical shifts of nitro and azoxy groups were –30–32 and –66–68 ppm, respectively. An X-ray diffraction study of compound **3b**, which is one of the rearrangement products, was performed in order to determine ultimately the structures of the products obtained. The structures of azoxy derivatives **4b**,**c** were found by comparison with authentic samples.[9,10]

With the use of X-ray diffraction analysis, we found that compound **3b** includes furoxan and 1,2,3-triazole rings arranged at an angle of 70.2° (Figure 1).‡ The geometry parameters of compound **3b** are significantly different from those of previously described 1,2,3-triazole 1-oxide derivatives (for example, see ref. 11). This manifests itself in considerable differences between N–N and N–C bond lengths (0.03 and 0.04 Å, respectively) and in the pyramidalization of the N(2) atom. The distance between the N(2) atom and the plane N(1), N(3) and C(4) is 0.09 Å, which is maximum for not only this heterocycle but also all of the previously described 1,2,3-triazoles, in which a maximum deviation of nitrogen atoms is 0.05 Å, as found by statistical data processing. The angle between the plane of 1,2,3-triazole and the C(4)–N(2) bond is 11.2°.

An analysis of intramolecular contacts demonstrated that, along with N–H···O hydrogen bonds [N···O 2.854(2)–

† All new compounds exhibited satisfactory elemental analyses, and their structures were confirmed by IR, ^{1}H and ^{13}C NMR spectroscopy. IR spectra were measured on an UR-20 spectrometer in KBr; ^{1}H and ^{13}C NMR spectra were recorded on Bruker WM-250 (250 MHz) and Bruker AM-300 (75.5 MHz) spectrometers, respectively (TMS was used as an internal standard). Mass spectra were measured on a Finnigan MAT INCOS-50 instrument. TLC was carried out on Silufol UV-254 plates, eluent: CH_2Cl_2–acetone, 5:1. The initial azofuroxans were synthesised according to known methods: **1a**,[9] **1b**,[10] **1c**,[9] **1d**.[9]

*2-(3-Methoxycarbonylfuroxan-4-yl)-4-nitro-5-methoxycarbonyl-2*H-*1,2,3-triazole 1-oxide* **3a**: yield 36%, mp 123–125 °C, R_f 0.35. ^{1}H NMR ([$^2H_6$]acetone) δ: 3.95 (s, 3H, MeOCO in furoxan ring), 4.07 (s, 3H, MeOCO in triazole oxide ring). ^{13}C NMR ([$^2H_6$]acetone) δ: 54.62 (MeOCO in furoxan ring), 54.83 (MeOCO in triazole oxide ring), 105.10 (C-3 of furoxan ring), 116.35 (C-3 of triazole oxide ring), 144.64 (C-4 of furoxan ring), 150.86 (C-4 of triazole oxide ring), 155.59 (MeOCO of triazole oxide ring), 155.73 (MeOCO of furoxan ring). ^{14}N NMR ([$^2H_6$]acetone) δ: –32.80 (NO_2). IR (KBr, ν/cm^{-1}): 960, 1030, 1060, 1180, 1210, 1320, 1370, 1440, 1480, 1510, 1580, 1670, 1770, 1870, 2935, 2985. MS, *m*/*z* (I, %): 330 (M^+, 17).

*2-(3-Carboxamidofuroxan-4-yl)-4-nitro-5-carboxamido-2*H-*1,2,3-triazole 1-oxide* **3b**: yield 52%, mp 182–183 °C, R_f 0.33. ^{1}H NMR ([$^2H_6$]DMSO) δ: 7.95–8.35 (d, 2H, H_2NCO of furoxan ring), 8.45–8.60 (d, 2H, H_2NCO of triazole oxide ring). ^{13}C NMR ([$^2H_6$]DMSO) δ: 106.27 (C-3 of furoxan ring), 118.45 (C-3 of triazole oxide ring), 144.92 (C-4 of furoxan ring), 148.82 (C-4 of triazole oxide ring), 153.37 (H_2NCO of triazole oxide ring), 154.10 (H_2NCO of furoxan ring). ^{14}N NMR ([$^2H_6$]acetone) δ: –31.08 (NO_2). IR (KBr, ν/cm^{-1}): 640, 668, 800, 1028, 1092, 1332, 1420, 1472, 1512, 1564, 1600, 1684, 1696, 2968, 2980, 3244, 3312, 3384, 3420. MS, *m*/*z* (I, %): 300 (M^+, 41).

*2-(4-Phenylfuroxan-3-yl)-4-nitro-5-phenyl-2*H-*1,2,3-triazole 1-oxide* **3d**: yield 26%, mp 121–122 °C, R_f 0.22. ^{1}H NMR ($CDCl_3$) δ: 7.52–7.71 (m, 10H, 2Ph). ^{13}C NMR ($CDCl_3$) δ: 120.94 (C-3 of furoxan ring), 122.77–132.53 (2Ph), 149.53 (C-3 of triazole oxide ring), 152.20 (C-4 of triazole oxide ring), 152.24 (C-4 of furoxan ring). ^{14}N NMR ($CDCl_3$) δ: –32.13 (NO_2). IR (KBr, ν/cm^{-1}): 688, 740, 750, 796, 848, 980, 1076, 1164, 1276, 1328, 1356, 1436, 1488, 1544, 1560, 1572, 1608, 1640, 2888, 3060. MS, *m*/*z* (I, %): 366 (M^+, 20).

*2-(3-Phenylfuroxan-4-yl)-4-nitro-5-phenyl-2*H-*1,2,3-triazole 1-oxide* **3′d**: yield 22%, mp 160–162 °C, R_f 0.13. ^{1}H NMR ([$^2H_6$]acetone) δ: 7.50–7.85 (m, 10H, 2Ph). ^{13}C NMR ([$^2H_6$]acetone) δ: 112.45 (C-3 of furoxan ring), 121.7–133.6 (2Ph), 147.11 (C-3 of triazole oxide ring), 151.10 (C-4 of triazole oxide ring), 153.27 (C-4 of furoxan ring). ^{14}N NMR ([$^2H_6$]acetone) δ: –30.81 (NO_2). IR (KBr, ν/cm^{-1}): 660, 692, 736, 756, 792, 852, 975, 1004, 1032, 1116, 1272, 1368, 1432, 1484, 1544, 1572, 1636, 3075. MS, *m*/*z* (I, %): 366 (M^+, 35).

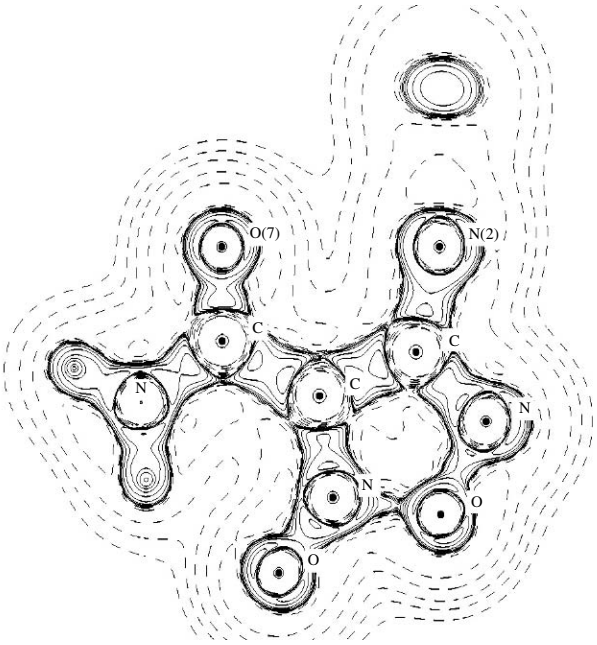


Figure 3 Section of laplacian of electron density function in **3b** in the plane of the N–H···O hydrogen bond and the N(2)···O(7) contact. Contours are drawn in a logarithmic scale. The positive values corresponding to local depletion of electron density are shown by dashed lines.

2.906(2) Å], a shortened contact between the O(7) oxygen atom of the amide group and the N(2) atom [O(7)···N(2) 2.924(2) Å] occurs in the structure (Figure 1). Taking into account that the N(2) atom deviates from the plane of the triazole ring in an opposite direc-tion with respect to O(7), we may assume that the pyrami-dalization of the N(2) atom is due to steric hindrances in the molecule and, as a result, electrostatic repulsion of O(7)···N(1). On the other hand, this interaction may have an attractive character (for example, see ref. 12).

In addition to the above intramolecular interactions, amide groups also participate in the formation of intermolecular N–H···O bonds [2.820(2)–3.191(2) Å], which join molecules in H-bonded layers parallel to the crystallographic plane *ab*. In turn, the layers are joined in a three-dimensional framework through O···O contacts [2.839(3) Å], formed by NO_2 groups. This compound is of interest from the standpoint of the design of high-energy materials because of the occurrence of such interactions between nitro groups in combination with the high density (1.766 g cm^{-3}) of the crystalline organic compound.

To evaluate the effect of crystal packing on the molecular conformation of **3b** and, as a result, the nature of N(2)···O(7) intramolecular contact, we performed quantum-chemical calculations using the G98W[13] program package. According to B3LYP/6-31G* data with the full geometry optimisation in **3b**, the mutual arrangement of heterocyclic rings in an isolated molecule remained unchanged (the dihedral angle was equal to 74°). In this case, the main geometry characteristics observed in the crystal were retained in an isolated state. In particular, the deviation of the N(2) atom even somewhat increased to 0.11 Å, an the N(2)···O(7) distance was 2.940 Å.

An analysis of the topology of the electron density distribution function $\rho(r)$[14] according to B3LYP/6-31G* data demonstrated that critical points (3, –1) are localised in the regions of both all expected bonds, intramolecular hydrogen bonds, and the N(2)···O(7) contact. Based on the fact that this characteristic set of critical points was retained for the function of potential energy density, we can unambiguously conclude[14(*b*)] that this interaction is of an attractive character. Taking into account that the laplacian of electron density function and energy density values of (3, –1) critical points of N–H···O bonds and the N(2)···O(7) contact are positive, we can conclude that these contacts are interactions of the closed-shell type (Figure 3). In this case, the values of $\rho(r)$ and, particularly, potential energy density in (3, –1) critical points (3, –1) in the region of N–H···O (0.12–0.15 eÅ^{-3} and –0.17 to –0.10 HÅ^{-3}) bonds and the N(2)···O(7) (0.07 eÅ^{-3} and –0.055 HÅ^{-3}) contact suggest that the latter is more than two times weaker and comparable in energy to intermolecular C–H···O interactions.[15]

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‡ *Crystallographic data*. Crystals of **3b** ($C_6H_8N_4O_4S$, M = 232.22) are triclinic, space group $P\bar{1}$, at 120 K: a = 5.731(1) Å, b = 9.339(2) Å, c = = 10.945(2) Å, α = 94.99(3)°, β = 101.96(3)°, γ = 97.34(3)°, V = 564.5(2) Å^3, Z = 2 (Z' = 1), d_{calc} = 1.766 g cm^{-3}, μ(MoKα) = 1.61 cm^{-1}, F(000) = 304. Intensities of 3164 reflections were measured with a Siemens P3 diffractometer [λ(MoKα) = 0.71072 Å, $\theta/2\theta$-scans, $2\theta < 60°$] and 2860 independent reflections [R_{int} = 0.0264] were used in the further refinement. The structure was solved by a direct method and refined by the full-matrix least-squares technique against F^2 in the anisotropic-isotropic approximation. Hydrogen atoms were located from the Fourier synthesis and refined in the isotropic approximation. The refinement converged to wR_2 = 0.1204 and GOF = 1.054 for all independent reflections [R_1 = 0.0422 was calculated against F for 2178 observed reflections with $I > 2\sigma(I)$] for **3b**. All calculations were performed using the SHELXTL PLUS 5.0.

Atomic coordinates, bond lengths, bond angles and thermal parameters have been deposited at the Cambridge Crystallographic Data Centre (CCDC). These data can be obtained free of charge *via* www.ccdc.cam.uk/conts/retrieving.html (or from the CCDC, 12 Union Road, Cambridge CB2 1EZ, UK; fax: +44 1223 336 033; or deposit@ccdc.cam.ac.uk). Any request to the CCDC for data should quote the full literature citation and CCDC reference number 227397. For details, see 'Notice to Authors', *Mendeleev Commun.*, Issue 1, 2003.

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