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CHEMISTRY OF FURAZANO[3,4-*b*]PYRAZINE. 1. SYNTHESIS AND THERMODYNAMIC APPRAISAL OF 4,8-DIHYDRODIFURAZANO[3,4-*b*,*e*]PYRAZINE AND ITS DERIVATIVES

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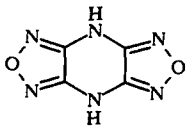
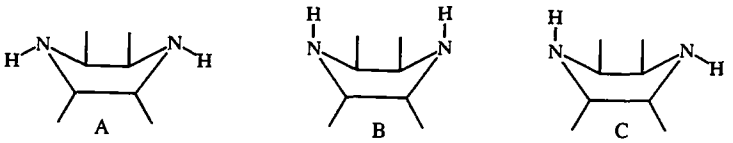
The thermodynamic stability of the antiaromatic 4,8-dihydrodifurazano[3,4-b,e]pyrazine (I) was studied by a quantum-chemical method. The molecular structure was investigated by x-ray crystallographic analysis, and the aromaticity index of the compound was calculated. It was shown that the oxidation or nitration of compound (I) leads to a stable aromatic radical.

Recently, compounds of the furazanopyrazine class have attracted the attention of specialists in the region of energy-rich compounds [1-3]. Of the greatest interest among these compounds is 4,8-dihydrodifurazano[3,4-*b*,*e*]pyrazine (I) and its derivatives [4-7].



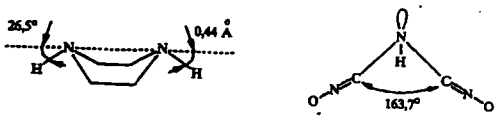
I

It is necessary to study the molecular structure of 4,8-dihydrodifurazano[3,4-*b*,*e*]pyrazine in order to predict the thermodynamic stability of its derivatives. The dihydropyrazine ring contains eight electrons in the π orbitals, and the whole system together with the furazan rings contains 16 electrons, i.e., is antiaromatic. Such compounds are usually unstable, since conjugation is energetically unfavorable in antiaromatic systems. The stability of compound (I) can only be explained by the strong electron-accepting characteristics of the two furazan rings, which promote delocalization of the excess electron density. The unfavorability of cyclic conjugation in antiaromatic structures must lead to loss of the planarity of the rings. In particular, sp^3 and not sp^2 hybridization must be more favorable for the nitrogen atom of the dihydropyrazine ring. In this case compound (I) can have three conformers, differing in the position of the hydrogen atoms.



A B C

In order to study its structure we undertook a quantum-chemical calculation by the semiempirical MNDO method with full optimization of the molecular geometry. The conformer A with, as supposed, a nonplanar molecule, where the angle between the planes is 163.7°, proved the most stable. The angle between the N—H bond and the line joining the nitrogen atom of the dihydropyrazine ring is 153.4°, and the deviation of the hydrogen atom is 0.44 Å.



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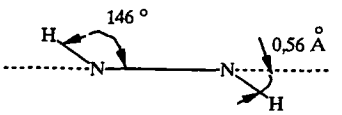
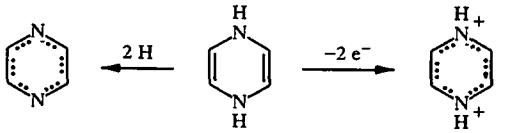
During calculation of the conformer B with optimization of the bond angles it was found that it does not correspond to a minimum on the potential curve describing the transformation of the conformer B to A. Thus, optimization of the geometry of the conformer B led to the geometry of conformer A.

During calculation of conformer C it was established that in this case the heterocyclic system was planar. The hydrogen atoms were equivalent and deviated from the plane by 0.56 Å:



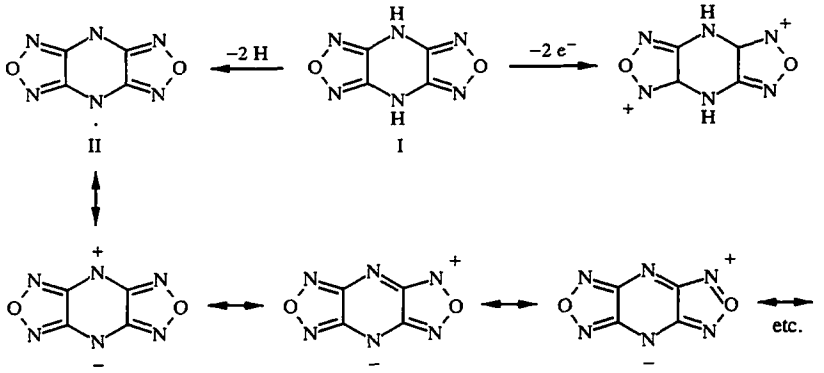
However, this isomer proved thermodynamically less favorable than isomer A. The heat of formation of the isomer A is 110.87 kcal/mole, while that of the isomer C is 111.71 kcal/mole. The small difference in the heats of formation of the isomers (0.84 kcal/mole) and the barrier-free transformation of conformer B to A bear witness to the high conformational mobility of the dihydrodifurazanopyrazine system.

The dihydrodifurazanopyrazine (I) is antiaromatic. However, the removal of two electrons from its π orbitals could lead to an aromatic structure. Such a transformation does not, in principle, encounter obstacles in the case of, for example, the uncondensed analogs:

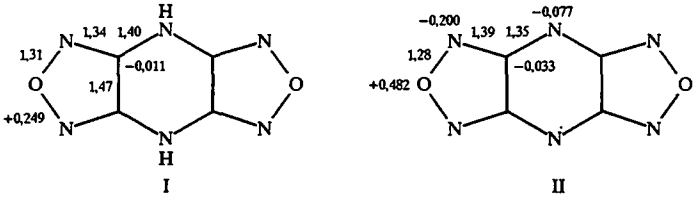


As seen, the aromatization of the dihydro derivatives can be realized either by dehydrogenation or by oxidation.

In the case of compound (I) the position is complicated by the fact that the presence of the condensed furazan rings makes recombination of the electrons in the pyrazine ring with the formation of an additional bond impossible. As a result the compound that forms must either be a biradical or correspond to a set of resonance structures with separated charges:



Quantum-chemical calculation showed that the difurazanopyrazine (II) can exist in the form of both a radical and a meso-ion with closed shells. The radical structure is less favorable for the isolated molecule. The difference amounted to 15.37 kcal/mole. In both cases the heterocyclic system was flat and contained 14 electrons in the π orbitals. The bond lengths in the difurazanopyrazine (II) (the data for the calculation of the molecule with closed shells) and its dihydro derivatives are given below.

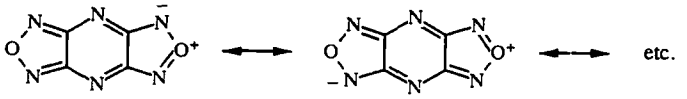


I II

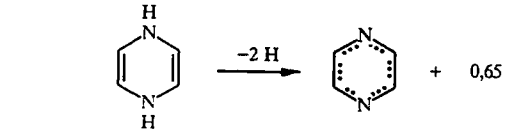
It follows from these data that in the difurazanopyrazine (II) the lengths of the single bonds were reduced (and also the orders were increased), and the lengths of the double bonds were increased (and the orders reduced). This bears witness to the appearance of aromaticity in the cyclic system. The fact that the length of the C—C single bond was slightly increased indicates that the delocalization of the electron mostly takes place in the outer contour of the molecule. The higher degree of

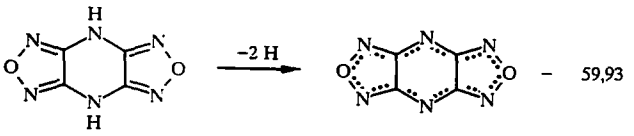
participation of the oxygen atom in conjugation leads to an increase of the π charge in it from +0.249 in the dihydro derivative (I) to 0.482 in the aromatic structure (II).

The presence of an extremely considerable negative π charge on the nitrogen atoms of the furazan ring indicates that the structure of the difurazanopyrazine (II) most accurately reflects the set of resonance structures in which the negative charge is localized on the nitrogen of the furazan ring and the positive charge is localized on the oxygen:



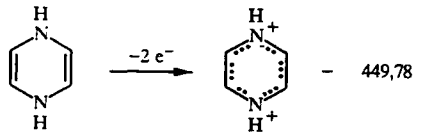
In order to determine how favorable the formation of the difurazanopyrazine (II) from the dihydro derivative (I) is and to determine what contribution the appearance of cyclic delocalization of the electrons makes to the stabilization of the molecule we compared the heats of the reactions:

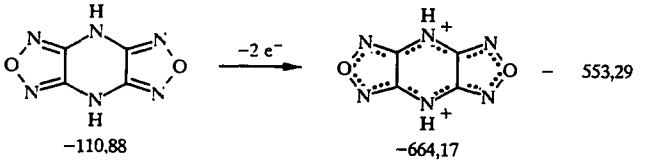




The heats of formation of the compounds were calculated by the MNDO method with full optimization of the molecular geometry and are given in kcal/mole. Thus, it follows from the presented data that whereas the energy effect from the appearance of cyclic delocalization fully compensates for the loss in energy due to the loss of the two (N—H) bonds during the dehydrogenation of dihydropyrazine the analogous effect is not observed in the case of the dihydrodifurazanopyrazine (I). Energy stabilization is not observed during the cyclic delocalization of electrons.

We made a similar comparison for the reactions:

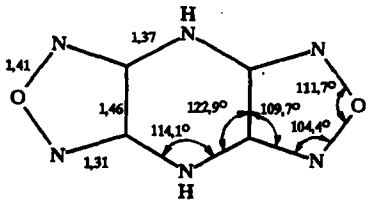




As seen from the heats of the reactions, aromatization with the formation of the deprotonated derivative from the difurazanopyrazine (II) is 103.51 kcal/mole less favorable than in the case of the uncondensed analog, i.e., the difference shows up even more strongly than for the unprotonated derivatives. This is clearly explained by the significantly lower proton affinity of the nitrogen atoms attached to the strong electron acceptor (the furazan ring).

Thus, it follows from the quantum-chemical calculations that the isolated molecule of the dihydrodifurazanopyrazine (I) is conformationally extremely mobile, and the nonplanar structure with the equatorially arranged hydrogen atoms corresponds to a potential energy minimum. Cyclic delocalization of the electrons in the outer contour of the molecule is absent. The removal of two electrons (oxidation or dehydrogenation) leads to a planar heterocyclic system with 14 π electrons and is accompanied by equalization of the lengths and orders of the bonds at the atoms of the heterocycles. However, an energy gain on account of aromatization is not observed, and as a result the system is significantly less stable.

In order to study the structure of the dihydrodifurazanopyrazine (I) an x-ray crystallographic analysis of a single crystal of the compound, produced during crystallization from an aqueous solution, was undertaken.



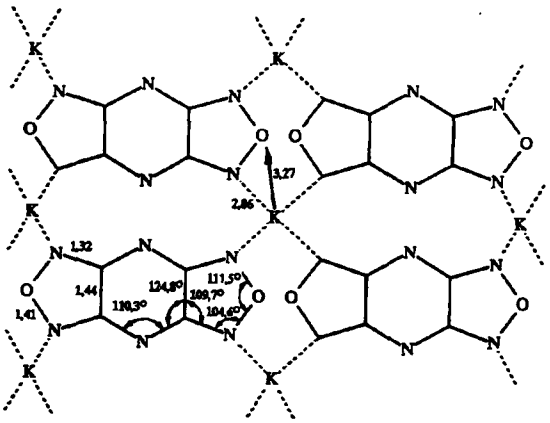
I

Comparison of the bond lengths in the molecule of (I) with the bond lengths in diaminofurazan [10] shows that these geometric parameters are practically identical (the difference amounts on the average to about 0.01 Å) and that closure of the ring is not accompanied by any substantial change in the electronic structure of the furazan ring. It is interesting that the molecule is planar in the crystalline state, whereas it follows from the results of quantum-chemical calculation that the state in which the dihydropyrazine ring has the "boat" conformation is energetically more favorable for the isolated molecule. The flattening of the molecule is clearly due to the more favorable packing of the planar molecules. Moreover, the difference in the energies of the planar and nonplanar conformers amounts to only 0.84 kcal/mole. There is no doubt that the strong electron-withdrawing effect of the two furazan rings promotes delocalization of the electron pairs of the nitrogen atoms of dihydropyrazine ring, thereby reducing their pyramidality and promoting flattening of the dihydropyrazine ring. This is supported by the fact that the dihydropyrazine ring condensed with less electron-withdrawing rings (e.g., in dihydroflavins) has a nonplanar structure [11].

We tried to assess the aromaticity of the dihydrodifurazanopyrazine (I) quantitatively using Birch's method, which shows good agreement with the experimental data for various heterocycles (including polycyclic compounds) [12]. Essentially, the method involves determination of the aromaticity index Ia of the molecule, which is calculated by statistical treatment of the deviations in the orders of the peripheral bonds. The orders of the bonds can easily be determined from the experimental bond lengths of x-ray crystallographic analysis. It was found that the dihydrodifurazanopyrazine (I) has a low degree of aromaticity Ia = 41, close to free furazan (Ia = 43) [13].

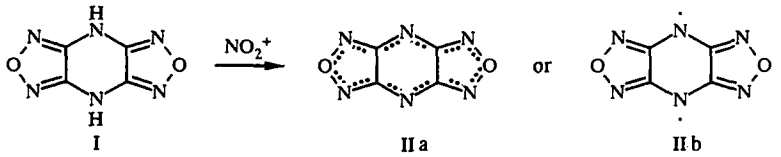
The density of the dihydrodifurazanopyrazine (2.008 ± 0.003 g/cm^3) was calculated from the data of x-ray crystallographic analysis.

The monopotassium salt of this compound forms prismatic crystals extremely sensitive to mechanical influences. The geometric parameters of the salt (I) are given below.



As in the previous case, the molecule is planar. Each potassium cation is coordinated with four anionic residues. Coordination is realized with the nitrogen atoms of the furazan and not of the pyrazine ring. This fact agrees with the data of the quantum-chemical calculations, according to which a significantly larger negative charge is concentrated on the nitrogen atoms of the furazan ring than at the nitrogen atoms of the pyrazine ring. On the whole the geometric parameters of the monopotassium salt differ little from the parameters of the base. The density of the salt is 2.07 ± 0.003 g/cm^3.

During investigation of the properties of the dihydrodifurazanopyrazine (I) it was established that it forms the dehydrogenation product (II) under the influence of various nitrating agents.

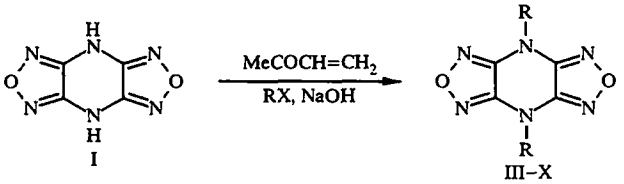


I IIa IIb

This compound has an intense color and is stable in the crystalline state. An ether or alcohol solution of the dehydro product is unstable. After a few minutes it is decolorized, and the final transformation product is compound (I). An acetonitrile solution is characterized by greater stability. A freshly prepared acetonitrile solution has three absorption maxima in the UV spectrum — at 860, 465, and 332 nm. After storage the intensity of the two long-wave bands decreases, while that of the long-wave band increases. The addition of water to the solution accelerates the process, and a new band appears with an absorption band at 286 nm, belonging to the dihydro derivative (I). The ESR spectra of the crystalline substance and of the acetonitrile solution indicated the presence of radicals. On the basis of these data it can be supposed that in the solid state the dehydro derivative (II) is present in the radical form (IIb) or in the form of an equilibrium mixture of the radical and mesoionic forms. If the mixture is dissolved, the radical form, which corresponds to absorption at 860 and 465 nm, quickly changes into the more stable form (according to the data from quantum-chemical calculation) with an absorption maximum at 332 nm. The latter is slowly reduced with the formation of the dihydrodifurazanopyrazine (I). It could be supposed that the biradical (IIb) is formed through a stage involving the formation of an unstable nitroamine. However, the fact that the product (II) is formed when compound (I) is treated with fluorine or Caro's acid indicates that an oxidation mechanism is more likely for the formation of the radical.

It is necessary to mention the very high electrochemical potential of the biradical. Its reduction during reaction with water must lead to the formation of either free oxygen or hydrogen peroxide.

While studying the reactivity of the NH group in the dihydrodifurazanopyrazine (I), we established that it exhibits weakly acidic properties (pK_a = 6.94 ± 0.03) and is readily alkylated by methyl vinyl ketone or by compounds containing a mobile halogen:

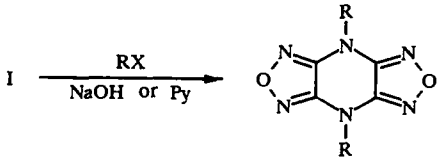


I III–X

III R = $CH_2CH_2C(O)CH_3$; IV R = CH_3, X = I; V R = CO_2CH_3, X = Cl; VI R = $CH_2CO_2CH_2CH_3$, X = Cl; VII R = $CH_2OC(O)C(CH_3)$, X = Cl; VIII R = $CH_2C(O)CH_3$, X = Br; IX R = 2,3-epoxypropyl, X = Cl; X R = $CH_2C_6H_5$, X = Br

Substitution of the ester group in compound (VI) by hydrazine leads smoothly to the corresponding hydrazide (XI): R = $CH_2C(O)NHNH_2$.

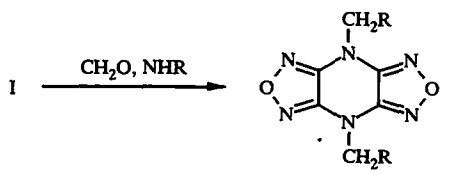
Acylation takes place just as readily:



XII, XIII

XII R = $C(O)CH_3$, X = Br; XIII R = $CO_2CH_2C_6H_5$, X = Cl

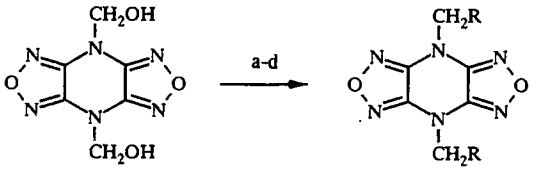
The dihydrodifurazanopyrazine (I) forms a stable dimethyl derivative (XIV) and Mannich bases (XV-XVII) with almost quantitative yields:



XIV–XVII

XIV R = OH; XV R = $NHCH_2CH_2SH$; XVI R = NHC_6H_4Cl-*p*; XVII R = N - morpholyl

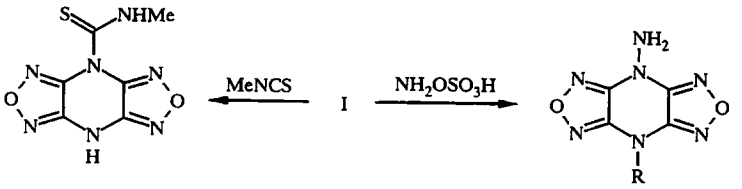
The hydroxymethyl groups in compound (XIV) were converted into a series of other derivatives:



XIV XVIII–XXI

XVIII R = $OC(O)CH_3$, (a) Ac_2O; XIX R = ONO_2, (b) Ac_2O, HNO_3; XX R = Cl, (c) $SOCl_2$; XXI R = N_3, (c), (d) NaN_3

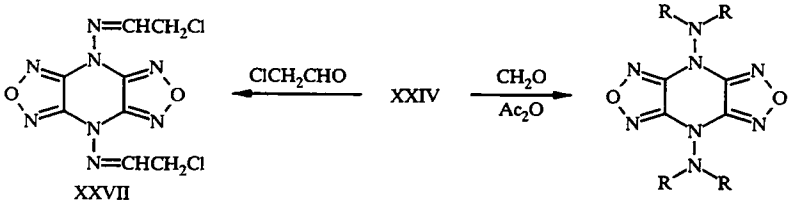
Methyl isothiocyanate adds only at one nitrogen atom of the dihydrodifurazanopyrazine (I) also under severe conditions. In an alkaline medium the anion of compound (I) is readily aminated by hydroxylaminosulfuric acid with the formation of the N-amino derivative (XXIII) and (XXIV):



XXII XXIII, XXIV

XXIII R = H; XXIV R = NH_2

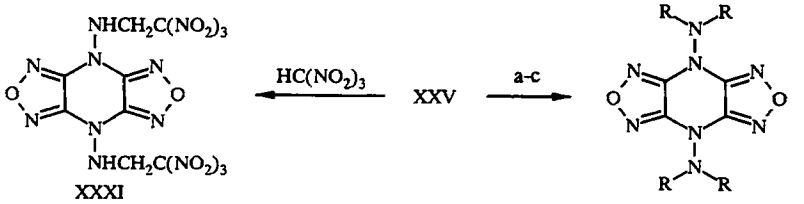
The N-amino derivative (XXIV) reacts with formaldehyde or acetic anhydride at all reaction centers with the formation of the tetrasubstituted products (XXV) and (XXVI). With chloroacetaldehyde the disubstituted hydrazone (XXVII) is formed:



XXVII XXV, XXVI

XXV R = CH_2OH; XXVI R = $C(O)CH_3$

Only the difurazanopyrazine (II) is formed during the nitration and oxidation of the N-amino derivative (XXIV). Nitration of the tetramethyl derivative (XXV) gave the nitrate (XXVIII). Treatment with thionyl chloride gave the chloromethyl derivative (XXIX), in which the chlorine is activated enough for substitution by the azide anion:



XXXI XXVIII–XXX

XXVIII R = CH_2ONO_2, (a) Ac_2O, HNO_3; XXIX R = CH_2Cl, (b) $SOCl_2$; XXX R = CH_2N_3, (b), (c) NaN_3

During study of the Mannich reaction of the tetramethyl derivative (XXV) with nitroform it was established that the reaction was accompanied by the elimination of two hydroxymethyl groups and the final formation of the di- and not the tetratrinitroethyl derivative. This agrees with experimental data on the stability of Mannich bases, according to which nitroform only gives the monosubstituted bases and bis(2,2,2-trinitroethyl)amine is only obtained with ammonia [14].

Stabilization of the trinitroethyl Mannich bases with a free NH fragment is realized effectively by the introduction of a nitro group, and the electron density at the amine nitrogen is reduced as a result of conjugation between the free electron pair of the amine nitrogen and the nitro group. However, nitration of the trinitroethylamine (XXXI) with various nitrating agents (mixtures of nitric acid with acetic and trifluoroacetic anhydrides, sulfuric acid, nitronium fluoroborate in acetonitrile) led

TABLE 1. Characteristics of Compounds (II-XXXII, XXXIV, XXXVI-XXXVIII)

Compound	Molecular formula	mp, °C	IR spectrum, ν, cm^{-1}				PMR spectrum, δ, ppm			Yield, %
			OH, NH	CH_2	furazan	others	OH, NH	CH_2	others	
1	2	3	4	5	6	7	8	9	10	11
II	$C_4N_6O_2$	145 decomp.	—	—	1030 (1012 in MeCN)	1582, 1536 (C=N)	—	—	—	97
III	$C_{12}H_{14}N_6O_4$	161...162	—	3038	1050	1600 (C=O)	—	3,02 (4H, t), 3,93 (4H, t)	2,11 (6H, s, CH_3)	80
IV	$C_6H_6N_6O_2$	217...218	—	—	—	—	—	—	3,42 (6H, s, CH_3)	88
V	$C_8H_6N_6O_6$	242...245	—	—	—	—	—	—	4,04 (6H, s, CH_3)	93
VI	$C_{12}H_{14}N_6O_6$	>260	—	—	—	—	—	1,95 (4H, q), 4,71 (4H, s)	1,20 (6H, t)	73
VII	$C_{16}H_{22}N_6O_6$	186...187	—	3040	1010	1750 (C=O), 1583 (C=N)	—	5,70 (4H, s)	1,13 (18H, s, CH_3)	90
VIII	$C_{10}H_{10}N_6O_4$	277...278	—	—	—		—	4,87 (4H, s)	2,27 (6H, s, CH_3)	74
IX	$C_{10}H_{10}N_6O_4$	135...137	—	—	—		—	2,78 (4H, s), 3,91 (4H, s)	5,64 (2H, s, CH)	58
X	$C_{18}H_{14}N_6O_2$	196...197; 170...175 decomp. [15]	—	—	962	1500, 1592 (Ph), 1641 (C=N)	—	4,93 (4H, s); 5,02 (acetone-d_6 D_6) [15]	7,29...7,56 (10H, t, Ph); 7,5 (acetone-d_6) [15]	94, 93 [15]
XI	$C_8H_{10}N_{10}O_4$	>260	—	—	—	—	4,82 (4H, s), 10,33 (2H, s)	4,47 (4H, s)	—	72

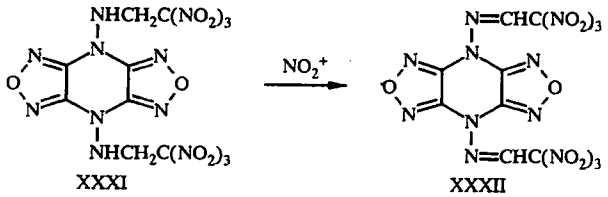
TABLE 1. (Continued)

Compound	Molecular formula	mp, °C	IR spectrum, ν, cm^{-1}				PMR spectrum, δ, ppm			Yield, %
			OH, NH	CH_2	furazan	others	OH, NH	CH_2	others	
1	2	3	4	5	6	7	8	9	10	11
XII	$C_8H_6N_6O_4$	260...262	—	—	—	—	—	—	2,64 (6H, s, CH_3)	68
XIII	$C_{20}H_{14}N_6O_6$	228...229	—	—	—	—	—	5,53 (4H, s)	7,31...7,56 (10H, m, Ph)	81
XIV	$C_6H_6N_6O_4$	310...315	3400	—	1000	—	7,05 (2H, t)	5,18 (4H, s)	—	95
XV	$C_{10}H_{16}N_8O_2S_2$	171...173	—	—	—	—	—	3,11...3,27 (8H, m, CH_2, SH, NH), 4,11 (4H, s) 4,51 (4H, s)		88
XVI	$C_{18}H_{14}N_8O_2Cl_2$	170...172	—	—	—	—	11,82 (2H, s)	4,89 (4H, s)	6,66...7,33 (8H, m, Ph)	91
XVII	$C_{14}H_{20}N_8O_4$	228...229	—	—	—	—	—	2,71 (8H, s), 3,56 (8H, s), 4,64 (8H, s)	—	91
XVIII	$C_{10}H_{10}N_6O_6$	195...196	—	—	—	—	—	5,81 (4H, s)	2,04 (6H, s, CH_3)	65
XIX	$C_6H_4N_8O_8$	210...211 decomp.	—	3040	1006	1665, 1280 (ONO_2)	—	6,24 (4H, s)	—	83
XX	$C_6H_4N_6O_2Cl_2$	261...262	—	3060	972	1595 (C=N)	—	5,82 (4H, s)	—	88
XXI	$C_6H_4N_{12}O_2$	118...118,5	—	—	1000	2150 (N_3), 1595 (C=N)	—	5,31 (4H, s)	—	87
XXII	$C_6H_5N_7O_2S$	>260 decomp.	—	—	—	—	12,51 (2H, s)	—	3,11 (3H, s, CH_3)	85
XXIII	$C_4H_3N_7O_2$	>260 decomp.	—	—	—	—	6,24 (3H, s)	—	—	4
XXIV	$C_4H_4N_8O_2$	295...300 decomp.	3310, 3240	—	966	1615 (C=N)	5,69 (4H, s)	—	—	91
XXV	$C_{18}H_{12}N_8O_6$	190...192	3250	—	988	—	6,00 (4H, s)	4,60 (8H, s)	—	91

TABLE 1. (Continued)

Compound	Molecular formula	mp, °C	IR spectrum, ν, cm^{-1}				PMR spectrum, δ, ppm			Yield, %
			OH, NH	CH_2	furazan	others	OH, NH	CH_2	others	
1	2	3	4	5	6	7	8	9	10	11
XXVI	$C_{12}H_{12}N_8O_6$	210...212	–	–	995	1760, 1730 (C=O)	–	–	2,55 (12H, s) CH_3)	93
XXVII	$C_8H_6N_8O_2Cl_2$	192...193	–	–	–	–	–	4,58 (4H, d)	8,55 (2H, t, CH)	77
XXVIII	$C_8H_8N_{12}O_{14}$	193...194 decomp.	–	3040	1013	1670, 1373, 1283 (ONO_2)	–	6,15 (8H, s)	–	81
XXIX	$C_8H_8N_8O_2Cl_4$	198...199	–	3050	980	–	–	5,62 (8H, s)	–	95
XXX	$C_8H_8N_{18}O_2$	115...116	–	–	995	2107 (N_3), 1580 (C=N)	–	4,84 (8H, s)	–	69
XXXI	$C_8H_6N_{14}O_{14}$	150...152 decomp.	3325	–	–	1570, 1307 [$C(NO_2)_3$]	7,73 (2H, t)	5,13 (4H, s)	–	83
XXXII	$C_8H_2N_{14}O_{14}$	168...172 decomp.	–	–	955	1603, 1295 $C(NO_2)_3$, 3010 (CH)	–	–	9,31 (2H, s) CH)	87
XXXIV	$C_6H_2N_8O_2$	315...320	3295	–	1020	1625, 1570 (C=N)	10,38 (2H, s)	–	–	65
XXXVI	$C_6N_8O_2$	170 decomp.	–	–	–	–	–	–	–	87
XXXVII	$C_8H_6N_8O_4$	280...290	3450	–	1000	1610 (C=N)	7,97 (2H, s)	3,33 (4H, s,	–	95
XXXVIII	$C_8H_4N_{10}O_8$	195...200 decomp.	–	–	1020	1655, 1275 (ONO_2), 1605 (C=N)	–	6,58 (4H, s,	–	83

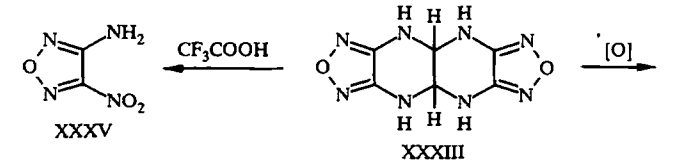
unexpectedly not to the nitroamine but to the oxidation product 4,8-di(trinitroethyleneamino)difurazano[3,4-*b*,*e*]pyrazine (XXXII)



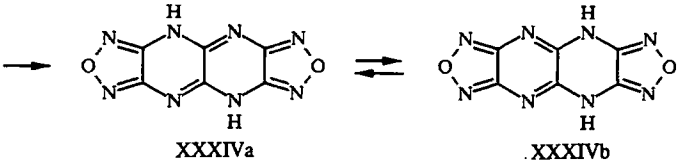
XXXI XXXII

The formation of the hydrazone (XXXII) must clearly be explained by the higher thermodynamic stability compared with the nitroamine, which is an intermediate product, on the basis of the idea that such a mild nitrating agent as nitronium fluoroborate does not have oxidizing characteristics.

As a result of the study of the oxidation of 1,4,5,8-tetraazadifurazano[3,4-*e*][3,4-*h*]decalin (XXXIII) [2] it was established that under the influence of such oxidizing agents as potassium ferricyanide, potassium permanganate, and selenium dioxide in perhydrol the analog of the dihydrodifurazanopyrazine (I) 1,5H-1,4,5,8-tetraazadifurazano[3,4-*b*][3,4-*h*]dihydronaphthalene (XXXIV) is formed. Under the influence of trifluoroperacetic acid 3-amino-4-nitrofurazan (XXXV) is formed:

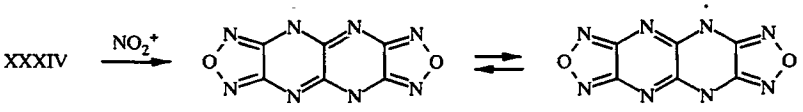


XXXV XXXIII



XXXIVa XXXIVb

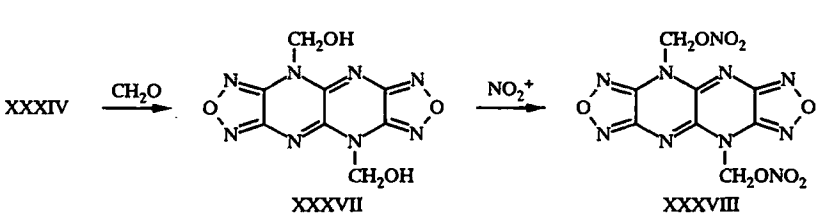
The dihydro derivative (XXXIV) can exist in two tautomeric forms (XXXIVa) and (XXXIVb). However, the data from spectroscopic analyses do not make it possible to choose between them unambiguously. During the nitration of the amine (XXXIV) the product from further oxidation (XXXVI), not containing nitrogen in the molecule, was obtained:



XXXVIa XXXVIb

The reaction product had an intense black color, which disappeared on heating (to 170°C) and in moist organic solvents. The ESR spectra showed that the product existed in radical form both in the solid state and in solution in acetonitrile. The solution was less stable, and the radical was transformed at a rate of about 2% per minute. Nevertheless, the solution of the biradical (XXXVI) was more stable than a solution of the previously described biradical (II). The enhanced stability of the biradical (XXXVI) is probably explained by the lower enthalpy of formation and by the larger set of possible resonance structures.

Like compound (I), the dihydro derivative (XXXIV) was transformed into the dimethyl derivative (XXXVII) and then into the dinitrate (XXXVIII):



XXXVII XXXVIII

EXPERIMENTAL

The UV spectra were recorded on a Specord UV-Vis spectrometer. The IR spectra were obtained in Nujol on a Perkin-Elmer 580B instrument. The PMR spectra were obtained in DMSO-d_6 on a Bruker WH-90/DS spectrometer at 90 MHz with TMS as internal standard. The mass spectra were obtained on a VS-50AET spectrometer at 70 eV. The purity of the products was monitored by TLC on Silufol UV-254 plates and also by HPLC on a Du Pont 850 chromatograph with a 4.6 × 250-mm column of Zorbax SIL. The elemental analyses for C, H, N, and S were conducted on a Perkin-Elmer instrument.

The molecular structure of the compounds was determined by means of a Syntex $P2_1$ diffractometer ($\theta/2\theta$ scan, $\lambda CuK\alpha$, graphite monochromator, $2\theta_{max} = 150°$). The structure was interpreted by the direct method using MULTAN software and was refined by least-squares treatment in anisotropic approximation. The derivatograms were recorded on an OD-102 MOM derivatograph (Hungary). The heating rate was 5 deg/min, and the sample weight was 50-80 mg.

Difurazano[3,4-*b*,*e*]pyrazine (II). To a nitration mixture consisting of 4.6 ml of trifluoroacetic anhydride and 2 ml of anhydrous nitric acid we added 0.83 g (0.005 mole) of 4,8-dihydrodifurazano[3,4-*b*,*e*]pyrazine (I). The mixture was kept at 0°C for 1 h. The acid was then distilled under vacuum at 20°C. The solid residue was washed with 2 × 10 ml of dry chloroform. After drying over alkali we obtained black crystals of the biradical (II). Mass spectrum, *m/e*: 164 (M^+). Found, %: C 28.80; N 50.81. $C_4N_6O_2$. Calculated: C 29.27; N 51.22.

4,8-Di(3-oxobutyl)difurazano[3,4-*b*,*e*]pyrazine (III). We boiled 1.66 g (0.01 mole) of 4,8-dihydrodifurazano[3,4-*b*,*e*]pyrazine (I) and 2.80 g (0.04 mole) of methyl vinyl ketone in 20 ml of ether with the addition of a few crystals of hydroquinone and a drop of hydrochloric acid for 1 h. The colorless prismatic crystals that separated after slow cooling were filtered off, washed with ether, and dried. Mass spectrum, *m/e*: 275 ($M - OCH_3$), 263 ($M - COCH_3$), 249 ($M - CH_2COCH_3$), 234 ($M - CH_2CH_2COCH_3$), 164 ($M - 2CH_2CH_2COCH_3$). Found, %: C 46.51; H 4.75; N 26.93. $C_{12}H_{14}N_6O_4$. Calculated, %: C 47.00; H 4.60; N 27.45.

General Procedure for the Alkylation of Dihydrodifurazano[3,4-*b*,*e*]pyrazine (I). To a solution consisting of 10 ml of water, 3 ml of acetonitrile, and 1.20 g (0.03 mole) of sodium hydroxide we added 1.66 g (0.01 mole) of dihydrodifurazano[3,4-*b*,*e*]pyrazine (I) and then, dropwise with vigorous stirring, 0.03 mole of the alkylating agent. After stirring for 24 h at room temperature the precipitate was filtered off and washed with water and with ether. The product was recrystallized from aqueous acetone. Compounds (IV-X) were obtained.

4,8-Dibenzyldifurazano[3,4-*b*,*e*]]pyrazine (X). Mass spectrum, *m/e*: 346 (M^+). Found, %: C 62.61; H 4.07; N 24.51. $C_{18}H_{14}N_6O_4$. Calculated, %: C 62.43; H 4.05; N 24.28.

4,8-Di(2-acetohydrazido)difurazano[3,4-*b*,*e*]pyrazine (XI). To a suspension of 1.01 g (0.03 mole) of 4,8-di(ethoxycarbonylmethyl)difurazano[3,4-*b*,*e*]pyrazine (VI) in 5 ml of ethanol while stirring we added 1 ml of anhydrous hydrazine. After 1 h the precipitate was filtered off and washed with alcohol and with water. The crude product was recrystallized from 300 ml of water. Found %: 30.95; H 3.02; N 45.16. $C_8H_{10}N_{10}O_4$. Calculated %: C 30.97; H 3.24; N 45.15.

4,8-Diacetylfurazano[3,4-*b*,*e*]pyrazine (XII). To a solution consisting of 15 ml of acetonitrile and 10 ml of pyridine we added 1.66 g (0.01 mole) of dihydrodifurazanopyrazine (I). While stirring and cooling with ice, we added 3.0 ml (0.03 mole) of acetyl bromide. The mixture was stirred for 2 h at 0°C. The precipitate was filtered off and washed with water. The product was recrystallized from aqueous acetone. Found %: C 41.25; H 2.39; N 32.86. $C_8H_6N_6O_4$. Calculated %: C 41.23; H 2.31; N 32.05.

The *Z* derivative (XIII) was obtained similarly.

4,8-Di(hydroxymethyl)difurazano[3,4-*b*,*e*]pyrazine (XIV). In an ultrasonic bath we dispersed 8.30 g (0.05 mole) of dihydrodifurazano[3,4-b,e]pyrazine (I) with 20 ml of 37% formalin and 5 ml of water for 10 min. The mixture was then stirred for 24 h. The precipitate was filtered off and washed with water (3 × 20 ml). The colorless crystals of the methylol derivative were dried over phosphorus pentoxide. Found %: C 31.75; H 2.58; N 37.23. $C_6H_6N_6O_4$. Calculated %: C 31.86; H 2.65; N 37.17.

The tetramethyl derivative (XXV) and the dimethylol derivative (XXXVII) were obtained similarly.

4,8-Di(N-methylenemorpholino)difurazano[3,4-*b*,*e*]pyrazine (XVII). To a suspension of 1.66 g (0.01 mole) of dihydrodifurazano[3,4-*b*,*e*]pyrazine (I) in 20 ml of water and 30 ml of methanol we added 2.62 ml (0.03 mole) of morpholine and then 2.8 ml of 31% formalin. After 30 min the suspension was cooled to 0°C. The precipitate was filtered off and washed with water (3 × 10 ml). The product was recrystallized from acetone. Found %: C 46.52; H 5.60; N 30.66. $C_{14}H_{20}N_8O_4$. Calculated %: C 46.15; H 5.53; N 30.75.

The Mannich bases (XV, XVI) were obtained similarly.

4,8-Di(acetoxymethyl)difurazano[3,4-*b*,*e*]pyrazine (XVIII). A mixture of 2.26 g (0.01 mole) of 4,8-di(hydroxymethyl)difurazano[3,4-*b*,*e*]pyrazine (XIV), 0.50 g of anhydrous sodium acetate, and 8 ml of acetic anhydride was heated with stirring at 80°C for 10 min. The mixture was cooled to 0°C and kept at this temperature for 1 h. The precipitate was filtered off, washed with water, and recrystallized from a mixture of 15 ml of acetone and 10 ml of isopropyl alcohol. Found %: C 38.57; H 3.20; N 27.27. $C_{10}H_{10}N_6O_6$. Calculated %: C 38.72; H 3.25; N 27.08.

4,8-Di(nitroxymethyl)difurazano[3,4-*b*,*e*]pyrazine (XIX). To a nitration mixture consisting of 60 ml of acetic anhydride and 30 ml of anhydrous nitric acid at 10-12°C we added over 5 min in small portions 11.30 g (0.05 mole) of 4,8-di(hydroxymethyl)difurazano[3,4-*b*,*e*]pyrazine (XIV). The mixture was stirred at 15-20°C for 2 h. The nitration mixture was poured onto ice and water (300 g). The precipitate was filtered off and washed with water (4 × 100 ml). The product was recrystallized from aqueous acetone. After drying over alkali colorless crystals were obtained. Vigorous decomposition began at 170°C (decomp. p.). Found %: C 23.04; H 1.25; N 35.25. $C_6H_4N_8O_8$. Calculated %: C 22.78; H 1.26; N 35.44.

This procedure was general for the production of the tetranitrate (XXVIII) (mp 153°C) and also for the dinitrate (XXXVIII).

4,8-Di(chloromethyl)difurazano[3,4-*b*,*e*]pyrazine (XX). We boiled 22.6 g (0.1 mole) of 4,8-di(hydroxymethyl)-difurazano[3,4-*b*,*e*]pyrazine (XIV) in 58 ml of thionyl chloride for 3 h under a reflux condenser. The excess of thionyl chloride was distilled under vacuum at a bath temperature of 50°C. The solid residue was dried over alkali and crystallized from aqueous acetone. Found %: C 27.77; H 1.61; N 31.67; Cl 26.80. $C_6H_4N_6O_2Cl_2$. Calculated %: C 27.38; H 1.52; N 31.94; Cl 27.00.

N,N′-Tetra(chloromethyl)-4,8-difurazano[3,4-*b*,*e*]pyrazine (XXIX) was obtained similarly.

4,8-Di(azidomethyl)difurazano[3,4-*b*,*e*]pyrazine (XXI). A mixture of 13.15 g (0.05 mole) of 4,8-di(chloromethyl)-difurazano[3,4-*b*,*e*]pyrazine (XX) and 9.00 g of sodium azide was stirred in 45 ml of acetone for 24 h at room temperature. The inorganic material and the precipitate were filtered off onto a filter and washed with acetone (2 × 10 ml). To the combined filtrates we added 10 ml of ethanol. The solution was left in the refrigerator at −20°C overnight to crystallize. The colorless crystals were then filtered off and washed with ethanol; decomp. p. 165°C. Found %: C 26.32; H 1.39; N 60.79. $C_6H_4N_{12}O_2$. Calculated %: C 26.09; H 1.45; N 60.87.

4,8-Di(diazidomethylamino)difurazano[3,4-*b*,*e*]pyrazine (XXX) was obtained similarly; decomp. p. 147°C.

4-Hydro-8-(methylaminothiocarbonyl)difurazano[3,4-*b*,*e*]pyrazine (XXII). A mixture of 0.83 g (0.005 mole) of dihydrodifurazano[3,4-*b*,*e*]pyrazine (I) and 0.88 g (0.012 mole) of methyl isothiocyanate was boiled in 5 ml of acetone under a reflux condenser for 2 h. The mixture was cooled to 0°C, and the product was filtered off. It was washed with 5 ml of acetonitrile and 2 × 10 ml of water. The product was recrystallized from 25 ml of DMFA. Found %: C 30.22; H 2.08; N 41.57. $C_6H_5N_7O_2S$. Calculated %: C 30.13; H 2.10; N 41.00.

4,8-Diaminodifurazano[3,4-*b*,*e*]pyrazine (XXIV). To a solution of 4.89 g (0.03 mole) of dihydrodifurazano[3,4-*b*,*e*]pyrazine (I) and 7.42 g (0.07 mole) of sodium carbonate in 140 ml of water at 70-75°C we added a solution of 9.94 g (0.08 mole) of hydroxylaminosulfuric acid in 50 ml of water for 30 min. The pH was kept at 9-10 by the addition of sodium bicarbonate. The mixture was kept at 70-75°C for 1 h and was then cooled to 20°C. The precipitate was filtered off, washed with water (3 × 30 ml) and acetone (30 ml), and dried. The product can be recrystallized from dimethylformamide. Mass spectrum, *m/e*: 196 (M^+), 181 (M − NH), 180 (M − NH_2). During neutralization of the alkaline mother solution with hydrochloric acid the monosubstitution product (XXIII) separated. It was washed with water and dried. It can be recrystallized from dioxane. Found %: C 24.75; H 1.84; N 57.51. $C_4H_4N_8O_2$. Calculated %: C 24.49; H 2.04; N 57.14.

4,8-Di(diacetamido)difurazano[3,4-*b*,*e*]pyrazine (XXVI). We boiled 1.96 g (0.01 mole) of 4,8-diaminodifurazano[3,4-*b*,*e*]pyrazine (XXIV) in 30 ml of acetic anhydride under a reflux condenser for 1 h. We then distilled 20 ml of acetic anhydride and cooled the mixture. The precipitate was filtered off and washed with water. The product was recrystallized from aqueous acetone. Mass spectrum, *m/e*: 364 (M^+), 322 (M − Ac + 2H), 280 (M − 2Ac + 2H), 238 (M − 3Ac + 3H). Found %: C 39.58; H 3.10; N 30.78. $C_{12}H_{12}N_8O_6$. Calculated %: C 39.56; H 3.29; N 30.77.

4,8-Di(2-chloroethyleneamino)difurazano[3,4-*b*,*e*]pyrazine (XXVII). We boiled 1.96 g (0.01 mole) of 4,8-diaminodifurazano[3,4-*b*,*e*]pyrazine (XXIV) in a mixture of 4 ml of 50% aqueous chloroacetaldehyde, 8 ml of dioxane, and one drop of boron trifluoride etherate for 10 min. The mixture was cooled, and the precipitate was filtered off and washed with water. The product was recrystallized from dioxane. Found %: C 30.49; H 1.82; N 35.67; Cl 21.70. $C_8H_6N_8O_2Cl_2$. Calculated %: C 30.30; H 1.90; N 35.33; Cl 22.35.

4,8-Di(trinitroethylamino)difurazano[3,4-*b*,*e*]pyrazine (XXXI). A mixture of 3.16 g (0.01 mole) of 4,8-tetramethylolaminodifurazano[3,4-*b*,*e*]pyrazine (XXV) and 17 ml of a 20% aqueous solution of nitroform (0.03 mole) was stirred at room temperature for 24 h. The precipitate was filtered off and washed with water (3 × 10 ml). The colorless product was dried over sodium hydroxide. It can be recrystallized from dioxane. Found %: C 18.72; H 1.22; N 37.25. $C_8H_6N_{14}O_{14}$. Calculated %: C 18.39; H 1.14; N 37.54.

4,8-Di(trinitroethyleneamino)difurazano[3,4-*b*,*e*]pyrazine (XXXII). To a nitration mixture consisting of 50 ml of trifluoroacetic anhydride and 23 ml of anhydrous nitric acid at −15°C we added over 10 min 10.44 g (0.02 mole) of 4,8-di(trinitroethylamino)difurazano[3,4-*b*,*e*]pyrazine (XXXI) in small portions. The nitration mixture was stirred at 10-15°C for 2 h and poured onto ice and water (250 g). The precipitate was filtered off and washed with water (3 × 50 ml). The product was dried over alkali and crystallized from ether—benzene solution. The product formed colorless crystals; decomp. p. 80°C. Found %: C 18.98; H 0.52; N 37.32. $C_8H_2N_{14}O_{14}$. Calculated %: C 18.53; H 0.39; N 37.84.

1,5-2H-1,4,5,8-Tetraazadifurazano[3,4-*b*][3,4-*h*]dihydronaphthalene (XXXIV). To a mixture of 2.22 g (0.01 mole) of 1,4,5,8-tetraazadifurazano[3,4-*e*][3,4-*h*]decalin, 50 ml of water, and 10 ml of 1 N potassium hydroxide solution we added a solution of 17.5 g (0.05 mole) of potassium ferrocyanide in 65 ml of water at room temperature. The suspension was stirred at 25°C for 4 h, and the precipitate was filtered off, washed with 20 ml of acetone, transferred to 100 ml of water, and acidified to pH 7. The precipitate was filtered and washed with water. After drying over phosphorus pentoxide colored crystals were obtained. Mass spectrum, *m/e*: 218 (M^+), 188 (M − NO), 158 (M − NO − NO). Found %: C 33.02; H 0.92; N 51.38;. $C_6H_2N_8O_2$. Calculated %: C 32.69; H 0.83; N 51.27.

1,4,5,8-Tetraazadifurazano[3,4-*b*][3,4-*h*]naphthalene (XXXVI). We added 0.44 g (0.002 mole) of 1,5-2H-1,4,5,8-tetraazadifurazano[3,4-*b*][3,4-*h*]dihydronaphthalene (XXXIV) at 0°C to a nitration mixture consisting of 5 ml of trifluoroacetic anhydride and 2.2 ml of anhydrous nitric acid. The mixture was kept at 0°C for 1 h. The precipitate was filtered off and washed with dry chloroform (3 × 5 ml). The product was dried over alkali, and black crystals of the biradical (XXXIV) were obtained; decomp. p. 170°C (decolorization). Found %: C 33.33; N 51.85. $C_6N_8O_2$. Calculated %: C 33.12; N 51.27.

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