Pergamon

Tetrahedron Vol. 51, No. 10, pp. 3061-3076, 1995

0040-4020/95 $9.50+0.00

0040-4020(95)00046-1

Experimental and Quantum Chemical Study of the Reactions of 1,10-Anthraquinones with Alcohols and Amines.

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Abstract: The primary stage of the reaction between 9-aryloxy-1,10-anthraquinones and methanol is the nucleophilic 1,4-addition which gives rise to the adduct, corresponding to 1-hydroxy-9-methoxy-9-aryloxy-10-anthrone. The reaction of 9-aryloxy-1,10-anthraquinones with the primary aliphatic and aromatic amines results in the formation of 9-alkyl(aryl)amino-1,10-anthraquinones that are in a tautomeric equilibrium with 1-hydroxy-9,10-anthraquinone-9-alkyl(aryl)imines. The quantum chemical calculations of the enthalpy of 9-amine-1,10-anthraquinone isomerization are in agreement with the experimentally recorded influence on the tautomeric equilibrium of the nature of amine, solvent, and substituent in the anthraquinone nucleus. The data of quantum chemical calculations confirm the addition-elimination mechanism of the reaction of 1,10-anthraquinones with amines.

INTRODUCTION

The 1,10-anthraquinone derivatives have long been unknown owing to their high reactivity and all the attempts to synthesize them have failed[1,2]. P. Boldt et al have tried to stabilize the 1,10-anthraquinone molecule by stabilizing the quinoid system with methyl groups[1,2]. However, 2,3,4,5,8-pentamethyl-1,10-anthraquinone has been detected only in solution and the attempts to isolate this substance have failed. Later, Boldt and Setiabudi[3,4] have isolated crystalline 3-tert-butyl-5,8-dimethyl-1,10-anthraquinone and identified it by the ^1H NMR and mass spectrometry data. In the presence of even the traces of water, ana-quinone transforms into 1-hydroxy-3-tert-butyl-5,8-dimethyl-9,10-anthraquinone.

Gorelik et al. have succeeded in isolating two chloro derivatives of 1,10-anthraquinone (2,4,9-trichloro- and 2,3,4,9-tetrachloro-1,10-anthraquinone) from the mixture, forming in the reaction of 1,4-dihydroxyanthraquinone with thionyl chloride in the presence of triethylamine[5,6]. When stored in the crystalline state, these ana-quinones are stable for a long time.

One of the first derivatives in the series of 1,10-anthraquinones has been isolated in the crystalline form by irradiating the 2-alkylamino derivatives of 1-phenoxyanthraquinone undergoing irreversible photoisomerization[7,8]. Unlike 2-alkylamino derivatives, the other derivatives of 1-phenoxyanthraquinone are the reversibly isomerizing compounds with good photochromic characteristics[8-10].

Therefore 1,10-anthraquinones (ana-anthraquinones) are a novel class of quinoid compounds that became the subject of study only 10-15 years ago. The investigations of the reactivity of this new class of compounds

could extend the knowledge on the chemistry of quinones as well as lead to the synthesis of new interesting compounds. For instance, studying the interaction between photoinduced 9-aryloxy-1,10-anthraquinones with aromatic and aliphatic amines has given a convenient method for obtaining the derivatives of 1-hydroxy-9,10-anthraquinone-9-imines. These compounds are the potential dyes for liquid-crystalline dispersed systems[11]. Usually, the anthraquinone imines are obtained in strict conditions, i.e., by heating of anthraquinones with amines in methanol or pyridine up to 100°.

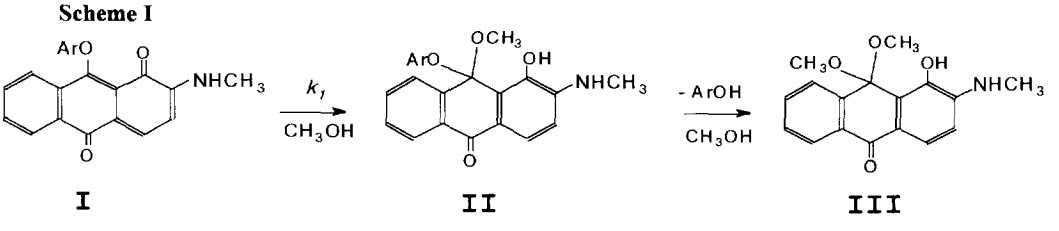
The aim of this contribution is to study the reactions of 1,10-anthraquinones with nucleophilic agents using the reactions of 9-aryloxy-1,10-anthraquinones with methanol and aliphatic and aromatic amines.

RESULTS

1. Reaction with methanol

a) 2-methylamino-9-(p-tert-butylphenoxy)-1,10-anthraquinone (I). The study of the reaction between 1,10-anthraquinones and alcohols has been initiated using 2-methylamino-9-(p-tert-butylphenoxy)-1,10-anthraquinone (I) obtained photochemically[8]. As has been mentioned, this compound undergoes irreversible transformation under light and can be isolated in the individual form. However, it displays all the characteristics typical of the highly reactive system of 1,10-anthraquinone. Thus, the reaction with methanol occurs at room temperature. Varying the time delay, we could isolate and characterize[12] both the mixed, 9-methoxy-9-(p-tert-butylphenoxy)-1-hydroxy-2-methylamino-10-anthrone (**II**) and substituted, 9,9-dimethoxy-1-hydroxy-2-methylamino-10-anthrone (**III**).

Scheme I



I II III

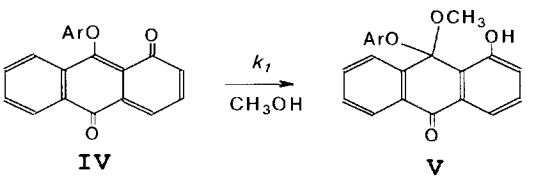
Thus, we have succeeded in establishing the stepwise mechanism of the reaction of ana-quinone **I** with methanol. The first stage (nucleophilic 1,4-addition of an alcohol molecule) is similar to that for α,β-unsaturated carbonyl compounds[13]. The second stage is the nucleophilic substitution of aryloxy group in position 9 by alkoxygroup. Note that 9,9-diethoxy-1-hydroxy-10-anthrone was isolated recently[14] under irradiation of the benzene solution of 1-phenoxy-9,10-anthraquinone in the presence of ethanol. The primary adduct was not detected by the authors[14].

Anthrones **II** and **III** are unstable and upon heating can easily eliminate the alcohol molecule. Thus, the mass-spectrum of compound **III** displays the line of ion with m/z=267 that refers to the product of methanol molecule elimination (299-32). The elimination of the alcohol molecule can also occur photochemically. Under irradiation in non-polar organic solvents the yellow solution of compound **III** becomes dark blue (λ_{max}=603 nm). The electronic absorption spectrum of the product is similar to those of 2-alkylamino-1,10-

anthraquinones[10]. However, all the attempts to isolate 2-methylamino-9-methoxy-1,10-anthraquinone have failed because it easily transforms into 1-hydroxy-2-methylamino-9,10-anthraquinone.

b) 9-(p-tr-butylphenoxy)-1,10-anthraquinone (IV). Unlike compound **I**, the unsubstituted in position 2 9-(p-tert-butylphenoxy)-1,10-anthraquinone (**IV**) has not been isolated. Therefore compound **IV** has been obtained by irradiating 1-(p-tert-butylphenoxy)-9,10-anthraquinone in toluene with added methanol (10^{-3}-10^{-1} mol/l). Ana-quinone **IV** obtained by photolysis, reacts with methanol to form the compound with a strong absorption band in the near UV-region (**fig. 1a**). The spectrum of this compound is observed to be close to the anthrone one (**fig. 1b**). The shift of the maximum in the absorption spectrum from 350 nm to 400 nm is determined by the influence of methylamino-group in position 2. Thus, for ana-quinone **IV** the reaction with methanol yields the adduct, 9-methoxy-9-(p-tert-butylphenoxy)-1-hydroxy-10-anthrone (**V**)

Scheme II



However, it is less stable and very easy transforms into 1-hydroxy-9,10-anthraquinone.

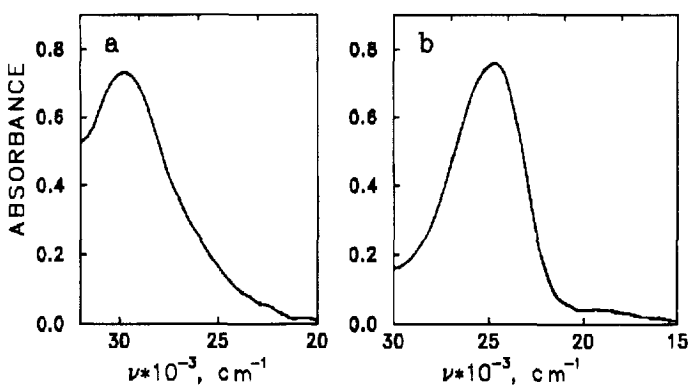


Figure 1. a) Electronic absorption spectrum (EAS) arising after irradiation of toluene solution of 1-(p-tert-butylphenoxy)-9,10-anthraquinone with methanol (0.8 M).
b) EAS of 9-methoxy-9-(p-tert-butylphenoxy)-1-hydroxy-2-methylamino-10-anthron (**II**) in toluene.

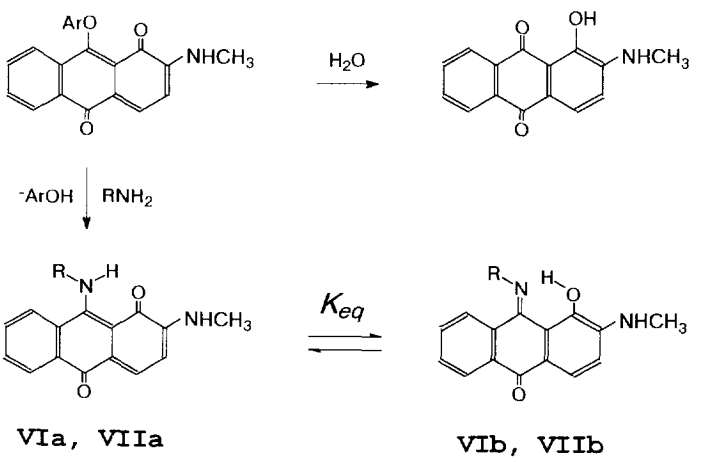
2. *Reactions with aliphatic and aromatic amines*

a) 2-methylamino-9-(p-tert-butylphenoxy)-1,10-anthraquinone (I). The reaction of 1,10-anthraquinones with amines has also been studied using 2-methylamino-9-(p-tert-butylphenoxy)-1,10-anthraquinone (**I**) as an example. On addition to solution of compound **I** in benzene of both n-butylamine and p-toluidine the equilibrium

mixture of the corresponding 9-amino-1,10-anthraquinones (**VIa, VIIa**) and 1-hydroxy-9,10-anthraquinones-9-imines (**VIb, VIIb**) forms with a high yield at room temperature. The trace quantities of 1-hydroxy-2-methylamino-9,10-anthraquinone have also been observed (**Scheme III**). Compounds **VI** and **VII** with yield up to 95% can also be obtained by irradiating the solution of 1-(p-tert-butylphenoxy)-2-methylamino-9,10-anthraquinone in benzene in the presence of amine without preliminary isolation of intermediate ana-anthraquinone.

The structure of products **VI** and **VII** has been determined by analyzing the spectral data (IR, NMR, UV, mass-spectrometry). The IR spectra of the tautomeric mixture of compounds **VI** and **VII** contain the characteristic vibrations of N-H, C=O and C=N groups. The electronic absorption spectra of compounds **VI** and **VII** are quite different (**fig. 2a,b**). Compound **VI** is dark blue and the visible spectrum region displays two maxima at 604 and 646 nm (**fig. 2a**) whereas compound **VII** is brown and has its maximum in the absorption spectrum at 490 nm and the shoulder at 650 nm (**fig.2b**). This difference can be attributed to the shift in the tautomeric equilibrium towards form **a** for compound **VI** and a large content of form **b** for compound **VII**. The assignment has been performed as described in papers[8,15], where a qualitative conclusion on the existence of 9,10-anthraquinone-9-imines in the form of the mixture of tautomers has been made on the basis of electronic absorption spectra.

Scheme III



VIa, VIIa **VIb, VIIb**

R = n-C_4H_9 (VIa, VIb); R = p-$CH_3C_6H_4$ (VIIa, VIIb)

It is useful to establish the compound structure by independent methods that can also be used for quantitative determination of the equilibrium between Forms **a** and **b**. Determining the quantitative characteristics of the intrachelate equilibrium **a** $\rightleftharpoons$ **b** one can not only specify the structure of forming products but can also synthesize the compounds with the given absorption region. The NMR technique is the appropriate method for studying the tautomeric equilibrium. Note that the tautomeric transformations **a** $\rightleftharpoons$ **b** are *"fast"* within the NMR time range (the condition of *"fast exchange"*). Therefore the NMR spectra give the averaged signals of two forms.

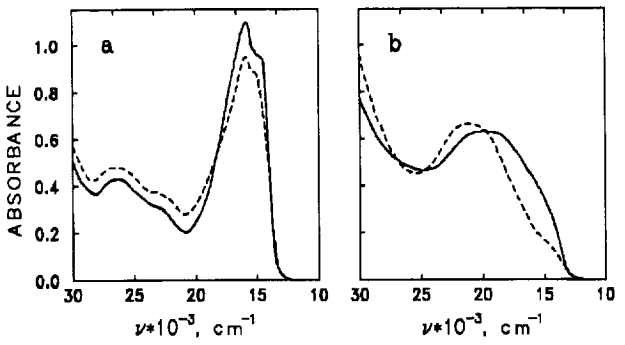
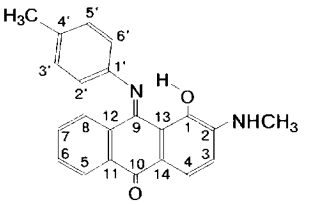


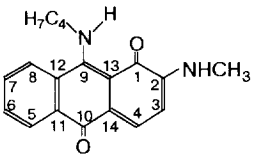
Figure 2. Electronic absorption spectra of equilibrium mixtures of 2-methylamino-9-buthylamino-1,10-anthraquinone and 1-hydroxy-2-methylamino-9,10-anthraquinone-9-buthylimine (**a**) and of 2-methylamino-9-tolylamino-1,10-anthraquinone and 1-hydroxy-2-methylamino-9,10-anthraquinone-9-tolylimine (**b**) in benzene (---) and ethanol (—) ($C = 10^{-3}$ mol/l, thickness 1 mm).

The conventional ^1H NMR method is practically unsuitable for studying the intrachelate equilibrium **a** $\rightleftharpoons$ **b** due to a narrow range of the change in the chemical shifts (CS) of the proton participating in the tautomeric rearrangement (δ_{OH}-δ_{NH} = 0.2 ppm).

In the ^{13}C NMR spectra the major changes upon transition from **VIa,b** to **VIIa,b** mixture are observed for the signals of atoms C_1 and C_{13} of a six-member cycle ($\Delta\delta(C_1)$ = +9.7 ppm, $\Delta\delta(C_{13})$ = -4.1 ppm). The difference in CS is due to the fact that the intrachelate equilibrium for aryl-derivatives is shifted towards the oxyimino-form of **VIIb**, and towards the enaminoquinoid form of **VIa** for alkyl-derivatives:



VIIb



VIa

The quantitative characteristics of the equilibrium can be determined from ^{13}C CS of individual tautomers **a** and **b**. This can be achieved by either the full shift of equilibrium towards one tautomer or the CS modeling which is a complex independent problem.

We assume the ^{15}N NMR to be more suitable for studying the equilibrium **a** $\rightleftharpoons$ **b**. The ^{15}N NMR spectra of the compounds studied have two signals of nitrogen atoms. The signal in a higher field refers to the $NHCH_3$ group in position *2*. The CS values and the constants of the spin-spin coupling (CSSC) of the nitrogen of this group ($J_{^{15}N\text{-}H}$) are actually the same for alkyl and aryl derivatives. The values of constants testify to the fact that the hydrogen atom of this amino group takes no part in tautomeric transformations. A substantial difference in the CS of chelate ^{15}N nitrogen atoms ($\Delta\delta(^{15}N)$ = 72.8 ppm) is related, so as for ^{13}C NMR, to the difference in the positions of the tautomeric equilibrium **a** $\rightleftharpoons$ **b** for compounds **VI** and **VII**. The correlation data[16] on ^{15}N CS also testify to a preferable existence of aryl derivative in hydroxyiminoform **VIIb**. The quantitative data on the equilibrium **a** $\rightleftharpoons$ **b** can be extracted from the CSSC values ($J_{^{15}N\text{-}H}$). For enaminoquinoid compounds with a six-member cycle it is known[16] to be J_0 = 91-92 Hz and for the hydroxyimino form it is absent. Upon fast exchange, the portion of form **a**, (P_a), obeys the equation:

$$Pa = \frac{J_{exp}}{J_0} \times 100\%, \qquad (1)$$

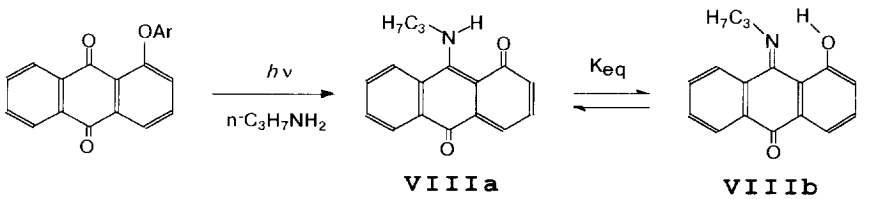
where J_{exp} is the experimental value of CSSC. According to calculations, the content of enaminoquinoid form (**a**) in chloroform solution at room temperature is 75±5% (K_{eq} = 0.34±0.09; ΔG = 1.4 kcal/mol) for the alkyl derivative (**VI**) and 25±2% (K_{eq} = 3.0±0.3, ΔG = −1.1 kcal/mol) for the aryl one (**VII**).

b) The influence of quinone and solvent nature on the equilibrium. As has been mentioned, ana-quinone **IV** cannot be isolated. Therefore the reaction of compound **IV** with amine has been carried out by irradiating 1-(p-tert-butylphenoxy)-9,10-anthraquinone in hexane with addition of n-propylamine. The resulting ana-quinone **IV** reacts with amine to form the equilibrium mixture of the corresponding 9-amino-1,10-anthraquinone (**VIIIa**) and 1-hydroxy-9,10-anthraquinone-9-imine (**VIIIb**) (**Scheme IV**).

The electronic absorption spectra of the equilibrium mixture of **VIIIa,b** in the different solvents are depicted in **fig. 3**. Comparing **fig. 3** and **fig. 2a** it is seen that unlike the equilibrium **VIa** ⇌ **VIb**, the equilibrium **VIIIa** ⇌ **VIIIb** is shifted towards the oxy-imino form (**b**)

This conclusion is confirmed by the ^{15}N NMR spectrum in $CDCl_3$. The ^{15}N signal of compound **VIII** (δ= 251.3 ppm) has been recorded in a weaker field compared to compounds **VI** (δ = 167.0 ppm) and **VII** (δ = 239 ppm). We have failed to determine CSSC $J_{^{15}N\text{-}H}$ due to a large signal width in the ^{15}N NMR spectrum of compound **VIII**. Taking the chemical shifts of compounds **VI** and **VII** with the corresponding contributions of tautomeric forms **a** and **b** as a model, we have estimated the portion of **VIIIa** in $CDCl_3$. It is equal to 18±5 % (K_{eq}=4.6±0.3; ΔG= −0.96±0.04 kcal/mol).

Scheme IV



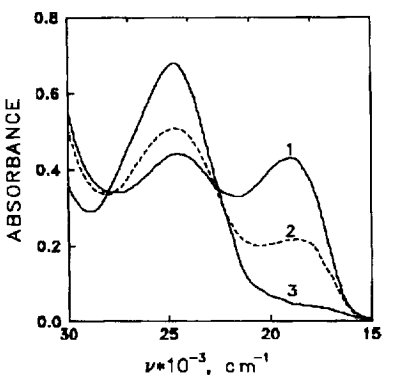


Figure 3. Electronic absorption spectra of equilibrium mixture of 1,10-anthraquinone-9-propylamine (**VIIIa**) and 1-hydroxy-9,10-anthraquinone-9-n-propylimine (**VIIIb**) in ethanol (**1**), chloroform (**2**) and hexane (**3**) (C = 7×10^{-4} mol/l, thickness 0.2 cm).

Not only the substituents in anthraquinone nucleus and the amine nature but also the solvent polarity have a substantial effect on intrachelate equilibrium. Analysing the data obtained (**figs.2** and

3) it is seen that in all the cases the increase in solvent polarity leads to the shift in the equilibrium towards enaminoquinoid form (**a**).

We have failed to obtain compounds **VIIIa,b** in the individual form. However, varying the solvent nature, one can considerably change the relation between tautomeric forms. Assuming that in the longwave absorption maximum of one tautomeric form another form does not actually absorbs, the extinction coefficients of tautomers can be estimated in their longwave maxima. Thus, the optical densities (**D**) of the solutions of tautomeric mixture in the different solvents in the maxima of longwave bands (515 nm for form **a** and 406 nm for form **b**) are related via the following equation:

$$D_{406} = - (\varepsilon_b / \varepsilon_a) \times D_{515} + C \times \varepsilon_b \qquad (2)$$

where C is the solution concentration; ε_a and ε_b are the extinction coefficients in the maxima of the longwave bands of tautomers **VIIIa** and **VIIIb**.

Indeed, a satisfactory linear correlation has been observed (**fig. 4**). According to formula (**2**) the values of extinction coefficients are $\varepsilon_a = 5.7\times10^3$ and $\varepsilon_b = 4.0\times10^3$ l/(mol×cm). Using these values one can readily estimate the composition of the equilibrium mixture **VIIIa** $\rightleftharpoons$ **VIIIb** and, hence, the values of equilibrium constants for different solvents (**Table 1**). The equilibrium constants are observed to vary by more than an order of magnitude with substitution of inert non-polar hexane by ethanol.

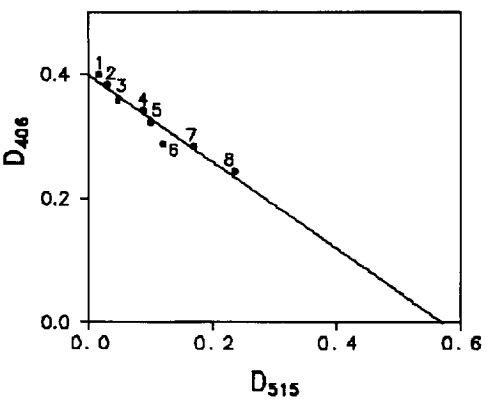


Figure 4. Relation between optical densities at 406 and 515 nm of equilibrium mixtures of 1,10-anthraquinone-9-propylamine (**VIIIa**) and 1-hydroxy-9,10-anthraquinone-9-n-propylimine (**VIIIb**) in different solvents (numbers of solvents are presented in **Table 1**).

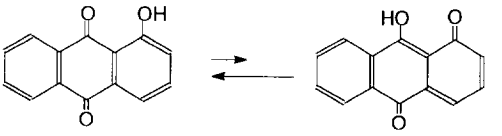
These estimates of course are approximate because the positions of the maxima and the extinction coefficients in the spectra of individual substances can depend on solvent characteristics[17]. Most rough is the assumption on the zero absorption of enaminoquinoid form **VIIIa** in the absorption maximum of hydroxy-imino form **VIIIb**. Nevertheless, despite an approximate estimation by both the given procedures and the ^{15}N NMR method, the results obtained in chloroform are in good agreement.

Table 1. The Content of the Form **VIIIa** in the Equilibrium Mixture; the Values of the Equilibrium Constants (K_{eq}), Free Energy of Isomerization (ΔG) and the Calculated Values of Isomerization Enthalpies (ΔH) for different solvents.

N	Solvent	(VIIIa), %	K_{eq}	ΔG, kcal/mol	ΔH, kcal/mol
1	hexane	4.0±0.5	24±3	-1.9±0.1	-8.1
2	CCl_4	5.4±0.7	17±2	-1.7±0.1	
3	ethyl acetate	8.3±1.0	11±1	-1.4±0.1	
4	dichloromethane	16±2	5.3±0.8	-1.0±0.1	
5	acetonitrile	18±2	4.6±0.6	-0.9±0.1	
6	chloroform	20±3 (18±5)	4.0±0.7 (4.6±0.3)	-0.8±0.1 (-96.0±0.04)	-7.0
7	isopropanol	30±4	2.3±0.4	-0.5±0.1	-7.4
8	ethanol	41±5	1.4±0.2	-0.2±0.1	-7.2

The values in brackets have been estimated from ^{15}N NMR data in $CDCl_3$.

c) Quantum chemical calculations. The experimental data obtained on the influence of the nature of quinone, amine, and solvent on intrachelate equilibrium are in qualitative agreement with the results of our quantum chemical calculations of the heat of isomerization reaction performed by the AM1 method[18]. For comparison we have also calculated the enthalpy of 1-hydroxyanthraquinone (**IX**) isomerization. According to calculations, the enthalpy of compound **IX** isomerization is large (13.3 kcal/mol). Indeed, the isomer with the structure of ana-anthraquinone (**IXa**) in this case fails to form.



IX **IXa**

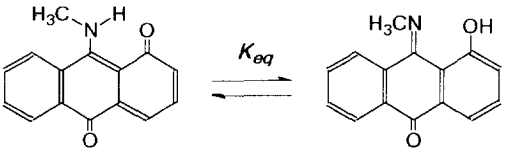
ΔH = 13.3 kcal/mol

Unlike 1-hydroxyanthraquinone, the isomerization enthalpy of 1-hydroxy-9,10-anthraquinone-9-imine (**X**) is small. This indicates the possibility of the existence of two isomers:

Xa **Xb**

ΔH = -1.4 kcal/mol

Quantum chemical calculations of the enthalpy of 1-hydroxy-9,10-anthraquinone-9-methylimine (**XI**) isomerization has been performed to model the characteristics of compound **VIII**:



ΔH = -8.2 kcal/mol

XIa **XIb**

We think that the value of isomerization enthalpy obtained for this case is underestimated (by 4-5 kcal/mol). To bring into agreement the experimental values given in Table 1 for the free energy of isomerization (ΔG) with the calculated ΔH values, the isomerization entropy is assumed to be very large (ΔS = –(20-23) cal/(mol×degr.)). Such values of ΔS are possible only in the case of substantial structural changes in reaction, e.g., with increasing quantity of bonds, the formation of one molecule from two, etc. In our case, the structural changes are minor. Therefore, the ΔS value cannot exceed a few entropy units.

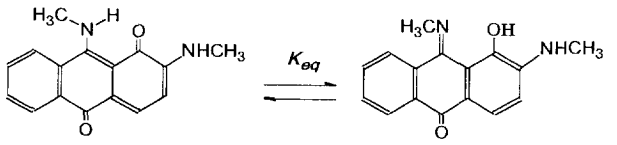
However, the calculation gives the correct tendencies in the change of isomerization enthalpy after the introduction of donor substituent into anthraquinone nucleus (2-$NHCH_3$) and the change of solvent polarity. Taking into account the influence of the solvent (the method of point dipoles[19,20]) in accord with experiments leads to the shift of equilibrium towards ana-anthraquinone structure (**XIa**) with increasing solvent polarity (**Table 1**).

Assuming the solvent to have effect mainly on the reaction enthalpy, one can estimate the change in the equilibrium constant upon transition from solvent 1 to solvent 2 by the formula:

$$K_{eq}(1)/K_{eq}(2) = \exp\{(\Delta H_2 - \Delta H_1)/RT\}$$

Using the calculated data (**Table 1**), we obtain a 6.4-times decrease in the equilibrium constant on substituting hexane by chloroform. This value is close to the relation between experimental equilibrium constants (5.0± 1.2). Substantial deviations are observed when comparing the constants for hexane and ethanol. This can be caused by a considerable influence of specific interactions with the ethanol, e.g., due to formation of hydrogen bonds. The specific interactions are neglected in the calculation procedure used[19,20].

Introducing methylamino group into position 2 of anthraquinone increases the calculated value of isomerization enthalpy which leads, according to the experiment, to the shift in equilibrium towards ana-quinoid form (**a**) compared with the case of unsubstituted compound **XI**.



ΔH = -5.1 kcal/mol

XIIa **XIIb**

The influence of substituent nature in aminogroup in position 9 can also be reproduced qualitatively by AM1 calculations. Substituting methyl by phenyl in the substituted amino group leads to the decrease in isomerization enthalpy down to -5.6 kcal/mol which reflects the tendencies recorded for the equilibria **VIa** ⇌ **VIb** and **VIIa** ⇌ **VIIb**.

Although there is no quantitative agreement between calculated and experimental data, the tendencies of the influence of different factors on intrachelate equilibrium can be reproduced correctly in the calculations by the AM1 method. Therefore analysing the data on the mechanism of the reactions of substituted 1,10-anthraquinones with alcohols and amines we have also used the results of quantum chemical calculations performed by the AM1 method.

DISCUSSION

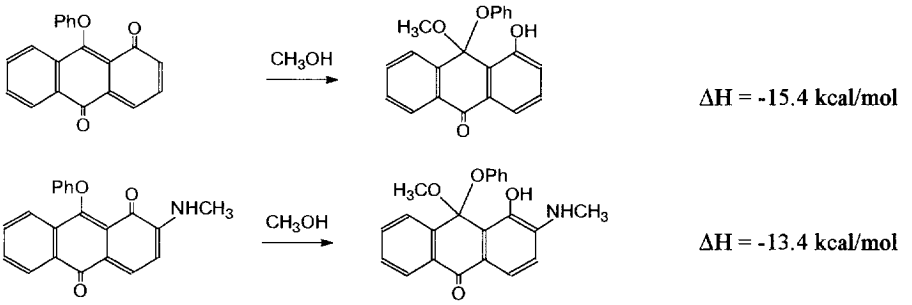
It has been established that position 9 of 1,10-anthraquinones is the most active in reactions with nucleophiles[3,6,7,21,22]. The action of alcohols (**Schemes I** and **II**) as well as of hydrogen halides[6,22] leads to the 1,4-addition of a nucleophile molecule so as in the case of α,β-unsaturated carbonyl compounds[13]. On the other hand, under the action of amines (**Schemes III** and **IV**), water, hydrogen sulfide and CH-acid anions, a noticeable substitution of the group in position 9 is observed[7,21,22]. An attempt has been made to analyze the reasons of these differences using the reactions of substituted 1,10-anthraquinones with methanol and amines studied in this paper.

As has been demonstrated in 1951[23,24], the reaction of nuclephilic substitution in the case of carbonyl compounds occurs not as a concert one-stage process but as a two-stage associative process running by addition-elimination mechanism and forming a tetrahedral intermediate. Now it is commonly accepted that the most of the nuclephilic substitution reactions in the case of unsaturated carbon atom proceed by the addition-elimination mechanism (AdE-mechanism)[25]. However, in most of cases it was practically impossible to record a tetrahedral intermediate by the physico-chemical methods . Either indirect data[23,24] or the data of quantum chemical calculations[25] are employed to verify the proceeding of the reaction via the AdE-mechanism.

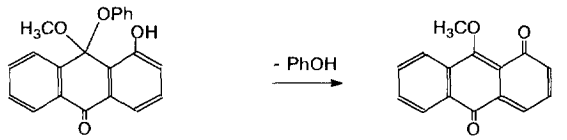
In the reaction of 1,10-anthraquinones with amines the nucleophilic 1,4-addition, resulting in the formation of an adduct (tetrahedral intermediate), is also primary step. However, the adduct in this case is unstable and quickly eliminates a phenol molecule to form the corresponding product of substitution - 9-amino-1,10-anthraquinone.

We have failed to record spectroscopically the formation of the intermediate adduct in the reaction performed at low temperature (-117° C). Thus, the reaction of elimination is fast enough even at such a low temperature. Therefore, we have used the data of quantum chemical calculations to understand the mechanism of the primary processes in the reaction of 1,10-anthraquinones with alcohols and amines.

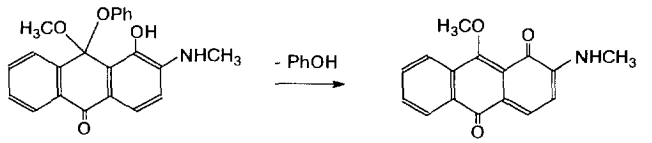
First, we have calculated the enthalpy of 1,4-addition of methanol molecule:



Indeed, according to experiment, this reaction is exothermal one and the adduct is a stable compound. The reaction of phenol molecule elimination is endothermal:

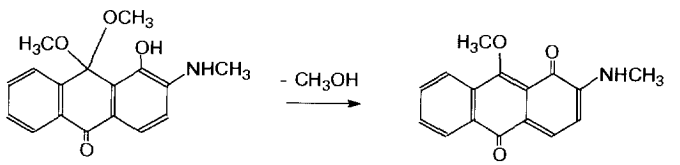


ΔH = 10.6 kcal/mol



ΔH = 13.0 kcal/mol

The similar data have been obtained for the reaction of the alcohol molecule elimination from adduct **III**:

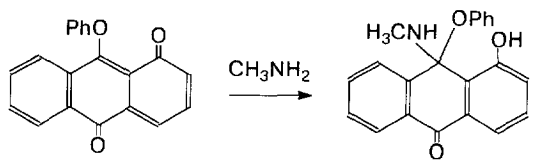


ΔH = 8.8 kcal/mol

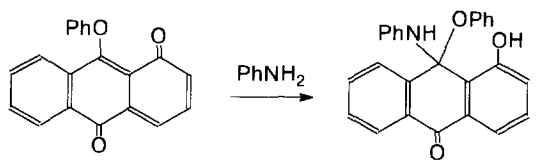
The calculated data are in agreement with the fact that this reaction occurs only photochemically or after heating (see, **RESULTS**, ***part 1a***).

Thus, the results of our calculations by the AM1 method are in fair agreement with mechanism established for the reaction with methanol. Therefore, the AM1 method has then been used to interpret the data on the mechanism of the reaction of 1,10-anthraquinones with amines.

According to our calculations the reaction of the 1,4-addition of amines is also exothermal:

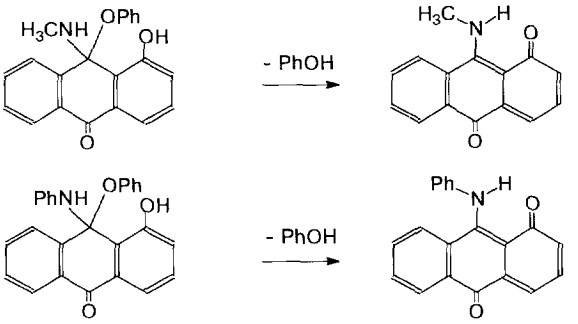


ΔH = -12.4 kcal/mol



ΔH = -9.2 kcal/mol

In this case, the minimum at the potential energy surface fits the hypothetical adduct of 1,10-anthraquinones with amines (both aliphatic and aromatic). The calculated structure of the adduct is presented on the fig.5. However the resulting adduct is less stable. The reaction of phenol elimination, giving the products of formal nucleophilic substitution, is exothermal:



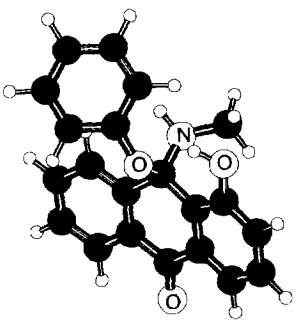


Figure 5. A computer generated drawing of the tetrahedral intermediate, 9-phenoxy-9-methylamino-1-hydroxy-10-anthrone.

Thus, our quantum chemical calculations testify that the primary processes are the same in the reactions of 1,10-anthraquinones with alcohols and amines. The differences in the final reaction products are due to exothermicity of the reaction of the phenol elimination by the adduct with amines. This, in turn, can be attributed to the larger thermodynamic stability of 9-aminosubstituted 1,10-anthraquinones compared to 9-phenoxy- and 9-methoxy-1,10-anthraquinones. Note that up to now the fairly stable derivatives of 1,10-anthraquinones have been obtained for two cases only, i.e. either upon the screening of position **9** by bulky substituents[3,4,21,26] or in the presence of electron donor group in position **9** (chlorine[5,6], phenoxy[7,8] or, as in our case, the substituted amino group). Surely, the more electron donor group (amino) gives the larger stabilizing effect.

EXPERIMENTAL

General methods

IR-spectra were recorded on a UR-20 spectrophotometer either in KBr tablets or in CCl_4. Electronic absorption spectra were recorded using a "Specord UV VIS" spectrophotometer. Mass-spectra were recorded on a "Finnigan MAT-8200" mass-spectrometer. The NMR spectra of ^1H, ^{13}C and ^{15}N (with natural content of isotopes) were recorded in $CDCl_3$ at 30° on a "Bruker AC-200" spectrometer with a working frequency of 200.13, 50.32 and 20.28 MHz, respectively. The chemical shifts (CS) in the NMR spectra of ^{15}N are given on a scale of liquid NH_3 via external standard - 90% formamide in DMSO-d_6 (δ = 112.4 ppm). The constant of spin-spin coupling (CSSC) $J_{^{15}N-^1H}$ were measured using the INEPT technique[16] to within ±0.65 Hz. The signals in the NMR spectra of ^1H and ^{13}C were assigned using the data of double resonance and the LRJMD technique (Long Range C-H J Modulation Difference Spectrum[27]).

Solutions were irradiated by the light of a DRSh-500 high-pressure mercury lamp. The necessary spectral regions were distinguished with the help of the appropriate combinations of glassy light filters.

The low-temperature studies were carried out putting the cuvette (1 mm thickness) with solution into a quartz cryostat with parallel windows. The cryostat was filled with cooled ethanol at its melting temperature (-117° C)[28]. The cuvette contained the solution of either ana-quinone **I** or 1-(p-tert-butylphenoxy)-9,10-anthraquinone that was irradiated to obtain ana-quinone **IV**. The reaction was started by addition of about 0.05 ml of the corresponding amine. The reaction was followed by recording the absorption spectra. When the reaction was over, the samples were heated to room temperature.

Quantum Chemical Calculations

The quantum chemical calculations of the geometry and enthalpy of the formation of studied compounds and assumed intermediates have been performed by the AM1 method[18] according to the modified program MNDO-85[29]. The conventional Davidon-Fletcher-Powell procedure has been used to optimize the geometry[30].

The influence of the solvent has been taken into account by the method of the point dipoles[19,20]. The dielectric constant of the solvent and the dipole moment density calculated from the data[31] have been used as the model parameters. A specific polarizability of the solvent has been estimated from data[31,32]. The value of the boundary disorder energy has been estimated from the characteristic values for the energies of the interaction of solvent molecules (0.6 kcal/mol for benzene, 1 kcal/mol for chloroform, and 4 kcal/mol for ethanol[33]).

Materials

9-(p-tert-butylphenoxy)-2-methylamino-1,10-anthraquinone (I). 3 g of 1-(p-tert-butylphenoxy)-2-methylami-no-9,10-anthraquinone was dissolved in benzene (0.5 l) dried over $CaCl_2$. The solution was irradiated with a SVD-120A Hg lamp for 10 hours. Then the solution was rapidly passed through a column with silica gel under pressure. A blue zone of compound **I** was washed out with a benzene-chloroform mixture (1:1). The eluent was evaporated under vacuum at 30° up to a small volume and filled up with hexane. The precipitate was filtered and washed with hexane. The yield of compound **I** was 75%. The IR-spectrum (CCl_4, cm^{-1}): 1630 (C=O) and 3390 (NH). ^1H NMR: δ 1.25 (s, 9H, $C(CH_3)_3$), 6.82 (d, 2H, H_3, H_5, OAr), 7.22 (d, 2H, H_2, H_6, OAr), 2.85 (d, 3H, $NHCH_3$, J=5.5 Hz), 6.14 (m, 1H, $NHCH_3$), 5.82 (d, 1H, H_3, J=8.5 Hz), 7.95 (d, 1H, H_4, J=8.5 Hz), 7.42-7.62 (m, 2H, H_6, H_7), 7.75-7.98 (m, 1H, H_8), 8.20-8.42 (m, 1H, H_5). ^{13}C NMR: δ 175.3 (C_1, C=O), 177.3 (C_{10}, C=O). m/z (M^+) 385.48, $C_{25}H_{23}NO_3$ requires 385.48.

The reaction of 9-(p-tert-butylphenoxy)-2-methylamino-1,10-anthraquinone (I) with methanol. 0.5 ml of methanol were added to the solution of 0.4 mmol of ana-quinone **I** in 20 ml of abs. benzene and mixed up for 1 h at room temperature to obtain compound **II** and for 5 h to obtain compound **III**. The reaction was under chromatographical control. The reaction mixture was evaporated under vacuum at 30°. Then 10 ml of dry ether were added. The solution was filtered and the precipitate was washed up with ether. The ether solition was evaporated to a small volume and filled up with hexane. The precipitate was filtered and washed up with hexane.

9-(p-tert-butylphenoxy)-9-methoxy-1-hydroxy-2-methylamino-10-anthron (II). The yield of compound **II** was 61%. The IR spectrum (CCl_4, cm^{-1}): 1670 (C=O), 1290 (C-C aromatic). ^1H NMR: δ 1.26 (s, 9H, tert-

Bu), 2.95 (s, 3H, OCH_3), 2.98 (d, 3H, $NHCH_3$, J=5 Hz), 5.09 (s, 1H, $NHCH_3$), 6.75 (d, 1H, H_3, J=9 Hz), 6.80 (d, 2H, H_1, H_5, Ar, J=9 Hz), 7.22 (d, 2H, H_2, H_4, Ar, J=9 Hz), 7.47-7.80 (m, 3H, H_6, H_7, H_8), 7.94 (d, 1H, H_4, J=9 Hz), 8.03 (s, 1H, OH), 8.29 (m, 1H, H_5). m/z (M^+) 417.53 [Found: C, 75.14; H, 6.6; N, 3.41%, $C_{26}H_{27}NO_4$ requires: C, 74.8; H, 6.52; N, 3.36%].

9,9-dimethoxy-1-hydroxy-2-methylamino-10-anthron (III). The yield of compound **III** was 52%. The IR spectrum (CCl_4, cm^{-1}): 1650 (C=O), 1280 (C-C aromatic). ^1H NMR: δ 2.97 (s, 6H, $2OCH_3$), 3.03 (d, 3H, $NHCH_3$, J=5 Hz), 5.03 (s, 1H, $NHCH_3$), 6.83 (d, 1H, H_3, J=9 Hz), 8.01 (d, 1H, H_4, J=9 Hz), 7.45-7.87 (m, 3H, H_6, H_7, H_8), 8.06 (s, 1H, OH), 8.23-8.42 (m, 1H, H_5). m/z (M^+) 299,34 [Found: C, 67.92 ; H, 5.59; N, 4.51%, $C_{17}H_{17}NO_4$ requires: C, 68.21; H, 5.73; N, 4.68%]

The reaction of 9-(p-tetr-butylphenoxy)-2-methylamino-1,10-anthraquinone (I) with n-butylamine and p-toluidine. 0.5 g (1.1-1.3 mmol) of compound **I** were dissolved in 0.5 l of benzene. Then 1.3-1.5 mmol of the corresponding amine were added and the solution was irradiated for 6-36 h till the initial compound disappeared (control by thin layer chromatography - TLC). Photolysis was performed at 20-25° with a complete spectrum of a "CVD-120A" Hg lamp or under the sun. The reaction mixture was evaporated under vacuum at 30°. The residue was washed up with hexane, filtered, purified with the help of TLC in $CHCl_3$ and crystallized from benzene-ethanol mixture. The product yield (tautomeric mixture of compounds VIa-VIIa to VIb-VIIb) was 85-95%.

The equilibrium mixture of 2-methylamino-9-butylamino-1,10-anthraquinone and 1-hydroxy-2-methylamino-9,10-anthraquinone-9-butylimine (VIa, VIb). T_{ml} was 162-164°. The IR spectrum (KBr, cm^{-1}): 3410 (N-H), 1640 (C=O, C=N). ^1H NMR: δ 0.97 (t, 3H, CH_3CH_2), 1.53 (m, 2H, CH_2CH_3), 1.85 (m, 2H, $CH_2CH_2CH_2$), 2.92 (d, 3H, NCH_3), 3.98 (t, 2H, CH_2N), 5.86 (m, 1H, NH), 6.31 (d, 1H, H_3), 7.52 (td, 1H, H_7), 7.57 (td, 1H, H_6), 7.67 (d, 1H, H_4), 7.96 (d, 1H, H_8), 8.36 (dd, 1H, H_5), 16.72 (s, 1H, OH). ^{13}C NMR: δ 13.5 (q, CH_3CH_2), 20.0 (t, CH_2CH_3), 29.3 (q, CH_3N), 32.6 (t, $CH_2CH_2CH_2$), 49.6 (t, CH_2N), 105.3 (d, C_3), 109.4 (s, C_{13}), 118.1 (s, C_{14}), 122.2 (d, C_4), 128.4 (d, C_8), 129.4 (s, C), 131.1 (d, C_7), 132.2 (d, C_6), 136.0 (s, C_{11}), 148.7 (s, C_2), 160.9 (s, C_9), 163.7 (s, C_1), 179.1 (s, C_{10}), 128.3 (s, C_5). ^{15}N NMR: δ 60.7 ($HNCH_3$, J_{NH}=93.6 Hz), 167.0 (CH_2N, J_{NH}=67 Hz). m/z(M^+) [Found: 308.15, $C_{19}H_{20}N_2O_2$ requires 308.15].

Equilibrium mixture of 2-methylamino-9-tolylamino-1,10-anthraquinone and 1-hydroxy-2-methylamino-9,10-anthraquinone-9-tolylimine (VIIa, VIIb). T_{ml} was 207-209°. The IR spectrum (KBr, cm^{-1}): 3390 (N-H), 1635 (C=O, C=N). ^1H NMR: δ 2.34 (s, 3H, CH_3Ph), 2.93 (d, 3H, $NHCH_3$), 5.46 (q, 1H, NH), 6.53 (d, 1H, H_3), 6.93 (d, 2H, H_2, H_6, tolyl), 7.15 (d, 2H, H_3, H_5, tolyl), 7.15 (td, 1H, H_7), 7.42 (d, 1H, H_8), 7.46 (td, 1H, H_6), 7.80 (d, 1H, H_4), 8.29 (dd, 1H, H_5), 16.52 (s, 1H, OH). ^{13}C NMR: δ 20.8 (q, CH_3Ph), 29.4 (q, CH_3NH), 107.8 (d, C_3), 113.5 (s, C_{13}), 118.9 (s, C_{14}), 121.1 (d, C_2, C_6, tolyl), 122.2 (d, C_4), 127.6 (C_5), 128.8 (d, C_8), 129.2 (s, C_{12}), 130.3 (d, C_3, C_5, tolyl), 130.6 (s, C_7), 131.7 (d, C_6), 135.3 (s, C_{11}), 135.4 (s, C_4, tolyl), 142.7 (s, C_1, tolyl), 146.0 (s, C_2), 154.0 (C_1), 159.7 (s, C_9), 180.4 (s, C_{10}). ^{15}N NMR: δ 55.0 ($HNCH_3$, J_{NH}=93.2 Hz), 239.8 (N-Ar, J_{NH}=24 Hz). m/z(M^+) [Found: 342.14, $C_{22}H_{18}N_2O_2$ requires 342.14].

Reaction of 9-(p-tert-butylphenoxy)-1,10-anthraquinone (IV) with n-propylamine. 37 mg of 1-(p-tert-butylphenoxy)-9,10-anthraquinone were dissolved in 100 ml of hexane and filled up with 0.1 ml of n-propylamine and irradiated with a SVD-120A lamp for 10 h. The solution was then evaporated under vacuum at 30-40°. The precipitate was dissolved in ethyl alcohol and evaporated to a small volume. Hexane was added to obtain a crystalline precipitate. The precipitate obtained was filtered and dried. The yield of a crystalline product (tautomeric mixture of compounds **VIIIa** and **VIIIb**) was 40%.

Equilibrium mixture of 9-propylamino-1,10-anthraquinone and 1-hydroxy-9,10-anthraquinone-9-propylimine (VIIIa, VIIIb). IR spectrum (KBr, cm^{-1}): 2955 (C-H), 1650 (C=O, C=N), 1600, 1580 (C-C aromatic). ^1H NMR: δ 1.05 (t, 3H, CH_3CH_2), 1.85 (m, 2H, $CH_2CH_2CH_3$), 4.01 (t, 2H, NCH_2CH_2), 7.10 (d, 1H, H_2), 7.31(t, 1H, H_3), 7.54 (m, 3H, $H_{4,6,7}$), 7.88 (d, 1H, H_8), 8.22 (d, 1H, H_5), 16.51 (s, 1H, OH). ^{13}C NMR: δ 11.8 (q, CH_3CH_2), 24.9 (t, CH_2CH_3), 54.6 (t, CH_2N), 117.1 (d, C_3), 117.1 (s, C_{13}), 124.8 (d, C_4), 128.3 (d, C_5), 128.8 (d, C_8), 130.1 (s, C_{14}), 131.3 (s, C_{12}), 131.7, 132.1, 132.4 (d, $C_{2,6,7}$), 133.5 (s, C_{11}), 160.3 (s, C_9), 163.5 (s, C_1), 183.2 (s, C_{10}). ^{15}N NMR: δ 251.3. m/z (M^+) [Found: 265.11, $C_{17}H_{15}NO_2$ requires 265.11].

Acknowledgments. This work was supported by grant of State Committee of High Education of Russian Federation (Scientific program "Universities of Russian Federation. Universities as a Centers of Fundamental Investigations"). We thank Dr. V. Vasilyev for his valuable assistance in preparing the manuscript.

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(*Received in UK* 7 *November* 1994; *revised* 12 *January* 1995; *accepted* 13 *January* 1995)