Design of crystal packings of styrylheterocycles and [2+2] photocycloaddition reactions in their single crystals

6.* Synthesis and crystal packings of neutral crown-containing and model styrylheterocycles**

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Neutral crown-containing and model styrylheterocycles of the 4-pyridine, 4-quinoline, and 9-acridine series were synthesized under acidic catalysis. The influence of the molecular geometry of these compounds, as well as of related styrylheterocycles of the 2-benzothiazole and benzobisthiazole series, on the formation of a particular crystal packing was investigated based on X-ray diffraction data. An extension of the conjugation system in the molecules can result in the sandwich-herringbone packing motif as the only one of the three packing motifs most typical of this class of compounds. This packing provides the preorganization of the structural units for the [2+2] photocycloaddition reaction. The styrylheterocycle containing the bulky 9-acridine moiety is nonplanar due to strong intramolecular steric interactions. The packing motifs formed by nonplanar molecules do not provide the preorganization of the molecules for the [2+2] photocycloaddition. The introduction of the crown ether moiety into the benzene ring of the styrylheterocycle can decrease the predictability of the packing motif as a result of the inclusion of solvent molecules capable of hydrogen bonding with the heteroatoms of the macrocycle in the crystal structure.

Key words: styrylheterocycles, synthesis, X-ray diffraction study, crystal packing, design of crystal packings.

Unsaturated organic compounds, such as cinnamic acid derivatives, stilbenes, their aza analogs and vinilogs containing one or several ethylene bonds within the π-conjugated fragment, can be involved in the [2+2] photocycloaddition (PCA) reaction to form cyclobutane derivatives (Scheme 1).[2—15] This method of the construction of carbon—carbon bonds holds promise because of the relative ease of the synthesis (irradiation at a specified wavelength), the reversibility and, in some cases, high stereoselectivity of the photoreaction yielding only some of the theoretically possible cyclobutane isomers. The PCA reaction can occur in concentrated solutions and in the solid state, including the single crystals. Single crystal-to-single crystal transformations (*i.e.*, the transformations that occur without the degradation of the single crystal) are of particular interest. Due to the topochemical control of the crystal lattice, these transformations virtually always occur stereospecifically and are accompanied by substantial changes in the physical properties of the crystals.[16—21]

We found that cationic styryl dyes, which are heteroanalogs of stilbene, are involved in the PCA reaction in solution[22—25] and in the solid state[1,25—29] under visible-light irradiation. An extended conjugation chain of the molecular cations of the dyes consists of the quaternized nitrogen-containing heterocycle and the substituted benzene ring bridged by an ethylene group. In these com-

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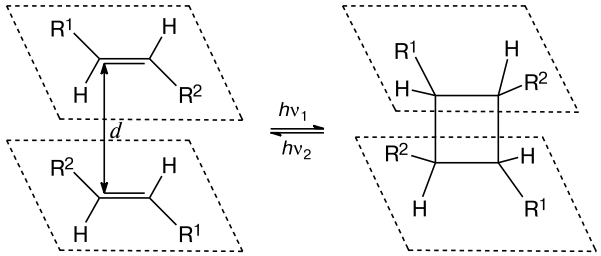
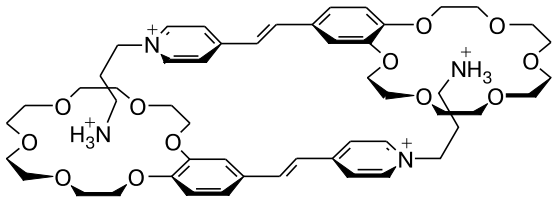
Scheme 1



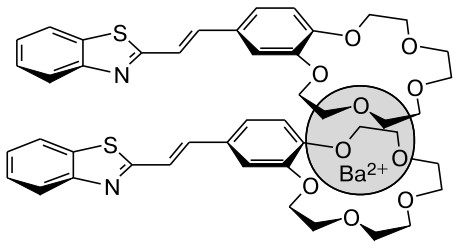
pounds, the PCA reaction can occur stereoselectively in the case of a particular preorganization of a pair of the starting structural units. It is known[3,14,18] that for the PCA reaction to occur in a pair of unsaturated molecules (a dimer pair), their ethylene fragments should be arranged approximately in the parallel planes one above another with a distance *d* between these fragments in a range of 3.3—4.2 Å (see Scheme 1). The preorganization of the dye molecules in solution is achieved due to the presence of the crown ether moiety facilitating the formation of dimeric head-to-tail complexes with ammonium ions (**A**) or head-to-head sandwich complexes with metal cations (**B**). In the solid state, styryl dyes are prone to form stacking motifs in the molecular packings due to stacking interactions between the conjugated fragments and the efficient intramolecular charge transfer in the organic cations from the donor benzene moiety to the acceptor heterocyclic fragment. Previously, the possibility of the solid-state PCA reaction in styryl dyes has been analyzed[27,28] and attempts have been made[1,29] to design crystal structures, *i.e.*, to predict and design such crystal packings, in which the PCA reaction can occur (including the single crystal-to-single crystal photoreaction) to give various isomers of cyclobutane.

Neutral styrylheterocycles, which are synthetic precursors of styryl dyes, are also of considerable interest for the PCA reaction. Previously,[30] we have shown that 15-crown-5-containing 2-styrylbenzothiazole forms head-to-head-type sandwich complexes (**B**) in the presence of Ba^{2+} ions in solution, and these complexes undergo stereoselective PCA. In the crystals, the dimethoxy derivative of 4-styrylquinoline forms dimer pairs. We have found[27] that this compound undergoes the single crystal-to-single crystal photoreaction giving the only *rctt* isomer of the cyclobutane derivative. Since the styrylheterocycle of the benzoxazole series containing the dimethylamino group in the benzene moiety is involved in the efficient reversible solid-state PCA reaction accompanied by a sharp change in the spectroscopic characteristics, it was suggested to use this compound in rewritable optical data storage systems.[31] However, the possibility of performing the PCA reaction in styrylheterocycles without the assistance of additional factors, such as the complexation with metal cations or the protonation of the heterocycle at the nitrogen atom, remains poorly known. Based on the data on the crystal structures of neutral styrylheterocycles (primarily, of derivatives of benzannulated five-membered nitrogen-containing heterocycles, such as benzothiazole, benzoselenazole, and benzimidazole; see, for example, Refs 32—36), no definite conclusions can be drawn as to the tendency of unsaturated compounds of this class to form a particular packing motif, which could be favorable for the solid-state PCA reaction.

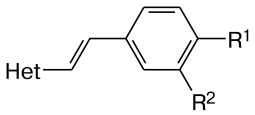
In the present study, we investigated the crystal packings of styrylheterocycles **1—6** containing heterocyclic moieties of different size along with the flexible bulky crown ether moiety in the benzene ring or small methoxy/dimethylamino groups, which mimic the electronic effect of (aza)crown ethers on the styryl chromogen. It was found that the successive extension of the con-



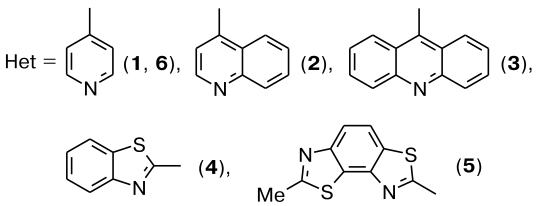
A



B



1a,b, **2a,b**, **3**, **4a,b**, **5**, **6a,b**



$R^1 = R^2 = OMe$ (**1a**, **2a**, **3**, **4a**);
$R^1 + R^2 = OCH_2(CH_2OCH_2)_nCH_2O$, $n = 3$ (**1b**, **4b**, **5**), 4 (**2b**);
$R^1 = NMe_2$, $R^2 = H$ (**6a**);
$R^1 = N[CH_2(CH_2OCH_2)_2CH_2]_2O$, $R^2 = H$ (**6b**)

jugation system in styrylheterocycles and the nature of the substituents in the benzene ring have an effect on the ability of the molecules to form dimer pairs preorganized for PCA.

For this purpose, we developed a procedure for the synthesis of new compounds **3** and **6b**, studied for the first time compounds **1a,b**, **3**, and **6a,b** by X-ray diffraction, and analyzed the changes in certain molecular geometric parameters and the crystal packings of these compounds, as well as of neutral styrylheterocycles **2a,b**,[27,37] **4a,b**,[36,38] and **5**,[39] which we have investigated previously. The structure of bisheterocyclic compound **7**, which is a product of the Michael addition of the methylheterocycle at the ethylene bond of the styrylheterocycle, was established by X-ray diffraction.

Synthesis of compounds 1—6. The synthesis of derivatives of 4-pyridine (*E*)-**1a,b**, 4-quinoline (*E*)-**2a,b**, 2-benzothiazole (*E*)-**4a,b**, and benzobisthiazole (*E*)-**5** by the condensation of the corresponding methyl-substituted heterocyclic bases with benzaldehydes in the presence of alkali metal alkoxides in aprotic solvents has been documented previously.[27,37—39] We found that under these conditions 9-methylacridine does not react with veratraldehyde. The synthesis of 9-styrylacridines containing various substituents in the benzene moiety by the condensation of 9-methylacridine with the corresponding benzaldehydes with heating in a mixture of acetic anhydride and acetic acid was described.[40] The condensation of 9-methylacridine with veratraldehyde under these conditions afforded an inseparable mixture of the *E* and *Z* isomers (1 : 4.3) of compound **3** in a total yield of 3% and gave bisacridine **7** as a result of the Michael addition of the second 9-methylacridine molecule at the activated C=C bond of compound **3** (Scheme 2) in 26% yield. The use of anhydrous $ZnCl_2$ in acetic acid as the catalyst resulted in an increase in the yield of compound **7** (to 36%), which was formed as the only product under these conditions.

Previously, we have obtained[27,37,41,42] the corresponding bisheterocycles as a result of the Michael addition of methylheterocycles to 4-styrylpyridines, 4-styrylpyrimidines, 4-styrylquinolines, and 2-styrylbenzothiazoles, when performing the condensation under basic conditions. It should be noted that the structure of the bisheterocyclic products was established for the first time by the X-ray diffraction study of compound **7** (see below). The unusually high reactivity of the ethylene bond in compound **3** with respect to nucleophilic agents is apparently attributed to a substantial disturbance of the π-conjugation in (*E*)-9-styrylacridine caused by the steric effects. This leads to a strong twisting of the chromogen (*E*)-**3**, as was confirmed by X-ray diffraction. Evidently, as a result of this twisting, the *E* isomer becomes thermodynamically less favorable than the *Z* isomer. Hence, the dehydration of the intermediate alcohol, which is formed through the nucleophilic addition of 9-methylacridine to veratraldehyde, affords both geometric isomers of **3** and/or substantially hinders the thermal $Z \rightarrow E$ isomerization.

The synthesis of styrylheterocycles by the condensation under acidic catalysis is more convenient than the corresponding synthesis under basic catalysis because it does not require the use of unstable alkali metal alkoxides and anhydrous solvents.[37] We synthesized the dimethoxy derivative of 4-styrylpyridine (*E*)-**1a** in 23% yield by the condensation of 4-picoline with veratraldehyde in acetic anhydride by analogy with the synthesis of styrylpyridines substituted at the benzene ring.[43] The dimethylamino-derivative (*E*)-**6a** was synthesized in 21% yield according to a known procedure[44] by the condensation of 4-picoline with 4-dimethylaminobenzaldehyde in the presence of benzoyl chloride and pyridine. Azacrown-containing 4-styrylpyridine (*E*)-**6b** was synthesized by the condensation of 4-picoline with *N*-(4-formylphenyl)aza-18-crown-6 ether in the presence of Lewis acids (see Scheme 2). The reaction was activated by the protonation of picoline with hydrogen chloride or anhydrous $SnCl_2$. In both cases, the target compound was prepared in moderate yield (22 and 27%, respectively).

The condensation of lepidine with veratraldehyde in acetic anhydride gave the compound (*E*)-**2a** in 7% yield and led to the recovery of the starting aldehyde (84%). Unlike the synthesis of styrylacridine **3**, the use of $ZnCl_2$ in acetic acid resulted in an increase in the yield of the target styrylquinoline (*E*)-**2a** to 36% without the formation of (*Z*)-**2a** or the side product of the Michael addition (TLC monitoring). Hence, this method can be recommended as the more convenient approach alternative to the condensation under strongly basic conditions,[27,37] which afforded (*E*)-**2a** in 38—46% yields.

X-ray diffraction study. To perform the design of molecular crystals, it is necessary to construct the unsaturated molecules, which are self-organized in the solid state and form dimer pairs with short distances between the ethylene fragments, resulting in the preorganization of these molecules for the PCA reaction. Our studies[1,26—29] on the crystal packings of a large series of crown-containing and model styryl dyes showed that, in most cases, the planar cations of these dyes are packed to form stacks with either a parallel (Fig. 1, *a*) or a herringbone (Fig. 1, *b*) mutual arrangement. Evidently, in the case of a stacked

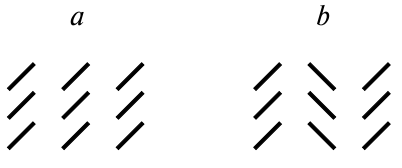
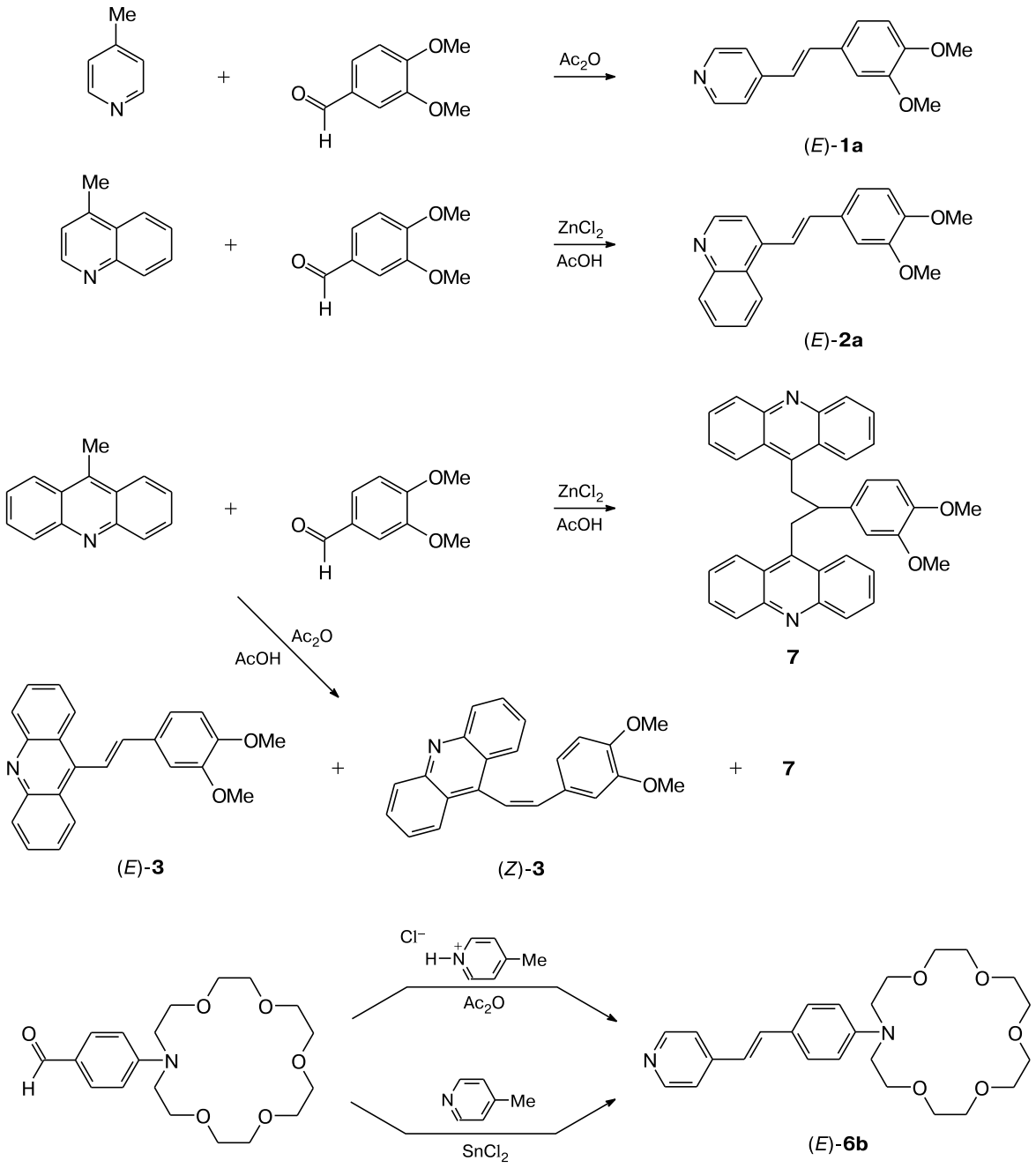


Fig. 1. Parallel (*a*) and herringbone (*b*) packing motifs of the cations of styryl dyes in the crystals; the lateral projections of the planar cations are indicated by lines.

Scheme 2



structure, the crystal lattice can retain structural units as dimer pairs. In such single crystals, the solid-state PCA reaction can occur. In most cases, this reaction is accompanied by the degradation of the single crystal. However, in some cases, the single crystal-to-single crystal PCA reaction is observed.[1,26–29]

The possibility of the single crystal-to-single crystal PCA reaction depends on many factors, including the symmetry of the stacks. The most often occurring stacks are those in which the cations of the dyes are arranged in a head-to-tail fashion; the head-to-head arrangement of the molecules in stacks is observed more rarely (Fig. 2). Any two adjacent cations in the stacks of the first type are related by a center of symmetry, resulting in that the stacks are composed of dimer pairs of the cations with the shorter distance d_1 between the ethylene fragments in the dimer pair compared to the distance d_2 between the ethylene fragments of adjacent dimer pairs.[27–29] This

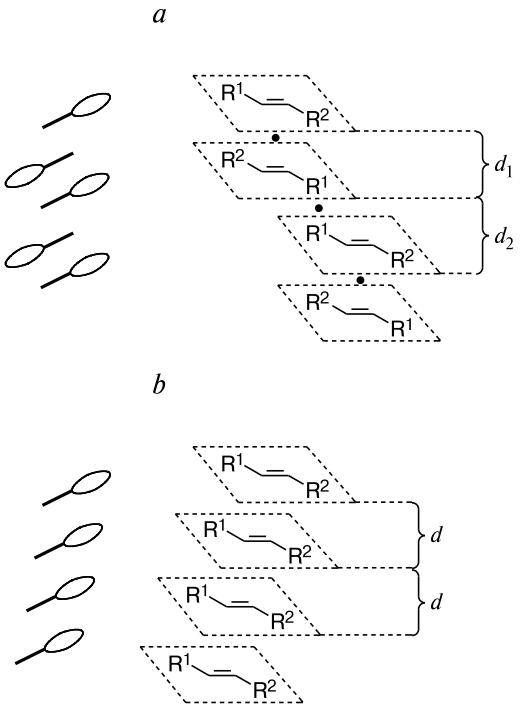


Fig. 2. Modes of the mutual arrangement of the cations of styryl dyes in the stacks formed in a head-to-tail fashion (*a*) and in a head-to-head fashion (*b*) presented in two ways; the conjugated fragments of the cations are indicated by lines; the substituents in the benzene ring are outlined by ovals, the centers of symmetry are indicated as •.

symmetry of the stacks is favorable for the single crystal-to-single crystal PCA reaction.

The stacks with a head-to-head arrangement of the molecules are formed by translationally related structural units. Hence, even one event of the PCA reaction in this stack necessarily leads to the violation of the local symmetry, *i.e.*, to the formation of defects. In addition, the pairs of adjacent cations in the stack of translationally related structural units are identical ($d_1 = d_2 = d$); hence, the PCA reaction occurs statistically. Thus, the reaction of the selected molecular cation can occur with equal probability with adjacent cations in the stack located above or below this cation. The progression of the PCA reaction throughout the bulk of the crystal will give rise to "extra" structural units in the stacks (*i.e.*, the structural units, which have no pairs for the PCA reaction), which results in an enlargement of defect regions. Hence, the PCA reaction in the crystals of styryl dyes packed in a head-to-head fashion cannot occur without the degradation of the single crystal.

It should also be noted that the positive charge in the cations of styryl dyes is located primarily on the heterocyclic moiety.[45] In stacks, Coulomb repulsions are minimized as a results of either a head-to-tail arrangement of the molecular cations or a substantial mutual shift in the parallel planes in the stacks arranged in a head-to-head fashion. In the latter case, the ethylene fragments of adjacent cations are generally so distant from each other (>5 Å) that the PCA reaction in single crystals becomes impossible.

In continuation of our research on the solid-state PCA reactions, we investigated these reactions with neutral styrylheterocycles related to styryl dyes, because the cations of the dyes are structurally similar to the corresponding styrylheterocycles. The main difference is that the quaternized fragment of the heterocyclic moiety in the dye is replaced by the non-quaternized fragment in the styrylheterocycle. This leads to substantial changes in the spectroscopic properties of the compounds, such as large hypsochromic shifts of the long-wavelength absorption maximum for the styrylheterocycles compared to that observed for the related dyes. This is associated with the fact that the intramolecular electron density transfer from the benzene ring to the uncharged heterocyclic moiety is less favorable. Therefore, for the PCA reaction to occur in styrylheterocycles, the irradiation should be performed at a shorter wavelength. Substantial changes associated with the destruction of the conjugation chain of the chromophore as a result of the formation of cyclobutane are observed in the near-UV region.[30,31] It should be noted that styrylheterocycles have a great scope for the crystal design, because the presence of the neutral nitrogen atom in the heterocyclic moiety allows their use as photosensitive ligands in coordination structures stabilized by hydrogen bonds or based on metal complexes.[19—21] Later, we will investigate this area of the crystal design of styrylheterocycles and examine the possibility of the solid-state PCA reactions in such structures.

Molecular structures. The molecular structures of neutral styrylheterocycles **1**—**6** and bisacridine **7** are shown in Figs 3 and 4. In a series of compounds **1**—**3** and **4**, **5**, the π-conjugation system gradually increases due to the annulation of the heterocyclic moiety to the benzene or thiazole rings. In compounds **1** and **6**, the heterocyclic moiety (4-pyridine) remains unchanged, but the substituents in the benzene ring are varied. Compounds **1a**, **2a**, **4a**, and **6a** contain electron-donating methoxy or dimethylamino groups, whereas the related compounds **1b**, **2b**, **4b**, and **6b** contain the crown ether moiety with the same type of annulation of the heteroatoms to the chromogen.

In the crystals, compounds **1b** and **4b** exhibit the so-called "bicycle-pedal" isomerization,[46] which is often observed in the crystal structures of styryl dyes[1,28,29] as a consequence of the temperature-dependent dynamic process in the crystals, resulting in that the ethylene fragment is twisted about the single bonds. This isomerization leads to the disorder of the central azastilbene moiety over two positions related by the rotation of the structural unit about its long axis by 180°. In the structure of **1b**, all atoms

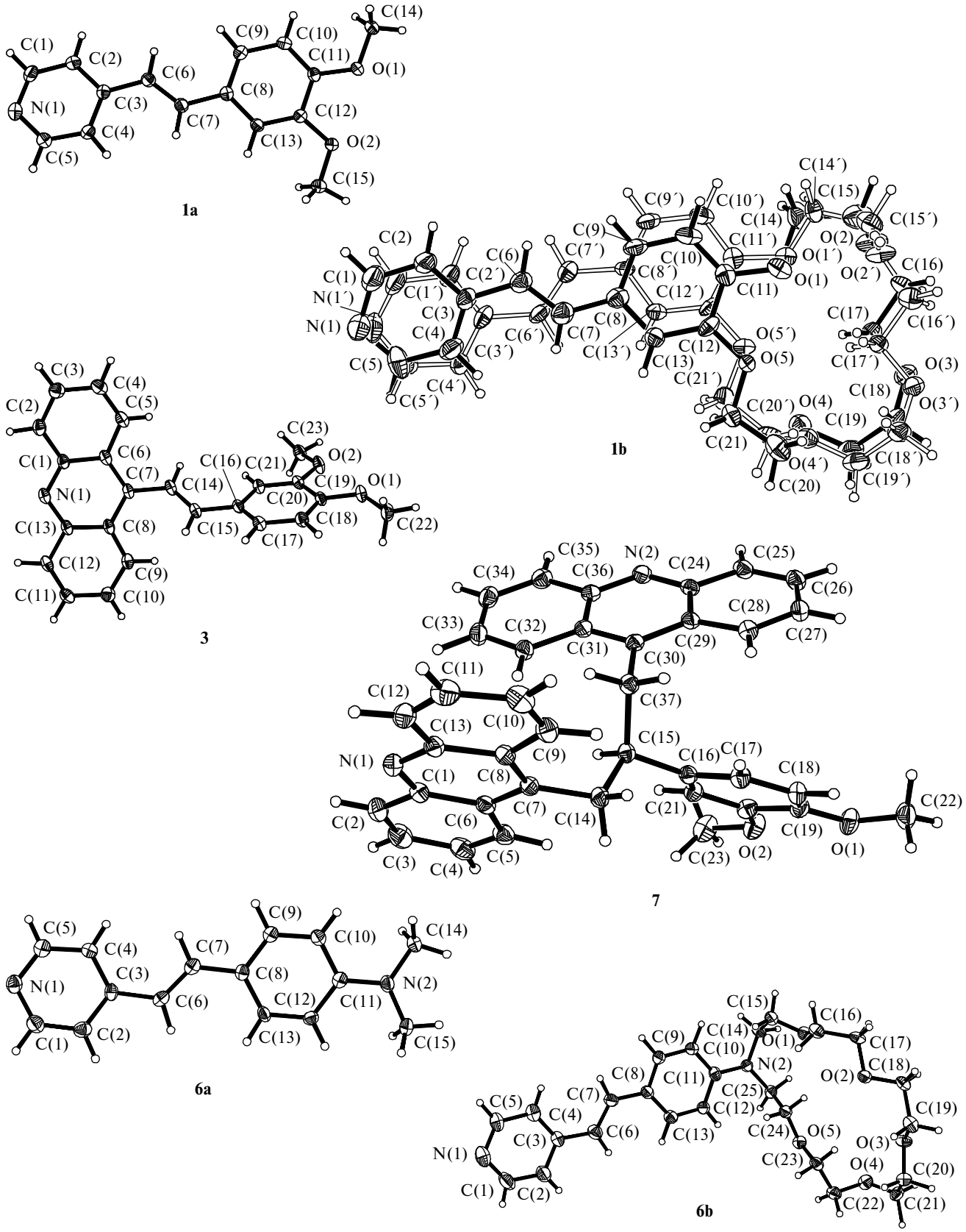


Fig. 3. Molecular structures of styrylheterocycles **1a,b**, **3**, and **6a,b** (two *s* conformers for **1b**) and bisacridine **7**. The nonhydrogen atoms are shown as displacement ellipsoids at the 50% probability level.

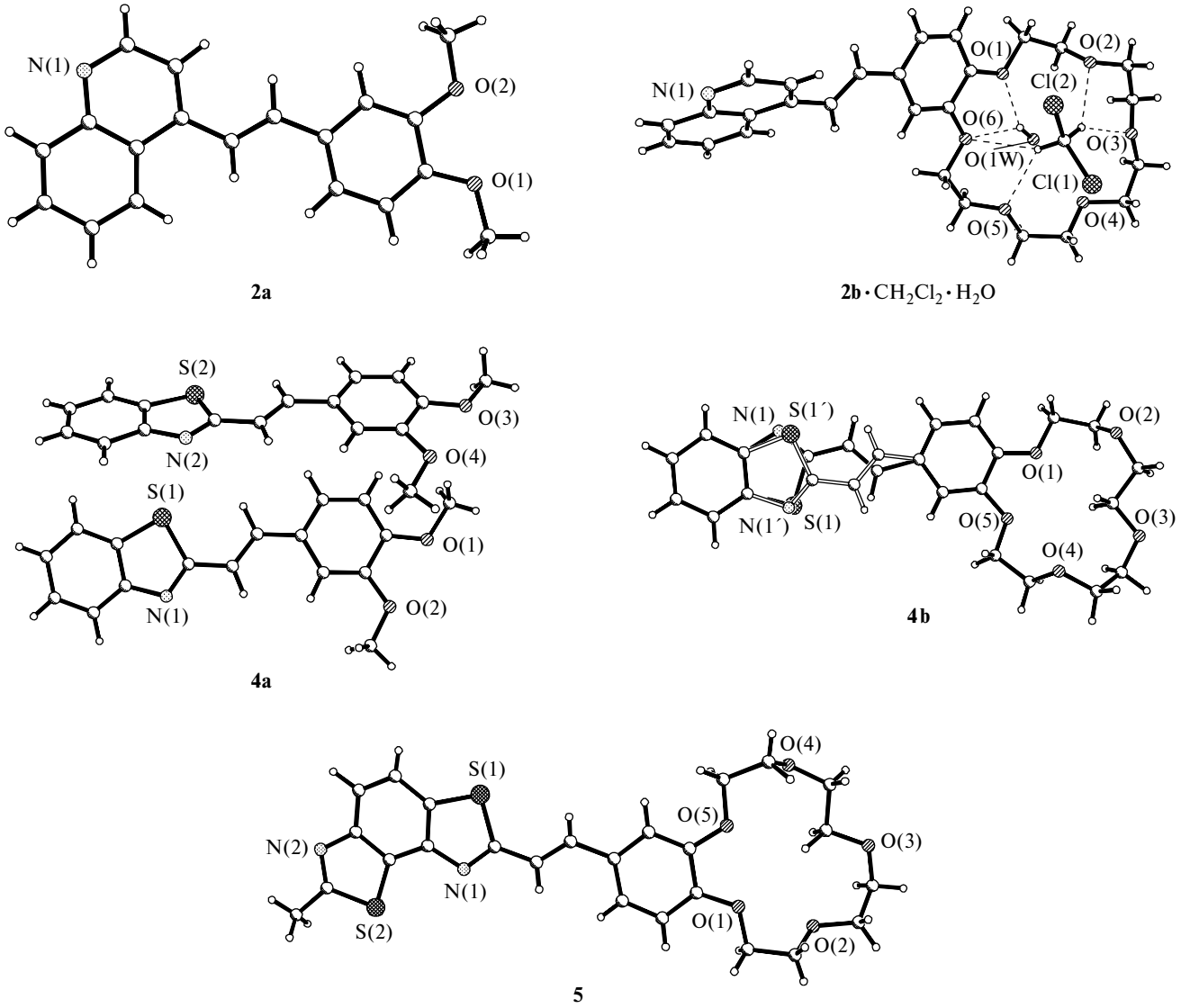


Fig. 4. Molecular structures of styrylheterocycles **2a,b**, **4a,b**, and **5** (two *s* conformers for **4b**; two independent molecules for **4a**; the solvate with CH_2Cl_2 and water for **2b**). The hydrogen bonds in the structure of **2b** · CH_2Cl_2 · H_2O are indicated by dashed lines.

of the same type of two "bicycle-pedal" *s* conformers are nonequivalent to each other. In the structure of **4b**, only atoms of the ethylene and thiazole fragments are nonequivalent.

The geometric characteristics of styrylheterocycles **1**—**6**, which are of most importance for our discussion, are as follows: the bond lengths in the ethylene fragment C_{Het}—C=C—C_{Ar} (l_1, l_2, and l_3, respectively) and the dihedral angles between the planes of the heterocycle and the ethylene bridge (τ_1), the ethylene bridge and the benzene ring (τ_2), and the heterocyclic and benzene rings (τ_3). These parameters for compounds **1**—**6** are given in Table 1.

The ethylene bond length l_2 in these compounds varies in the range of 1.31—1.35 Å, which is typical of C=C double bonds and is indicative of a high degree of localization of the π-electron density on this bond and, consequently, of a weak influence of the conjugation on the stabilization of a particular molecular conformation of the styrylheterocycle. This conclusion is consistent with the existence of two 4-styrylquinolines, **2a** and **2b**, having planar and nonplanar conformations, respectively, whereas the corresponding bond lengths in the ethylene fragments of the molecules are virtually equal. It should be noted that the substantial twisting of the planar heterocyclic moiety in crown ether **2b** with respect to the ethylene fragment (τ_1 = 41.8°) is not a consequence of the steric repulsion, because the same fragments in dimethoxy derivative **2a** are only weakly twisted (τ_1 = 16.0°). In all the molecules under consideration, the lengths of the

Table 1. Bond lengths in the ethylene fragment C_{Het}—C=C—C_{Ar} (l_1, l_2, and l_3, respectively) and the dihedral angles between the planes of the heterocycle and the ethylene bridge (τ_1), the ethylene bridge and the benzene ring (τ_2), and the heterocyclic and benzene rings (τ_3) in molecules **1**—**6**

Compound	Bond/Å			Angle/deg		
	l_1	l_2	l_3	τ_1	τ_2	τ_3
1a	1.469(2)	1.341(2)	1.470(2)	5.7	10.2	15.7
1b*	1.463(5), 1.447(8)	1.331(5), 1.313(7)	1.469(6), 1.471(7)	6.2, 4.8	11.1, 10.0	17.2, 14.8
2a	1.471(1)	1.341(2)	1.469(2)	16.0	16.6	2.3
2b	1.471(8)	1.342(4)	1.466(8)	41.8	13.3	55.0
3	1.478(2)	1.332(2)	1.469(2)	51.5	21.7	73.2
4a*	1.455(2), 1.451(2)	1.341(2), 1.342(2)	1.463(2), 1.467(2)	5.4, 8.7	9.6, 3.9	14.9, 11.9
4b*	1.453(7), 1.458(8)	1.327(10), 1.349(9)	1.530(9), 1.444(11)	5.9, 8.2	7.5, 6.2	13.2, 14.2
5b	1.438(6)	1.322(6)	1.485(6)	2.1	4.6	4.2
6a	1.474(4)	1.336(4)	1.469(4)	3.8	0.9	4.4
6b	1.459(6)	1.353(6)	1.471(6)	2.4	2.5	4.9

* For two orientations corresponding to the disordered ethylene fragment or for two independent molecules.

formally single bonds l_1 and l_3 vary in the range of 1.44—1.53 Å, which is typical of an essentially localized ethylene bonds.

Most of the molecules under study are almost planar (except for **2b** and **3**). The molecule of 9-styrylacridine **3** cannot be planar due to considerable steric interactions between the hydrogen atoms at the C(15) and C(5) (or C(15) and C(9)) atoms. The simple geometric consideration shows that if this molecule is planar, the distances between the above-mentioned hydrogen atoms would be shorter than 0.7 Å. In the planar conformation of **5**, which (like compound **3**) contains the bulky heterocyclic moiety, the ethylene fragment directly interacts only with the heteroatoms S and N devoid of hydrogen atoms. Hence, there is no substantial steric hindrance in molecule **5**, and the latter is almost planar (see Table 1).

Crystal packings. To perform the rational crystal design of neutral styrylheterocycles, it is important to analyze the crystal packings of a large number of structurally related compounds. Compounds **1**—**6** serve this purpose. For these compounds, it is interesting to reveal the relationship between the gradual extensions of the conjugation system and the bulkiness of the substituents in the benzene ring, on the one hand, and the packing motif of these compounds, on the other hand, and consequently, to reveal the structural parameters favorable for the preorganization of styrylheterocycles to the PCA reaction.

Previously,[27,36—39] we have shown with several examples that the stacking motifs typical of styryl dyes (see Fig. 1, *a* and *b*) are not characteristic of neutral styrylheterocycles. The latter compounds tend to form

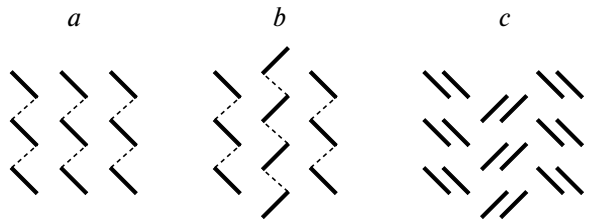


Fig. 5. Typical crystal packing motifs (ladder (*a*), ladder-herringbone (*b*), and sandwich-herringbone (*c*)) of neutral styrylheterocycles; the lateral projections of the conjugated fragments of the molecules are indicated by solid lines; the projections of the conjugated fragments onto each other are indicated by dashed lines.

ladder (Fig. 5, *a*), ladder-herringbone (Fig. 5, *b*), and sandwich-herringbone (Fig. 5, *c*) packings. Undoubtedly, there is a genetic relationship between these types of the arrangement of the structural units. The packing motifs presented in Fig. 5, *a* and *b* are derived from the motifs presented in Fig. 1, *a* and *b*, respectively, by the shift of each subsequent molecule in the stack with respect to the previous molecule in the same direction until the mutual projection disappears. The packing shown in Fig. 5, *c* is formed in the case of the analogous destruction of the stacking architecture (see Fig. 1, *b*) but with respect not only to one structural unit but also with respect to the dimer pair of the molecules.

The presence of stacked or ladder-herringbone packings in the crystal structures depends on the different contributions of two weak directed interactions most typical of aromatic compounds, which are responsible for the self-organization of the molecules in solution followed by the nucleation and the crystal growth. These are the π...π interactions (stacking interactions) and the weak C—H...π-system hydrogen bonds.[47] These two types of interactions require a different geometry of the mutual arrangement of the pair of molecules, from which the self-assembly of a supramolecular structure begins. For benzene and aromatic compounds devoid of heteroatoms, the perpendicular (T-shaped) mutual arrangement of two molecules corresponds to the global minimum, whereas the parallel arrangement of the molecules with a shift is energetically less favorable.[48] In the packings shown in Fig. 5, *a* and *b*, the C—H...π-system hydrogen bonds play the major role in the stabilization of the crystal structure. In heteroaromatic compounds or aromatic compounds containing an electron-withdrawing substituent, the contribution of stacking interactions increases due to an increase in the donor-acceptor contribution.[48] Hence, at least regions with stacking interactions (for example, of relatively isolated dimer pairs of molecules), if not the stacking arrangement of the molecules most favorable for the PCA reaction, would be expected to appear. It is this situation that is observed in the sandwich-herringbone packing (see Fig. 5, *c*), where both the C—H...π-system

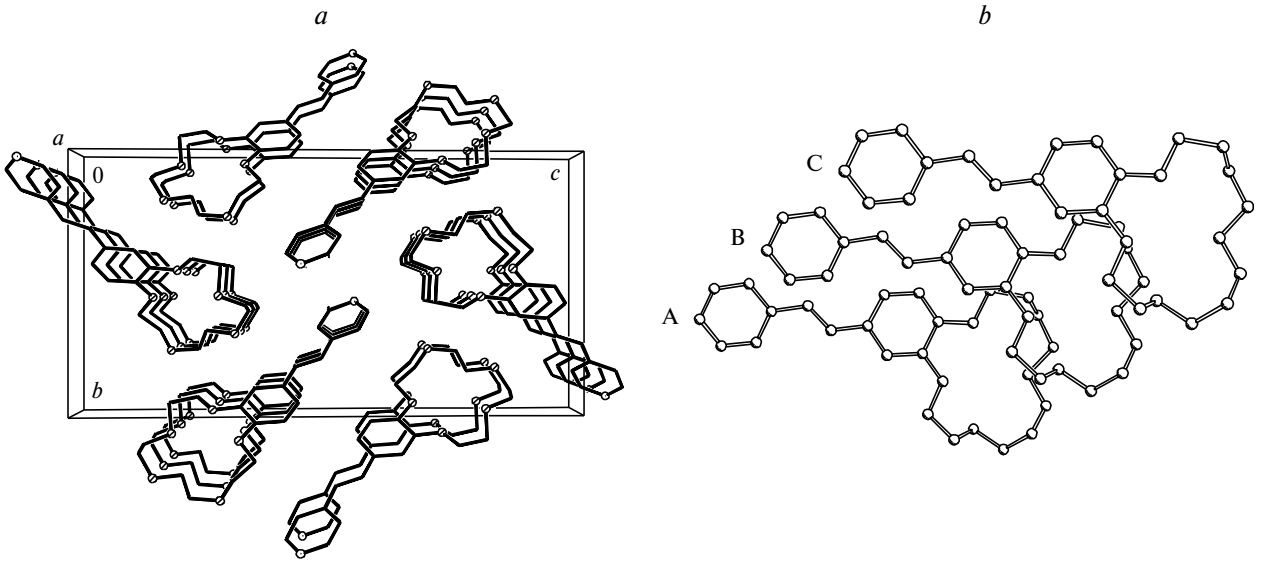


Fig. 6. Projection of the crystal packing of **1b** along the *a* axis (*a*) and the projection of adjacent molecules located in the parallel planes onto the mean plane of the conjugated fragment of the molecule labeled A (*b*). Only the major conformers of **1b** are shown for clarity.

hydrogen bonds and the stacking interactions are present. Among the known packing motifs, only the latter motif provides the preorganization of the structural units for the PCA reaction to occur in crystals of neutral styrylheterocycles.

We made an attempt to design the packing of styrylheterocycles **1**—**6** favorable for the PCA reaction by extending the conjugation system of the heterocyclic moiety, which should increase the contribution of stacking interactions to the total stabilization of the crystal structure. We also varied the bulkiness of the substituents in the benzene fragment of styrylheterocycles with the retention of their electron-donating character, because, as has been found previously[26,28] for styryl dyes, flexible crown ether moieties are favorable for single crystal-to-single crystal PCA reactions.

The crystal packing of crown-containing styrylpyridine **1b** is shown in Fig. 6, *a*. This packing can be described as a ladder, in which the planar conjugated fragments of the molecules that form the ladders are separated from each other by vast hydrophilic layers composed of the crown ether moieties. In the ladders, the adjacent mol-

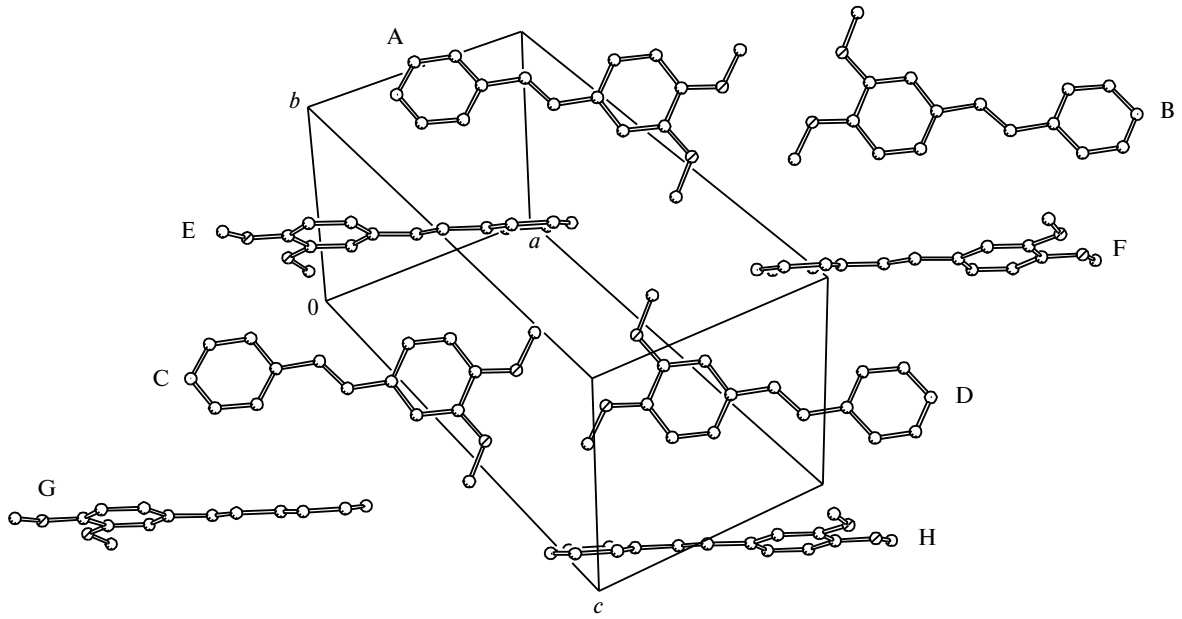


Fig. 7. Fragment of one herringbone layer of the packing of **1a** projected onto the mean plane of the molecules labeled A, B, C, and D.

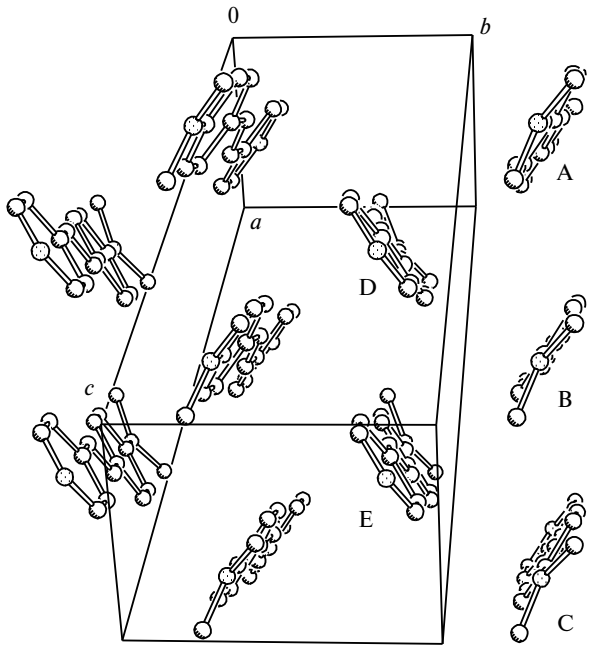


Fig. 8. Ladder-herringbone packing of the molecules in the crystal structure of **6a**.

ecules labeled A, B, and C are related by the translation along the *a* axis and are arranged in a head-to-head fashion, without the mutual projection of their conjugated fragments (see Fig. 6, *b*). The ethylene fragments of adjacent molecules are substantially shifted with respect to each other in the parallel planes; the distance between their carbon atoms is 5.22 Å. Evidently, there are no geometric conditions for the PCA reaction to occur in this crystal packing.

In the crystal structure, molecules **1a** form a ladder-herringbone packing (see Fig. 5, *b*). The fragment of one herringbone layer in the packing of **1a** projected onto the mean plane of four molecules labeled A, B, C, and D is shown in Fig. 7. Molecules labeled E, F, G, and H are located between the above-described layers; the planes of the latter molecules are inclined at an angle of 85.5° to the planes of the molecules of the first group. The subsequent layers in the packing are shifter with respect to the previous layers so that the nearest molecules from the other layers are located above any molecule of the layer under consideration at the same angle (85.5°). Within one herringbone layer, any two adjacent molecules **1a** are arranged in a head-to-tail fashion.

The similar crystal packing is observed for compound **6a** containing the dimethylamino group in the benzene ring. In the projection of the crystal packing shown in Fig. 8 (*cf.* Fig. 5, *b*), the ladder-herringbone packing of the planar molecules of this styrylpyridine is clearly seen. The mean planes of the molecules labeled A, B, and C are inclined at an angle of 65.5° to the mean planes of the molecules D and E.

In the crystal structure of azacrown-containing styrylpyridine **6b**, the molecules also form a ladder-herringbone packing motif. However, unlike the packings of compounds **1a** and **6a**, molecules **6b** within a herringbone layer are arranged in a head-to-head fashion. This packing leads to an alternation of the close-packed layers formed by the conjugated fragments and the loose layers composed of the crown ether moieties (Fig. 9, *a*). The mean planes of the conjugated fragments of the molecules labeled A and C and the molecules labeled B and D, which are located in one herringbone layer, are inclined with respect to each other at an angle of 69.2° (Fig. 9, *b*).

Two independent molecules of 2-styrylbenzothiazole **4a**, like molecules **6b**, form a ladder-herringbone packing. In the herringbone layers, the molecules are arranged

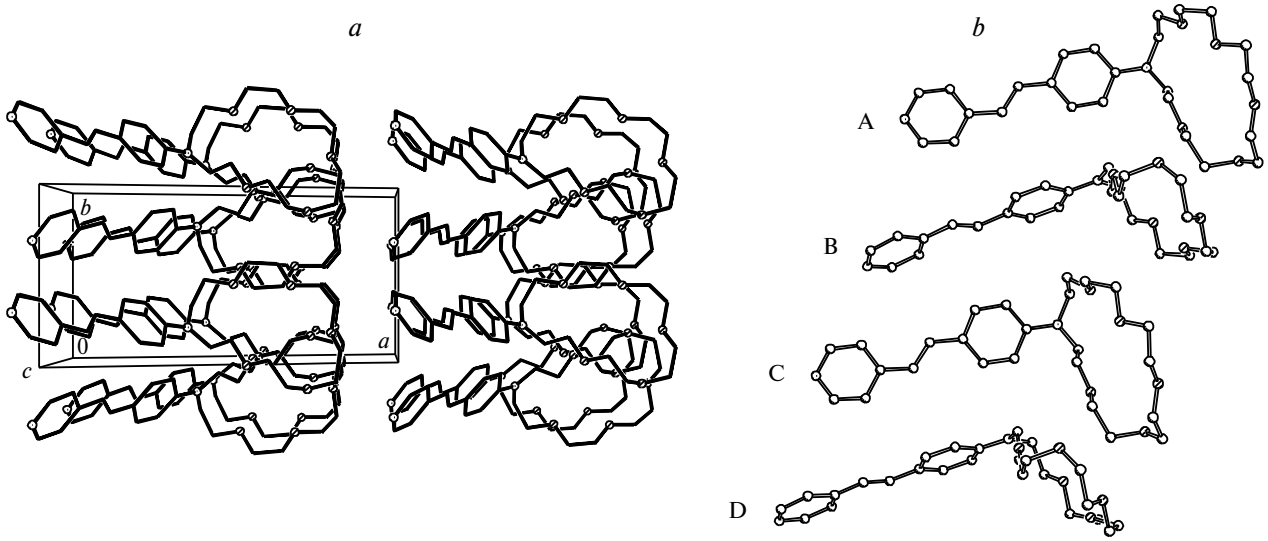


Fig. 9. Projection of the crystal packing of **6b** along the *c* axis (*a*) and the herringbone packing motif of the molecules projected onto the mean plane of the conjugated fragments of the molecules labeled A and C (*b*).

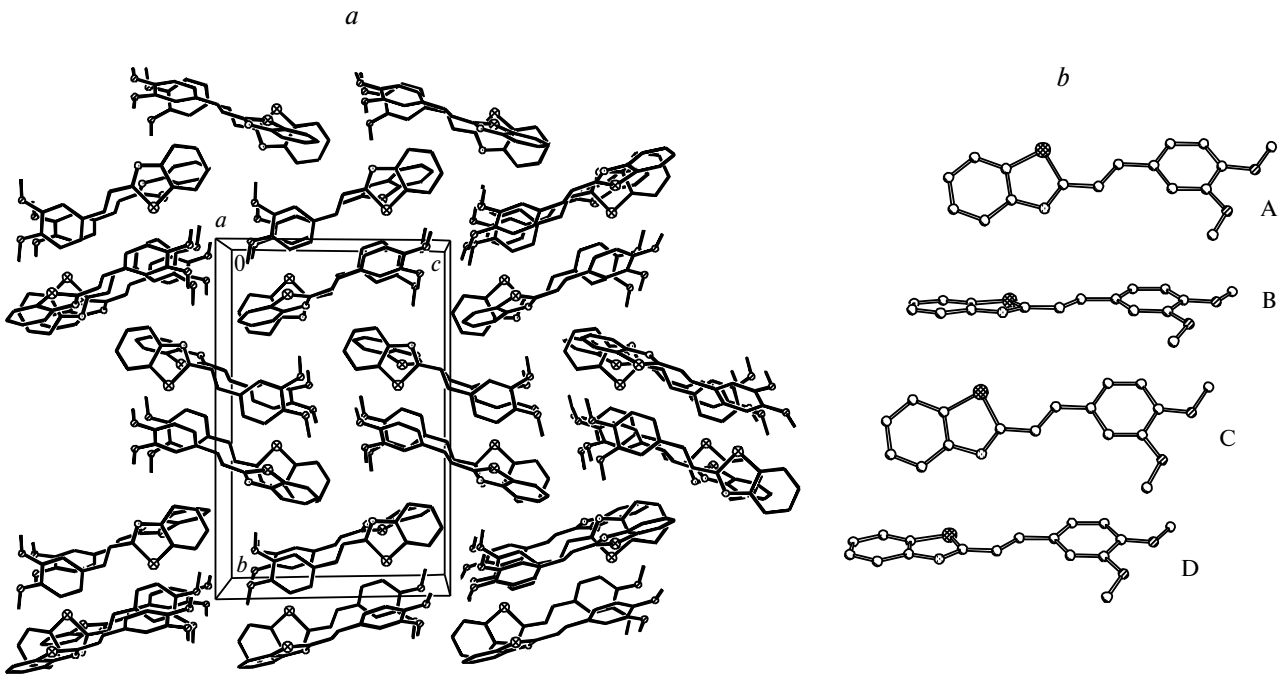


Fig. 10. Projection of the crystal packing of **4a** along the *a* axis (*a*) and the herringbone packing motif of the molecules projected onto the mean plane of the molecules labeled A and C (*b*).

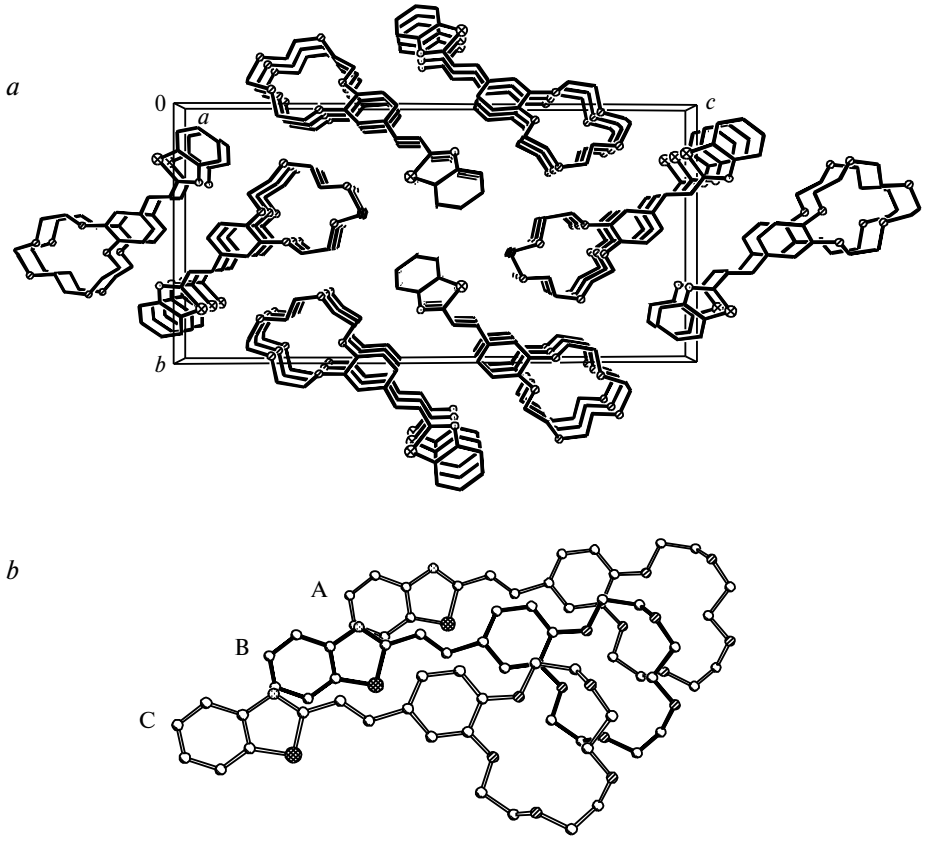


Fig. 11. Projection of the crystal packing of **4b** along the *a* axis (*a*) and the mutual projection of three adjacent molecules in the stack onto the mean plane of the conjugated fragment of the molecule labeled A (*b*). Only the major conformers of **4b** are shown for clarity.

in a head-to-head fashion. In this crystal structure, the herringbone layers are parallel to the *ac* plane (Fig. 10, *a*). The pairs of the molecules labeled A and C and alternating molecules labeled B and D, which are located in one herringbone layer, are related by the translation along the *a* axis. The mean planes of the independent molecules A and B are inclined at an angle of 38.4° to each other (Fig. 10, *b*). The distances between the carbon atoms of the ethylene bonds of adjacent molecules labeled A and B, B and C are in the range of 4.57—5.71 Å. Therefore, it is evident that the ladder-herringbone packing in the crystal structures of **1a**, **4a**, and **6a,b** excludes the possibility of the PCA reaction.

Basically, an increase in the contribution of stacking interactions could be expected in going to styrylheterocycles of the benzothiazole and quinoline series due to their more extended conjugation systems compared to styrylpyridines and, consequently, to the formation of a different packing motif. This is actually observed in the crystal structures of compounds **4b** and **2a**, but it is accomplished in different ways. The crystal packing of **4b**, which is similar to the ladder packing of crown-containing styrylpyridine **1b** (see Fig. 6, *a*), is shown in Fig. 11, *a*. However, the mutual projection of adjacent molecules in the ladder presented in Fig. 11, *b* is more similar to the packing of the stacks in a head-to-head fashion typical of styryl dyes (see Fig. 2, *b*). In the crystal structure of **4b**, the projection of the conjugated fragments is observed only at the periphery. Hence, the latter packing motif can be considered as the incomplete transition between the stacking packing (see Fig. 1, *a*) and the ladder packing (see Fig. 5, *a*). In the stack formed by translationally related structural units, the distances between the corresponding atoms of the ethylene fragments are 5.06 Å, and, consequently, the PCA reaction in this case is hardly probable.

In the crystals of 4-styrylquinoline **2a**, the molecules are packed in a sandwich-herringbone fashion (Fig. 12, *a*) (*cf.* Fig. 5, *c*). The structure of the dimer pair of molecules **2a** is presented in two projections in Fig. 12, *b*. In the upper projection, it is clearly seen that the mutual projection of the molecules includes virtually the whole π-conjugation system. The ethylene fragments in the dimer pair are strictly antiparallel due to its centrosymmetric structure, and the distance between the carbon atoms of these fragments is 3.63 Å. Therefore, there are all geometric conditions necessary for the efficient PCA reaction to occur in this crystal. Actually, the visible-light irradiation of a single crystal of **2a** afforded the only *rctt* isomer of the corresponding cyclobutane derivative without the degradation of the single crystal, which was established[27] by X-ray diffraction and NMR spectroscopy. It should be noted that a comparison of the molecular structure of cyclobutane prepared by the irradiation of a crystal of **2a** and the molecular structure of the same cyclobutane recrystallized from solution showed[27] that the former

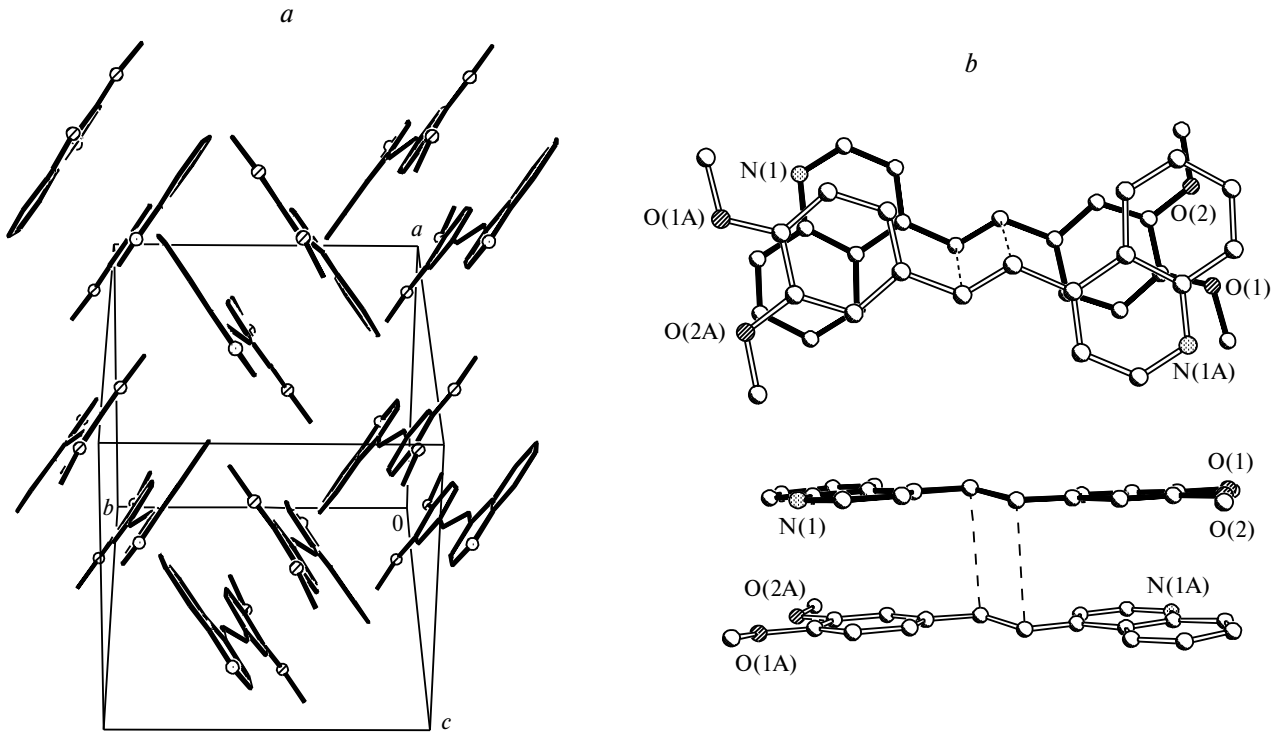


Fig. 12. Sandwich-herringbone packing motif in the crystal structure of **2a** (*a*) and two projections of the centrosymmetric pair of the molecules (*b*) (the upper part of the panel represents the projection onto the mean plane of the molecule with continuous bonds).

structure is somewhat strained. These single crystals appeared to be unstable during storage, which indicates that the strained core of the cyclobutane derivative has a substantial effect on the possibility of the single crystal-to-single crystal PCA reaction.

The structure of **2a** is strongly contrast[27] to the structure of its crown-containing analog **2b**. As mentioned above, the conjugated fragment of molecule **2b**, unlike those in many known compounds, is essentially nonplanar (see Table 1). The crystal packing of the nonplanar molecules cannot be described like those presented in Figs 1 and 5. Although the projection of the crystal packing of **2b** along the *b* axis shown in Fig. 13, *a* is similar to the projections of the packings of styrylheterocycles **1b** and **4b** (see Fig. 6, *a* and Fig. 11, *a*, respectively), these packings are different. The interactions between the oxygen atoms of the 18-crown-6-ether moiety and the solvent dichloromethane and water molecules located on the opposite sides of the plane of the macrocycle play a key role in the formation of the packing of **2b** (see Fig. 4). The CH_2Cl_2 molecule forms two pairs of bifurcated hydrogen bonds with C—H...O distances varying in the range of 2.51—2.67 Å. The water molecule is involved in one bifurcated hydrogen bond with the crown ether moiety with the O(1W)—H...O(1)/O(6) distances of 2.37 and 2.53 Å. Another hydrogen atom of the water molecule was not located due apparently to its disorder. Thus, this hydrogen atom can be oriented toward the O(4) atom of the macrocycle or toward the Cl(1) atom of adjacent solvate **2b** • CH_2Cl_2 • H_2O related to the reference molecule by the translation along the *b* axis. The formation of this hydrogen-bonded framework involving the molecules labeled A and E, B and F (see Fig. 13, *b*) in the crystals of **2b** results in that the nearest ethylene fragments of the molecules A and B, E and F are not projected onto each other and are far spaced (4.95 Å). This arrangement is unfavorable for the PCA reaction in the crystal.

Therefore, the presence of the crown ether moiety in the neutral styrylheterocycle molecule increases the probability of the influence of new, stronger interactions on the formation of the crystal structure as a results of the trapping of small molecules by this fragment. This leads to the formation of supramolecular architectures, which are not typical of this class of compounds, resulting in that the crystal packing is less predictable. This is the difference between styrylheterocycles and the corresponding styryl dyes, in which the presence of the crown ether moiety only improves the situation with respect to the formation of the packing in a head-to-tail fashion favorable for the PCA reaction in crystals.[28,29]

The nonplanarity of the 9-styrylacridine molecule **3** is apparently a consequence of intramolecular steric interactions between the heterocyclic moiety and the ethylene system (see above). Hence, the expected crystal packing of this compound can also differ from the packings presented in Figs 1 and 5. Actually, only large acridine fragments in the crystal packing of **3** are arranged in stacks that are formed by the structural units related by a center of symmetry, where the dimer pairs of the molecules labeled A and B, C and D are clearly distinguished,

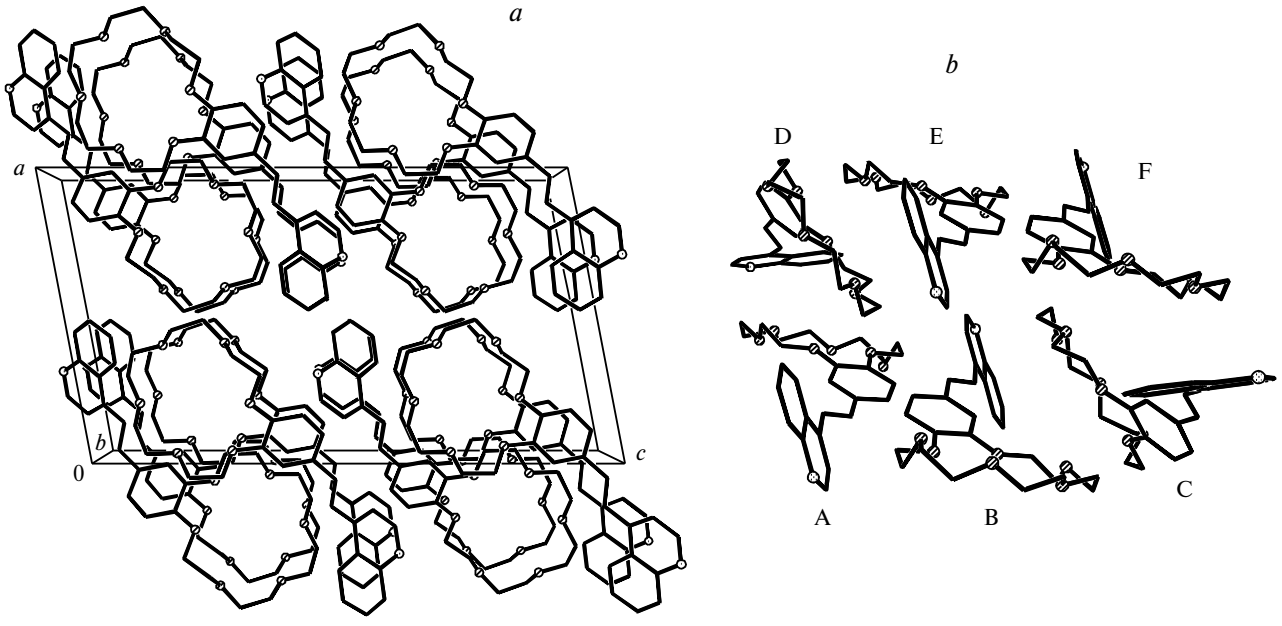


Fig. 13. Crystal packing of **2b** • CH_2Cl_2 • H_2O along the *b* axis (*a*) and the fragment of this packing (*b*). The solvent molecules are not shown for clarity.

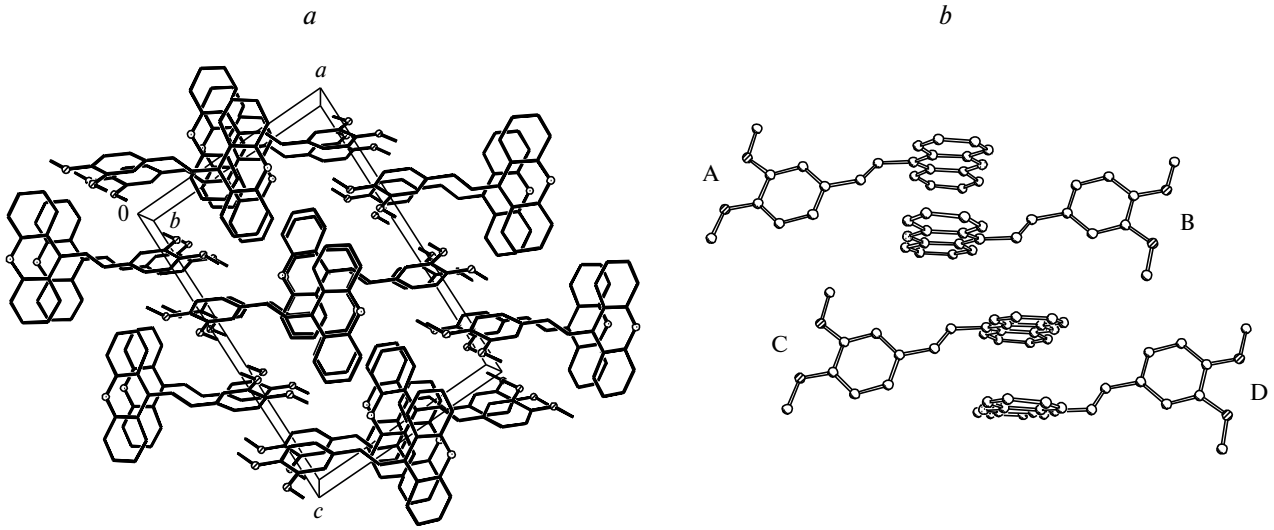


Fig. 14. Crystal packing of **3** along the *b* axis (*a*) and the fragment of this packing projected onto the mean plane of the benzene rings (*b*).

whereas the styryl fragments form a ladder motif (Fig. 14). The tendency of the acridine fragment to form dimer pairs is manifested also in the crystal structure of bisheterocycle **7**, in which the N(1),C(1)...C(13) fragment is involved in the centrosymmetric dimer pair stabilized by stacking interactions.

Crown-containing compound **5**, in which the N and S atoms of the benzobisthiazole fragment nearest to the ethylene fragment do not contain exocyclic substituents, represents a successful attempt to extend the π-conjugated fragment, which is not accompanied by the twisting of the chromophore system. An extension of the conjugation system in compound **5** compared to the related 2-styrylbenzothiazole **4b** leads to the formation of dimer pairs of the molecules due to the sandwich-herringbone packing motif (Fig. 15). In the centrosymmetric pairs, the ethylene fragments of the molecules are antiparallel and are spaced by 3.80 Å, *i.e.*, they are preorganized for the PCA reaction. Since the PCA reaction in the crystals of **2a** having a similar packing motif is efficient, this reaction

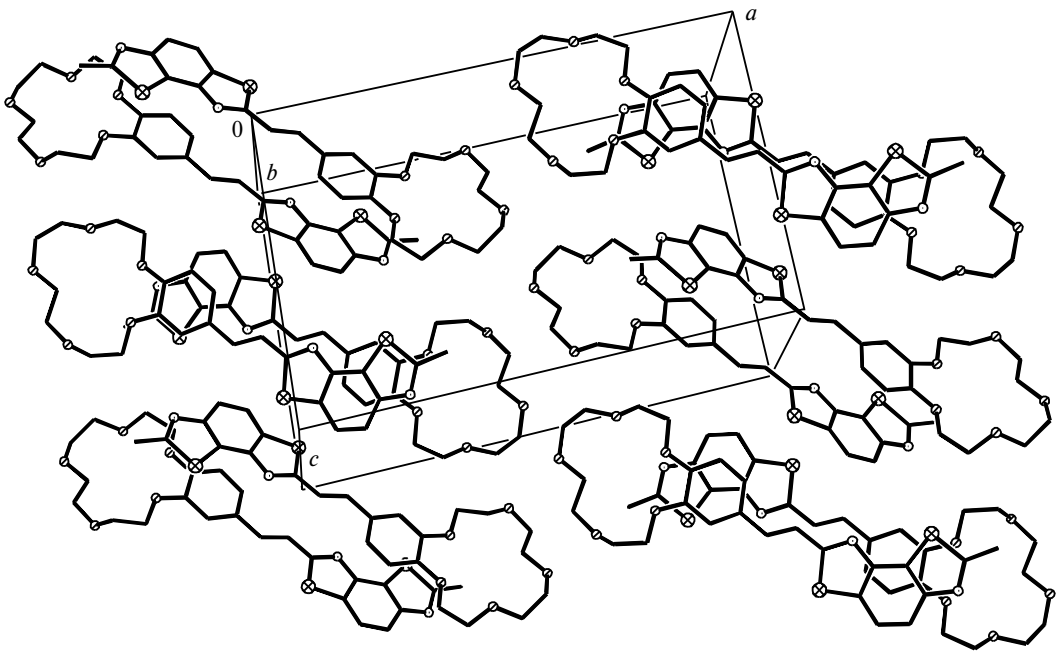


Fig. 15. Fragment of one sandwich-herringbone layer in the crystal structure of **5**.

would be expected to occur in the crystals of **5** as well. The possibility of the single crystal-to-single crystal reaction of compound **5** will be considered elsewhere.

To conclude, the present study showed that the design of the crystal packing of neutral styrylheterocycles can be performed. The (herringbone)ladder packing motif, to which weak C—H...π-system interactions make the major contribution, is the most typical motif for these compounds. This packing motif is unfavorable for the solid-state [2+2] photocycloaddition reaction because of the nonparallel arrangement of the ethylene fragments of adjacent molecules or their strong mutual shift in the parallel planes by more than 5 Å. Only the sandwich-herringbone arrangement in the crystals of styrylheterocycles facilitates the organization of the molecules as centrosymmetric dimers with the antiparallel closely spaced C=C bonds. In this structural motif, there are all geometric conditions necessary for the efficient PCA reaction, including single crystal-to-single crystal reactions. To form the sandwich-herringbone packing, the styrylheterocycle molecule should have the following structural characteristics: first, it should have a rather large planar heterocyclic moiety favorable for strong stacking interactions; second, it should have a planar π-conjugation system throughout the chromophore; and, third, the benzene moiety of the molecule should not contain fragments, which are prone to form a hydrogen bond network with solvent molecules.

However, it should be noted that the crystal structures of neutral styrylheterocycles are less predictable than the structures of related cationic styryl dyes. The packings of the compounds under consideration can also be designed with the use of their protonated forms or complexes with metal salts at the heterocyclic nitrogen atom. In this case, the electronic structures of styrylheterocycles are more similar to those of styryl dyes, and their crystalline architectures would be expected to be more similar. The results of the examination of this possibility will be published elsewhere.

Experimental

The melting points (uncorrected) were measured in capillaries on a Mel-Temp II instrument. The mass spectra were obtained on a Varian MAT 311A instrument using a direct inlet system; the ionization energy was 70 eV. The elemental analysis was carried out in the Laboratory of Microanalysis of the A. N. Nesmeyanov Institute of Organoelement Compounds of the Russian Academy of Sciences (Moscow). The TLC monitoring was performed on DC-Alufolien Aluminiumoxid 60 F_{254} (Merck) plates. The ^1H and ^{13}C NMR spectra were recorded on a Bruker DRX500 spectrometer (500.13 and 125.76 MHz, respectively) in $CDCl_3$, MeCN-d_3, and DMSO-d_6 at 25—30 °C using the solvent as the internal standard (δ_H 7.27, 1.96, and 2.50, respectively; δ_C 77.00 for $CDCl_3$, and δ_C 39.43 for DMSO-d_6). The chemical shifts and the spin-spin coupling constants were measured with an accuracy of 0.01 ppm and 0.1 Hz, respectively. The assignment of the signals for protons and carbon atoms was made based on the two-dimensional homonuclear $^1H—^1H$ COSY and NOESY spectra and heteronuclear $^1H—^{13}C$ COSY spectra (HSQC and HMBC).

4-Picoline, lepidine, 9-methylacridine, veratraldehyde, anhydrous $ZnCl_2$, and anhydrous $SnCl_2$ (Aldrich) were used without additional purification. *N*-(4-Formylphenyl)aza-18-crown-6 ether,[49] 4-[(*E*)-2-(2,3,5,6,8,9,11,12-octahydrobenzo-1,4,7,10,13-pentaoxacyclopentadecyn-15-yl)-1-ethenyl]-pyridine (**1b**),[37] 4-[(*E*)-2-(2,3,5,6,8,9,11,12,14,15-decahydro-1,4,7,10,13,16-benzohexaoxacyclooctadecyn-18-yl)-1-ethenyl]-quinoline (**2b**),[27] 2-[(*E*)-2-(3,4-dimethoxyphenyl)-1-ethenyl]-1,3-benzothiazole (**4a**),[41] 2-[(*E*)-2-(2,3,5,6,8,9,11,12-octahydro-1,4,7,10,13-benzopentaoxacyclopentadecyn-15-yl)-1-ethenyl]-1,3-benzothiazole (**4b**),[41] 2-methyl-7-[(*E*)-2-(2,3,5,6,8,9,11,12-octahydro-1,4,7,10,13-benzopentaoxacyclopentadecyn-15-yl)-1-ethenyl][1,3]thiazolo[5,4-*e*][1,3]benzothiazole (**5**),[39] and *N*,*N*-dimethyl-*N*-{4-[(*E*)-2-(4-pyridyl)-1-ethenyl]-phenyl}amine (**6a**)[44] were synthesized according to known procedures.

4-[(*E*)-2-(3,4-Dimethoxyphenyl)-1-ethenyl]pyridine (1a). A mixture of 4-picoline (4.87 mL, 0.044 mol), veratraldehyde (8.30 g, 0.050 mol), and acetic anhydride (9 mL) was heated at 140 °C (oil bath) for 10 h. The reaction mixture was poured into water (130 mL). Then a 10% KOH solution was added to pH >9, the mixture was extracted with benzene (3×60 mL), and the combined benzene extracts were extracted with 10% hydrochloric acid (2×70 mL). Then a 25% NH_4OH solution was added to the acidic aqueous phase to pH >9. The precipitate that formed was filtered off, washed with water, dried in air, and recrystallized from anhydrous EtOH (10 mL). Compound **1a** was obtained in a yield of 2.48 g (23%) as pale-yellow crystals, m.p. 130—131 °C (from ethanol) (*cf.* lit. data[37]: m.p. 113—115 °C). Found (%): C, 74.69; H, 6.24; N, 5.74. $C_{15}H_{15}NO_2$. Calculated (%): C, 74.67; H, 6.27; N, 5.81. ^1H NMR (DMSO-d_6), δ: 3.79 (s, 3 H, 4´-OMe); 3.84 (s, 3 H, 3´-OMe); 7.00 (d, 1 H, H(5´), J = 8.6 Hz); 7.15 (d, 1 H, CH=C<u>H</u>Py, J = 16.3 Hz); 7.17 (dd, 1 H, H(6´), J = 8.6 Hz, J = 1.8 Hz); 7.31 (d, 1 H, H(2´), J = 1.8 Hz); 7.48 (d, 1 H, C<u>H</u>=CHPy, J = 16.3 Hz); 7.52 (d, 2 H, H(3), H(5), J = 5.9 Hz); 8.52 (d, 2 H, H(2), H(6), J = 5.9 Hz). ^{13}C NMR (DMSO-d_6), δ: 55.42 (2 OMe); 109.45 (C(2´)); 111.60 (C(5´)); 120.46 (C(3), C(5)); 120.89 (C(6´)); 123.55 (CH=<u>C</u>HPy); 128.94 (C(1´)); 132.94 (<u>C</u>H=CHPy); 144.55 (C(4)); 148.89 (C(3´)); 149.47 (C(4´)); 149.86 (C(2), C(6)).

4-[(*E*)-2-(3,4-Dimethoxyphenyl)-1-ethenyl]quinoline (2a). A mixture of lepidine (0.40 mL, 3.0 mmol), veratraldehyde (0.42 g, 2.5 mmol), anhydrous $ZnCl_2$ (0.41 g, 3.0 mmol), and glacial acetic acid (2 mL) was heated in the dark at 120 °C (oil bath) for 42 h. Water (60 mL) was added to the dark-brown reaction mixture, and the mixture was extracted with chloroform (3×20 mL). The chloroform extracts were carefully concentrated *in vacuo*, and the residue was chromatographed on silica gel (Kieselgel 60, 0.063—0.100 mm, Merck) using the gradient elution with a benzene—AcOEt mixture to 50% of AcOEt. The fraction containing the reaction product was concentrated *in vacuo*, and the yellowish residue was extracted with boiling isooctane (2×20 mL). The extracts were cooled to 5 °C, and the precipitate that formed was separated by decantation and dried in air in the dark. Compound **2a** was obtained in a yield of 0.26 g (36%) as a pale-yellow powder, m.p. 132—134 °C

(from isooctane) (*cf.* lit. data[27]: m.p. 130—132 °C). ^{1}H NMR (DMSO-d_6), δ: 3.81 (s, 3 H, 4´-OMe); 3.89 (s, 3 H, 3´-OMe); 7.02 (d, 1 H, H(5´), J = 8.2 Hz); 7.30 (dd, 1 H, H(6´), J = 8.2 Hz, J = 1.8 Hz); 7.51 (d, 1 H, H(2´), J = 1.8 Hz); 7.54 (d, 1 H, CH=CHHet, J = 16.2 Hz); 7.66 (m, 1 H, H(6)); 7.79 (m, 1 H, H(7)); 7.82 (d, 1 H, H(3), J = 4.8 Hz); 7.97 (d, 1 H, CH=CHHet, J = 16.2 Hz); 8.03 (d, 1 H, H(8), J = 7.7 Hz); 8.56 (d, 1 H, H(5), J = 8.2 Hz); 8.86 (d, 1 H, H(2), J = 4.8 Hz).

9-[(*E*/*Z*)-2-(3,4-Dimethoxyphenyl)-1-ethenyl]acridine (3) and 9-[3-(9-acridyl)-2-(3,4-dimethoxyphenyl)propyl]acridine (7). A mixture of 9-methylacridine (205 mg, 1.1 mmol), veratraldehyde (265 mg, 1.6 mmol), acetic anhydride (0.5 mL), and glacial acetic acid (2 mL) was heated in the dark at 120 °C (oil bath) for 15 h. The reaction mixture was carefully concentrated *in vacuo*, and the residue was chromatographed on silica gel (Kieselgel 60, 0.063—0.100 mm, Merck) using the gradient elution with a benzene—AcOEt mixture to 40% of AcOEt. Two fractions were collected. The first fraction contained a mixture of the *E* and *Z* isomers of **3** in a ratio of 1 : 4.3 (NMR monitoring) in a total yield of 3% (10.5 mg). A solution of a mixture of the *E* and *Z* isomers of **3** in a 1 : 1 CH_2Cl_2—hexane mixture (3 mL) was slowly concentrated in the dark at room temperature. The yellow single crystal of (*E*)-**3** that formed was used for X-ray diffraction. ^{1}H NMR of the isomer (*Z*)-**3** ($CDCl_3$), δ: 2.91 (s, 3 H, 3´-OMe); 3.72 (s, 3 H, 4´-OMe); 6.12 (d, 1 H, H(2´), J = 1.8 Hz); 6.55 (d, 1 H, H(5´), J = 8.3 Hz); 6.62 (dd, 1 H, H(6´), J = 8.3 Hz, J = 1.8 Hz); 7.07 and 7.16 (2 d, 1 H each, CH=CHHet and CH=CHHet, J = 12.6 Hz, J = 12.6 Hz); 7.47 (m, 2 H, H(2), H(7)); 7.76 (m, 2 H, H(3), H(6)); 8.22 (d, 2 H, H(1), H(8), J = 8.7 Hz); 8.25 (d, 2 H, H(4), H(5), J = 8.6 Hz). ^{1}H NMR of the isomer (*E*)-**3** ($CDCl_3$), δ: 3.97 (s, 3 H, 4´-OMe); 4.02 (s, 3 H, 3´-OMe); 6.97 (d, 1 H, H(5´), J = 8.2 Hz); 7.01 and 7.78 (2 d, 1 H each, CH=CHHet and CH=CHHet, J = 16.5 Hz, J = 16.5 Hz); 7.23 (dd, 1 H, H(6´), J = 8.2 Hz, J = 1.7 Hz); 7.26 (d, 1 H, H(2´), J = 1.7 Hz); 7.54 (m, 2 H, H(2), H(7)); 7.79 (m, 2 H, H(3), H(6)); 8.28 (d, 2 H, H(4), H(5), J = 9.1 Hz); 8.36 (d, 2 H, H(1), H(8), J = 8.6 Hz).

Bisacridine **7** was isolated from the second fraction in a yield of 76 mg (26%) as a yellowish powder, m.p. 180—182 °C (from isooctane). Found (%): C, 82.56; H, 5.71; N, 5.14.

Table 2. Crystallographic characteristics and the X-ray diffraction data collection and refinement statistics for compounds **1a,b**, **3** and **7**.

Parameter	**1a**	**1b**	**3**	**7**
Molecular formula	$C_{15}H_{15}NO_2$	$C_{21}H_{25}NO_5$	$C_{23}H_{19}NO_2$	$C_{37}H_{30}N_2O_2$
Molecular weight	241.28	371.42	341.39	534.63
Crystal system	Monoclinic		Monoclinic	
Space group	$P2_1/c$	$P2_1/c$	$P2_1/c$	$P2_1/c$
a/Å	8.7021(5)	5.2229(10)	12.0961(7)	14.8238(13)
b/Å	7.8008(5)	13.648(3)	7.5847(4)	10.7294(8)
c/Å	18.9403(12)	25.997(5)	18.3393(11)	18.6919(17)
α/deg	90	90	90	90
β/deg	95.367(3)	93.438(3)	91.817(2)	109.978(4)
γ/deg	90	90	90	90
V/Å^3	1280.09(14)	1849.7(6)	1681.70(17)	2794.1(4)
Z	4	4	4	4
d_{calc}/g cm^{-3}	1.252	1.334	1.348	1.271
F(000)	512	792	720	1128
μ(Mo-Kα)/mm^{-1}	0.083	0.095	0.086	0.079
Crystal dimensions/mm	0.36×0.34×0.08	0.60×0.10×0.04	0.55×0.48×0.14	0.36×0.35×0.32
θ Scan mode/range, deg	ω/2.16—28.99	ω/1.69—29.00	ω/1.68—30.01	ω/1.46—29.96
Ranges of indices of measured reflections	$-11 \le h \le 11$, $-6 \le k \le 10$, $-25 \le l \le 24$	$-7 \le h \le 7$, $-18 \le k \le 18$, $-34 \le l \le 35$	$-17 \le h \le 16$, $-10 \le k \le 10$, $-25 \le l \le 21$	$-20 \le h \le 18$, $-14 \le k \le 14$, $-16 \le l \le 26$
Number of measured reflections	9280	19996	10176	24426
Number of independent reflections	3343 (R_{int} = 0.0228)	4907 (R_{int} = 0.0613)	4862 (R_{int} = 0.0332)	7562 (R_{int} = 0.0269)
Number of reflections with $I > 2\sigma(I)$	2537	2555	3506	5985
Number of refined parameters	223	488	311	490
R factors based on reflections with $I > 2\sigma(I)$ based on all reflections	R_1 = 0.0466, wR_2 = 0.1091 R_1 = 0.0699, wR_2 = 0.1189	R_1 = 0.0508, wR_2 = 0.1013 R_1 = 0.1234, wR_2 = 0.1180	R_1 = 0.0537, wR_2 = 0.1365 R_1 = 0.0764, wR_2 = 0.1491	R_1 = 0.0493, wR_2 = 0.1194 R_1 = 0.0661, wR_2 = 0.1308
Goodness-of-fit on F^2	1.056	0.974	1.046	1.041
Residual electron density (min/max)/e Å^{-3}	−0.257/0.339	−0.154/0.139	−0.259/0.366	−0.205/0.413

$C_{37}H_{30}N_2O_2 \cdot 0.25H_2O$. Calculated (%): C, 82.43; H, 5.70; N, 5.20. ^{1}H NMR (DMSO-d_6), δ: 3.51 (s, 3 H, 3´-OMe); 3.52 (m, 1 H, C<u>H</u>$(CH_2)_2$); 3.65 (s, 3 H, 4´-OMe); 4.12 (dd, 2 H, 2 C<u>H</u>H´Het, J = 13.8 Hz, J = 6.5 Hz); 4.20 (dd, 2 H, 2 CH<u>H</u>´Het, J = 13.8 Hz, J = 7.9 Hz); 6.14 (br.d, 1 H, H(6´), J = 8.1 Hz); 6.39 (d, 1 H, H(5´), J = 8.1 Hz); 7.06 (br.s, 1 H, H(2´)); 7.37 (m, 4 H, 2 H(2), 2 H(7)); 7.74 (m, 4 H, 2 H(3), 2 H(6)); 8.03 (d, 4 H, 2 H(1), 2 H(8), J = 8.6 Hz); 8.08 (d, 4 H, 2 H(4), 2 H(5), J = 8.7 Hz). ^{13}C NMR ($CDCl_3$), δ: 33.64 (CH(<u>C</u>$H_2)_2$); 49.13 (<u>C</u>H$(CH_2)_2$); 55.80 (3´-OMe); 55.98 (4´-OMe); 111.44 (C(2´)); 111.47 (C(5´)); 118.90 (C(6´)); 123.92 (2 C(1), 2 C(8)); 125.24 (2 C(8a), 2 C(9a)); 125.56 (2 C(2), 2 C(7)); 129.61 (2 C(3), 2 C(6)); 130.29 (2 C(4), 2 C(5)); 135.68 (C(1´)); 143.95 (2 C(9)); 148.20 (C(4´)); 148.44 (2 C(4a), 2 C(10a)); 148.68 (C(3´)). MS, m/z (I_{rel} (%)): 534 $[M]^+$ (0.6), 193 (100), 97 (53), 96 (63), 89 (54), 84 (72), 73 (57), 72 (54), 59 (90), 58 (69).

9-[3-(9-Acridyl)-2-(3,4-dimethoxyphenyl)propyl]acridine (7). A mixture of 9-methylacridine (211 mg, 1.1 mmol), veratraldehyde (218 mg, 1.3 mmol), anhydrous $ZnCl_2$ (180 mg, 1.3 mmol), and glacial acetic acid (2 mL) was heated in the dark at 120 °C (oil bath) for 43 h. Water (60 mL) was added to the reaction mixture, and the resulting mixture was extracted with chloroform (4×25 mL). The chloroform extracts were carefully concentrated *in vacuo*, and the residue was chromatographed on silica gel (Kieselgel 60, 0.063—0.100 mm, Merck) using the gradient elution with a benzene—AcOEt mixture to 50% of AcOEt. The fraction containing the desired product was concentrated *in vacuo*, and the yellowish residue was extracted with boiling isooctane (2×25 mL). The extracts were cooled to 5 °C, and the precipitate that formed was separated by decantation and dried in air. Compound **7** was obtained in a yield of 105 mg (36%) as greish-yellow crystals, m.p. 180—182 °C (from isooctane).

16-{4-[(*E*)-2-(4-Pyridyl)-1-ethenyl]phenyl}-1,4,7,10,13-pentaoxa-16-azacyclooctadecane (6b). ***A.*** Concentrated hydrochloric acid (0.32 mL, 3.7 mmol) was added to a solution of 4-picoline (0.30 mL, 3.1 mmol). The solvent was carefully concentrated *in vacuo* at 60 °C (water bath). *N*-(4-Formylphenyl)-aza-18-crown-6 ether (0.44 g, 1.2 mmol) and acetic anhydride (3 mL) were added to the resulting 4-picoline hydrochloride. The reaction mixture was heated at 140 °C (oil bath) for 12 h and then concentrated *in vacuo*. A 1% NaOH solution (100 mL) was added to the viscous black residue, and the mixture was extracted with chloroform (4×25 mL). The chloroform extracts were concentrated *in vacuo*, and the residue was chromatographed on silica gel (Kieselgel 60, 0.035—0.070 mm, Merck) using a 1 : 1 benzene—AcOEt mixture as the eluent and then a benzene—Pr^{i}OH mixture for the gradient elution to 20% of Pr^{i}OH. The fraction containing the target product was concentrated *in vacuo*, and the red-orange residue (0.15 g) was extracted with boiling hexane (2×40 mL). The extracts were cooled to room temperature, and the precipitate that formed was separated by decantation and dried in air. Compound **6b** was obtained in a yield of 0.12 g (22%) as yellowish crystals, m.p. 94—96 °C (from a CH_2Cl_2—hexane mixture). Found (%): C, 67.72; H, 7.80; N, 6.19. $C_{25}H_{34}N_2O_5$. Calculated (%): C, 67.85; H, 7.74; N, 6.33. ^{1}H NMR (MeCN-d_3), δ: 3.57—3.65 (m, 20 H, $N(CH_2)_2$, 8 CH_2O); 3.67 (m, 4 H, 2 C<u>H</u>$_2$C<u>H</u>$_2$N); 6.76 (d, 2 H, H(3´), H(5´), J = 8.9 Hz); 6.91 (d, 1 H, CH=C<u>H</u>Py, J = 16.3 Hz); 7.36 (d, 1 H, C<u>H</u>=CHPy, J = 16.3 Hz); 7.41 (d, 2 H, H(3), H(5), J = 5.5 Hz); 7.45 (d, 2 H, H(2´), H(6´), J = 8.9 Hz); 8.48 (d, 2 H, H(2), H(6), J = 5.5 Hz). ^{13}C NMR (DMSO-d_6), δ: 50.52 ($N(CH_2)_2$); 67.82 (2 <u>C</u>H_2CH_2N); 69.85 (2 CH_2O); 69.91 (4 CH_2O); 69.98 (2 CH_2O); 111.29 (C(3´), C(5´)); 120.08 (C(3), C(5)); 120.21 (C<u>H</u>=<u>C</u>HPy); 123.25 (C(1´)); 128.44 (C(2´), C(6´)); 133.20 (<u>C</u>H=CHPy); 145.05 (C(4)); 148.08 (C(4´)); 149.64 (C(2), C(6)). MS, m/z (I_{rel} (%)): 442 $[M]^+$ (50), 265 (24), 253 (19), 223 (34), 209 (46), 208 (37), 181 (22), 59 (49), 58 (100), 57 (24).

B. A mixture of 4-picoline (0.67 mL, 5.8 mmol), *N*-(4-formylphenyl)aza-18-crown-6 ether (0.50 g, 1.4 mmol), and anhydrous $SnCl_2$ (0.19 g, 1.0 mmol) was heated at 160 °C (oil bath) for 4 h. 4-Picoline was carefully removed from the reaction mixture by heating *in vacuo*, and the viscous brown residue was chromatographed on silica gel (Kieselgel 60, 0.063—0.100 mm, Merck) using a 1 : 1 benzene—AcOEt mixture as the eluent and then a benzene—Pr^{i}OH mixture for the gradient elution to 50% of Pr^{i}OH. The fraction containing the target product was concentrated *in vacuo*, and the red-orange residue (0.26 g) was

Table 3. Crystallographic characteristics and the X-ray diffraction data collection and refinement statistics for compounds **6a,b**

Parameter	**6a**	**6b**
Molecular formula	$C_{15}H_{16}N_2$	$C_{25}H_{34}N_2O_5$
Molecular weight	224.30	442.54
Crystal system	Monoclinic	
Cpace group	$P2_1/c$	Pc
a/Å	5.9823(4)	16.7934(15)
b/Å	7.5827(5)	8.3363(7)
c/Å	26.3656(19)	8.6303(8)
α/deg	90	90
β/deg	93.936(4)	103.886(4)
γ/deg	90	90
V/Å^3	1193.17(14)	1172.89(18)
Z	4	2
d_{calc}/g cm^{-3}	1.249	1.253
F(000)	480	476
μ(Mo-Kα)/mm^{-1}	0.074	0.087
Crystal dimensions/mm	0.22×0.16×0.08	0.38×0.30×0.06
θ Scan mode/range, deg	ω/1.55—29.00	ω/2.44—29.00
Ranges of indices of measured reflections	$-7 \le h \le 8$, $-9 \le k \le 10$, $-33 \le l \le 35$	$-22 \le h \le 22$, $-11 \le k \le 10$, $-11 \le l \le 11$
Number of measured reflections	7214	8000
Number of independent reflections	3049 (R_{int} = 0.0759)	5567 (R_{int} = 0.1195)
Number of reflections with $I > 2\sigma(I)$	1546	2695
Number of refined parameters	218	398
R factors based on reflections with $I > 2\sigma(I)$ based on all reflections	R_1 = 0.0866, wR_2 = 0.1339 R_1 = 0.1811, wR_2 = 0.1565	R_1 = 0.0657, wR_2 = 0.1357 R_1 = 0.1566, wR_2 = 0.1617
Goodness-of-fit on F^2	1.023	0.857
Residual electron density (min/max)/e Å^{-3}	−0.200/0.259	−0.236/0.261

extracted with boiling hexane (4×30 mL). The extracts were cooled to −10 °C, and the precipitate that formed was separated by decantation and dried in air. Compound **6b** was obtained in a yield of 0.16 g (27%) as pale-yellow crystals, m.p. 93—94 °C (from hexane).

X-ray diffraction study. Single crystals of all compounds were grown by the slow evaporation of their solutions in a 1 : 1 CH_2Cl_2—hexane mixture in the dark at room temperature. The single crystals were mounted on a Bruker SMART-CCD diffractometer under a cold nitrogen stream (T = 180(2) K for **1b** and 120.0(2) K for the other compounds). The unit cell parameters were measured and the X-ray diffraction data sets were collected using Mo-Kα radiation (λ = 0.71073 Å, graphite monochromator, ω-scan mode). The X-ray data were processed with the use of the SAINT program.[50] All structures were solved by direct methods and refined by the least-squares method with anisotropic displacement parameters for all nonhydrogen atoms. In the crystal structure of **1b**, the molecules are disordered over two sites; the occupancy ratio for two *s* conformers was 0.55 : 0.45. The hydrogen atoms were positioned geometrically and refined isotropically (for the structures of **1a**, **3**, **6a**, and **7**), using a riding model (for **1b**), or using a mixed scheme (isotropically and using a riding model; for **6b**).

The crystallographic characteristics and the X-ray diffraction data collection and refinement statistics are given in Tables 2 and 3. All calculations were carried out with the use of the SHELXTL-Plus program package.[51]

The atomic coordinates and other experimental data were deposited with the Cambridge Crystallographic Data Centre;* the CCDC numbers 714928 (**1a**), 714929 (**1b**), 714930 (**3**), 714931 (**6a**), 714932 (**6b**), and 714933 (**7**).

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References

1. L. G. Kuz´mina, A. I. Vedernikov, J. A. K. Howard, M. V. Alfimov, S. P. Gromov, *Rossiiskie Nanotekhnologii*, 2008, **3**, No. 7—8, 32 [*Nanotechnologies in Russia* (*Engl. Transl.*), 2008, **3**, No. 7—8].
2. J. L. R. Williams, S. K. Webster, J. A. Van Allan, *J. Org. Chem.*, 1961, **26**, 4893.
3. G. M. Schmidt, *J. Pure Appl. Chem.*, 1971, **27**, 647.
4. V. Ramamurthy, K. Venkatesan, *Chem. Rev.*, 1987, **87**, 433.
5. J. H. Kim, Y. Tani, V. Matsuoka, K. Fukunishi, *Dyes Pigments*, 1999, **43**, 7.
6. K. S. S. P. Rao, S. M. Hubig, J. N. Moorthy, J. K. Kochi, *J. Org. Chem.*, 1999, **64**, 8098.
7. W.-Q. Zhang, J.-P. Zhuang, C.-B. Li, H. Sun, X.-N. Yuan, *Chin. J. Chem.*, 2001, **19**, 695.
8. X.-H. Li, L.-Z. Wu, L.-P. Zhang, C.-H. Tung, *Org. Lett.*, 2002, **4**, 1175.
9. X. Yu, D. Scheller, O. Rademacher, T. Wolff, *J. Org. Chem.*, 2003, **68**, 7386.
10. V. Darcos, K. Griffith, X. Sallenave, J.-P. Desvergne, C. Guyard-Duhayon, B. Hasenknopf, D. M. Bassani, *Photochem. Photobiol. Sci.*, 2003, **2**, 1152.
11. D. G. Amirsakis, A. M. Elizarov, M. A. Garcia-Garibay, P. T. Glink, J. F. Stoddart, A. J. P. White, D. J. Williams, *Angew. Chem., Int. Ed.*, 2003, **42**, 1126.
12. I. Abdelmoty, V. Buchholz, L. Di, C. Guo, K. Kowitz, V. Enkelmann, G. Wegner, B. M. Foxman, *Cryst. Growth Design*, 2005, **5**, 2210.
13. H. Maeda, K. Nishimura, K. Mizuno, M. Yamaji, J. Oshima, S. Tobita, *J. Org. Chem.*, 2005, **70**, 9693.
14. F. H. Allen, M. F. Mahon, P. R. Raithby, G. P. Shields, H. A. Sparkes, *New J. Chem.*, 2005, **29**, 182.
15. M. Nagarathinam, J. J. Vittal, *Angew. Chem., Int. Ed.*, 2006, **45**, 4337.
16. K. Honda, F. Nakanishi, N. Feeder, *J. Am. Chem. Soc.*, 1999, **121**, 8246.
17. S. Ohba, Y. Ito, *Acta Crystallogr., Sect. B*, 2003, **59**, 149.
18. I. Turowska-Tyrk, *J. Phys. Org. Chem.*, 2004, **17**, 837.
19. Y.-F. Han, Y.-J. Lin, W.-G. Jia, G.-L. Wang, G.-X. Jin, *Chem. Commun.*, 2008, 1807.
20. L. R. MacGillivray, G. S. Papaefstathiou, T. Friscic, T. D. Hamilton, D.-K. Busar, Q. Chu, D. B. Varshney, I. G. Georgiev, *Acc. Chem. Res.*, 2008, **41**, 280.
21. L. R. MacGillivray, *J. Org. Chem.*, 2008, **73**, 3311.
22. S. P. Gromov, M. V. Alfimov, *Izv. Akad. Nauk, Ser. Khim.*, 1997, 641 [*Russ. Chem. Bull. (Engl. Transl.)*, 1997, **46**, 611].
23. A. I. Vedernikov, N. A. Lobova, E. N. Ushakov, M. V. Alfimov, S. P. Gromov, *Mendeleev Commun.*, 2005, **15**, 173.
24. S. P. Gromov, *Rossiiskie Nanotekhnologii*, 2006, **1**, No. 1—2, 29 [*Nanotechnologies in Russia* (*Engl. Transl.*), 2006, **1**, No. 1—2].
25. S. P. Gromov, A. I. Vedernikov, N. A. Lobova, L. G. Kuz´mina, S. N. Dmitrieva, O. V. Tikhonova, M. V. Alfimov, Pat. RF 2278134; *Byul. izobret.* [*Inventor Bull.*], 2006, No. 17 (in Russian).
26. A. I. Vedernikov, S. P. Gromov, N. A. Lobova, L. G. Kuz´mina, Yu. A. Strelenko, J. A. K. Howard, M. V. Alfimov, *Izv. Akad. Nauk, Ser. Khim.*, 2005, 1896 [*Russ. Chem. Bull., Int. Ed.*, 2005, **54**, 1954].
27. L. G. Kuz´mina, A. I. Vedernikov, N. A. Lobova, A. V. Churakov, J. A. K. Howard, M. V. Alfimov, S. P. Gromov, *New J. Chem.*, 2007, **31**, 980.
28. A. I. Vedernikov, L. G. Kuz´mina, S. K. Sazonov, N. A. Lobova, P. S. Loginov, A. V. Churakov, Yu. A. Strelenko, J. A. K. Howard, M. V. Alfimov, S. P. Gromov, *Izv. Akad. Nauk, Ser. Khim.*, 2007, 1797 [*Russ. Chem. Bull., Int. Ed.*, 2007, **56**, 1860].
29. L. G. Kuz´mina, A. I. Vedernikov, S. K. Sazonov, N. A. Lobova, P. S. Loginov, J. A. K. Howard, M. V. Alfimov, S. P. Gromov, *Kristallografiya*, 2008, **53**, 460 [*Crystallogr. Repts (Engl. Transl.)*, 2008, **53**, 428].
30. S. P. Gromov, A. I. Vedernikov, Yu. V. Fedorov, O. A. Fedorova, E. N. Andryukhina, N. E. Shepel´, Yu. A. Strelenko, D. Johnels, U. Edlund, J. Saltiel, M. V. Alfimov, *Izv. Akad. Nauk, Ser. Khim.*, 2005, 1524 [*Russ. Chem. Bull., Int. Ed.*, 2005, **54**, 1569].
31. F. Li, J. Zhuang, G. Jiang, H. Tang, A. Xia, L. Jiang, Y. Song, Y. Li, D. Zhu, *Chem. Mater.*, 2008, **20**, 1194.

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32. J. A. Muir, O. Cox, L. A. Bernard, M. M. Muir, *J. Crystallogr. Spectrosc. Res.*, 1992, **22**, 695.
33. J. A. Yang, P. Kumar, J. R. Dimmock, J. W. Quail, *Acta Crystallogr., Sect. C*, 1995, **51**, 2700.
34. O. Cox, M. Cordero, S. Pineiro, S. P. D. Huang, *Acta Crystallogr., Sect. C*, 1997, **53**, 310.
35. E. Cariati, D. Roberto, R. Ugo, V. I. Srdanov, S. Galli, P. Macchi, A. Sironi, *New J. Chem.*, 2002, **26**, 13.
36. L. G. Kuz´mina, O. A. Fedorova, E. N. Andryukhina, M. M. Mashura, S. P. Gromov, M. V. Alfimov, *Kristallografiya*, 2006, **51**, 467 [*Crystallogr. Repts (Engl. Transl.)*, 2006, **51**, 434].
37. E. N. Andryukhina, M. M. Mashura, O. A. Fedorova, L. G. Kuz´mina, J. A. K. Howard, S. P. Gromov, *Izv. Akad. Nauk, Ser. Khim.*, 2005, 1650 [*Russ. Chem. Bull., Int. Ed.*, 2005, **54**, 1700].
38. Yu. V. Fedorov, O. A. Fedorova, E. N. Andryukhina, S. P. Gromov, M. V. Alfimov, L. G. Kuz´mina, A. V. Churakov, J. A. K. Howard, J.-J. Aaron, *New J. Chem.*, 2003, **27**, 280.
39. Yu. V. Fedorov, O. A. Fedorova, N. E. Shepel´, S. P. Gromov, M. V. Alfimov, L. G. Kuz´mina, J. A. K. Howard, J. Saltiel, *Izv. Akad. Nauk, Ser. Khim.*, 2005, 2056 [*Russ. Chem. Bull., Int. Ed.*, 2005, **54**, 2119].
40. M. El Azami, N. Bitit, A. Kerbal, S. Lahlou, S. A. Lyazidi, J.-P. Desvergne, H. Bouas-Laurent, D. Bassani, *Heterocycles*, 2001, **55**, 2325.
41. O. A. Fedorova, E. N. Andryukhina, A. V. Lindeman, S. S. Basok, T. Yu. Bogashchenko, S. P. Gromov, *Izv. Akad. Nauk, Ser. Khim.*, 2002, 302 [*Russ. Chem. Bull., Int. Ed.*, 2002, **51**, 319].
42. S. P. Gromov, E. N. Ushakov, O. A. Fedorova, I. I. Baskin, A. V. Buevich, E. N. Andryukhina, M. V. Alfimov, D. Johnels, U. G. Edlund, J. K. Whitesell, M. A. Fox, *J. Org. Chem.*, 2003, **68**, 6115.
43. J. L. R. Williams, R. E. Adel, J. M. Carlson, G. A. Reynolds, D. G. Borden, J. A. Ford, *J. Org. Chem.*, 1963, **28**, 387.
44. A. K. Sheinkman, L. G. Piotrkovskaya, *Metody polucheniya khimicheskikh reaktivov i preparatov* [*Methods of Synthesis of Chemical Reagents and Preparations*], IREA, Moscow, 1965, Vol. **13**, 29 (in Russian).
45. I. I. Baskin, K. Ya. Burshtein, A. A. Bagatur´yants, S. P. Gromov, M. V. Alfimov, *J. Mol. Struct.*, 1992, **274**, 93.
46. J. Harada, K. Ogawa, *J. Am. Chem. Soc.*, 2004, **126**, 3539.
47. S. K. Kearsley, *Studies in Organic Chemistry. 32. Organic Solid State Chemistry*, Ed. G. R. Desiraju, Elsevier, Amsterdam, 1987, 69.
48. K. Müller-Dethlefs, P. Hobza, *Chem Rev.*, 2000, **100**, 143.
49. J. P. Dix, F. Vögtle, *Chem. Ber.*, 1980, **113**, 457.
50. *SAINT, Version 6.02A*, Bruker AXS Inc., Madison, Wisconsin (USA), 2001.
51. *SHELXTL-Plus, Version 5.10*, Bruker AXS Inc., Madison, Wisconsin (USA), 1997.

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