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MOLECULAR AND CRYSTAL STRUCTURES OF 4-CYANO-3(2*H*)-FURANONES AND STRUCTURAL EFFECTS IN ^{1}H NMR SPECTRA*

A. V. Afonin[1], A. V. Vashchenko[1], O. G. Volostnykh[1], A. V. Stepanov[1], and A. G. Mal'kina[1]**

Features of the molecular structure in crystals of a series of functionalized 4-cyano-3(2*H*)-furanones with a spiro-cyclohexane substituent or two methyl groups at position 2 of the furanone ring and also an aryl or heteroaryl substituent at position 5 are analyzed in comparison with the literature data. Effects appearing in ^{1}H NMR spectra, which are caused by the features of the molecular structures of these compounds are interpreted. Their crystal structure is considered and intermolecular interactions responsible for the supramolecular architecture of the crystals formed are revealed.

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INTRODUCTION

Functionalized 3(2*H*)-furanones have an exclusively broad spectrum of application in medicine and pharmacology. Thus, the furanone moiety is contained in the composition of many drugs such as bullatenone [1], geiparvarine [2], eremantholide A [3], jatrophone [4], pseurotin A [5], and (–)-englerin A [6]. 3(2*H*)-Furanone derivatives are considered to be promising precursors in the production of pharmaceuticals exhibiting antitumor [7-10], antiulcer [11], and antiallergic [12] activities, and also selective inhibition of the activity of cyclooxygenase-2 [13-15], monoamine oxidase-B [10, 15-17], and human tyrosinase [18]. Moreover, a series of functionally substituted 3(2*H*)-furanones are applied as nonsteroid anti-inflammatory [14, 19], analgesic [12, 20], and anticancer [8-10, 15, 21] drugs used in the treatment of metabolic disorders [20]. Recently [22-26], based on the reaction of tertiary cyanopropargyl alcohols with carboxylic acids in the presence of triethylamine a series of 4-cyano-3(2*H*)-furanones functionalized by pharmacophore substituents were synthesized. Among them are: 4-oxo-2-(thiophen-2-yl)-1-oxaspiro[4.5]dec-2-ene-3-carbonitrile (**1**), 2-(benzo[*b*]thiophen-2-yl)-4-oxo-1-oxaspiro[4.5]dec-2-ene-3-carbonitrile (**2**) [22], 2-(naphthalen-1-yl)-4-oxo-1-oxaspiro[4.5]dec-2-ene-3-carbonitrile (**3**) [23] and 2-[1-vinyl-5-(4-chlorophenyl)-1*H*-pyrrol-2-yl)-4-oxo-1-oxaspiro[4.5]dec-2-ene-3-carbonitrile (**4**) [24], 2-(1-vinyl-1*H*-pyrrol-2-yl)-5,5-dimethyl-4-oxo-4,5-dihydrofuran-3-carbonitrile (**5**) and 5,5-dimethyl-2-(1-vinyl-5-phenyl-4-ethyl-1*H*-pyrrol-2-yl)-4-oxo-4,5-dihydrofuran-3-carbonitrile (**6**) [24], and also 5,5-dimethyl-4-oxo-2-phenyl-4,5- dihydrofuran 3-carbonitrile

[1]Favosky Institute of Chemistry, Siberian Branch, Russian Academy of Sciences, Irkutsk, Russia; **sasha@irioch.irk.ru. Original article submitted October 20, 2018; revised November 14, 2018; accepted November 14, 2018.

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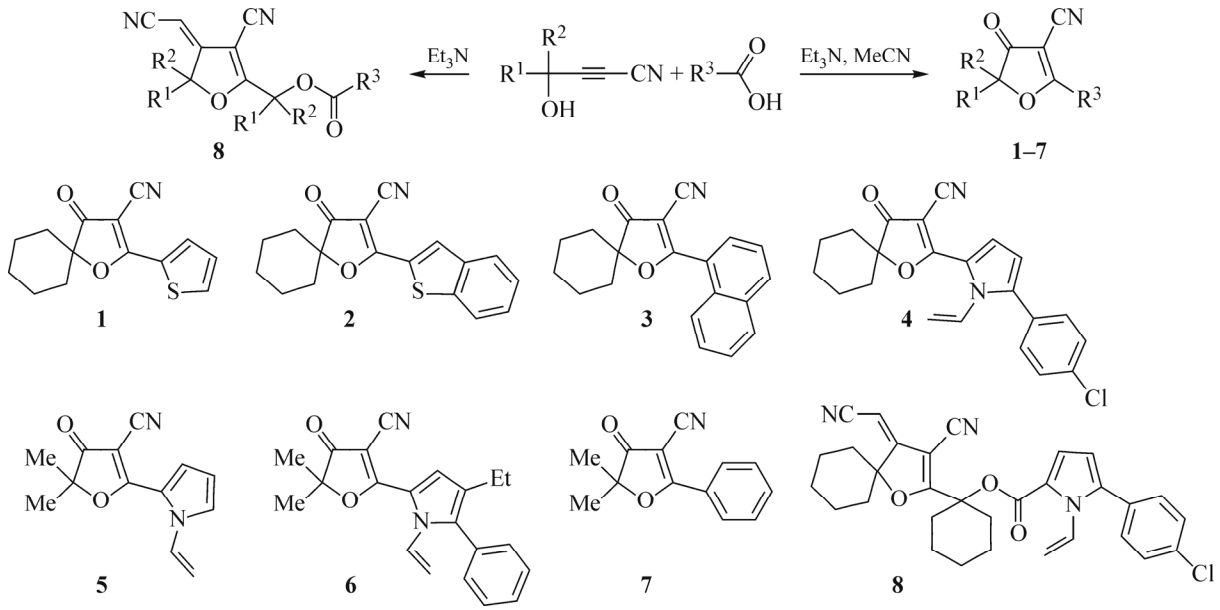


Scheme 1. Synthesis of 4-cyano-3(2*H*)-furanones **1**-**7** and 3-cyanomethylene-4,5-dihydrofuran **8**.

(**7**) [25], (*Z*)-1-(3-cyano-4-(cyanomethylene)-1-oxaspiro[4.5]dec-2-ene-2-yl)cyclohexyl 1-vinyl-5-(4-chlorophenyl)-1*H*-pyrrole-2-carboxylate (**8**) [26] (Scheme 1).

The structure of 4-cyano-3(2*H*)-furanones **4**-**7** and 3-cyanomethylene-4,5-dihydrofuran **8** is proved by X-ray crystallography (CCDC codes 1449929, 1411948, 1411949, 772519, and 992073 respectively) [24-26], however, the molecular and crystal structures of these compounds has not been discussed. The X-ray crystallographic data for **1**-**3** molecules is presented for the first time. In order to generalize the X-ray crystallographic data for known 4-cyano-3(2*H*)-furanones whose single crystals were obtained, the molecular and crystal structures of compounds **1**-**7**, and also compound **8** with a heterocyclic fragment having a similar structure, were studied in detail in this work.

EXPERIMENTAL

The synthesis of compounds **1**-**8** was described in [22-26] (see INTRODUCTION). The crystals of compounds **1**, **2**, and **3**, representing yellow plates, colorless and yellow prisms, respectively, were obtained by slow evaporation of solutions of the compounds in acetone.

The X-ray diffraction experiment was performed on a single crystal Bruker D8 Venture diffractometer with a Photon 100 detector using ω–φ scanning. The main crystallographic characteristics and parameters of the experiment are listed in Table 1. The reflection intensity was integrated using the Bruker SAINT program package. The X-ray absorption correction was applied from the analysis of equivalent reflection intensities. After their averaging only independent reflections were used. The model was searched for by direct methods using the SHELXS program [27]. As a result, the coordinates of all non-hydrogen atoms were found. Positions of hydrogen atoms were determined in the riding model. The obtained structure was refined by the least squares technique using the SHELXL program [27].

Full information on the crystal structure of compounds **1**, **2**, and **3** has been deposited with the Cambridge Crystallography Data Center (CCDC Nos. 1868513, 1868515, and 1868514 respectively).

^{1}H NMR spectra of compounds **1**, **4**, and **5** were measured on a Bruker DPX-400 spectrometer (400.1 MHz) in a $CDCl_3$ solution with TMS as the internal standard.

The main results were obtained using the facilities of the Baikal Analytical Center, Siberian Branch, Russian Academy of Sciences.

TABLE 1. Crystallographic Data and Details of the X-Ray Diffraction Experiment

Compound	**1**	**2**	**3**
Formula	$C_{14}H_{13}NO_2S$	$C_{18}H_{15}NO_2S$	$C_{20}H_{17}NO_2$
M, g/mol	259.31	309.37	303.35
Crystal system	Triclinic	Orthorhombic	Monoclinic
Space group	*P*-1	*Pcnb*	$P2_1/n$
a, Å	7.0895(3)	7.0760(3)	11.829(9)
b, Å	11.1436(4)	19.4721(8)	9.589(7)
c, Å	16.0985(6)	22.5722(10)	14.318(10)
α, deg	80.9020(10)	–	–
β, deg	87.2040(10)	–	99.52(3)
γ, deg	83.2170(10)	–	–
V, Å^3	1246.44(8)	3110.1(2)	1602(2)
Z	4	8	4
ρ_{calc}, g/cm^3	1.382	1.321	1.258
Absorption coefficient, mm^{-1}	0.25	0.21	0.08
Wavelength λ, Å	MoK_α, 0.71073	MoK_α, 0.71073	MoK_α, 0.71073
Temperature, K	273.0(2)	273.0(2)	293.0(2)
2θ, deg	5.4-46.2	5.2-48.6	5.0-46.2
Crystal dimensions, mm	0.77×0.73×0.37	0.83×0.54×0.24	0.90×0.44×0.38
Crystal description	Yellow plates	Yellow prisms	Colorless prisms
F(000)	544	1296	640
Total number of reflections	33384	57021	34388
Number of indep. reflections	5707	3645	3414
Number of parameters	320	199	208
R_1 / wR (F^2)	0.0450/0.1178	0.0584/0.1807	0.0456/0.1537
R_{int}	0.034	0.061	0.033
GOOF / F^2	1.03	1.03	1.16
Max and min el. density, e/Å^3	1.87 and –0.73	0.99 and –0.44	0.17 and –0.23
Weight scheme, $P = (F_0^2 + 2F_c^2)/3$	$w = 1/[\sigma^2(F_0^2) + (0.0539P)^2 + + 1.665P]$	$w = 1/[\sigma^2(F_0^2) + (0.095P)^2 + + 1.539P]$	$w = 1/[\sigma^2(F_0^2) + + (0.1P)^2]$
CCDC code	1868513	1868515	1868514

RESULTS AND DISCUSSION

Molecular structures of compounds **1**-**8** and atomic numbering are depicted in Fig. 1*a*–*h*. The crystal structures of **1** and **7** contain two crystallographically independent molecules in the unit cell, which differ in the values of dihedral angles between the heterocyclic (aryl) fragments.

In the molecules of **1**-**8** the 4-cyano-3(2*H*)-furan (or 4-cyano[3-cyanomethylene]-2,3-dihydrofuran) component is almost planar. The maximum mean square deviation of atoms from the plane formed by atoms of this part of the **1**-**8** molecules marks the position in the molecule of **8** (0.028 Å). Heterocyclic fragments in the molecules of **1**, **2**, **4**-**6** have the *syn*(O,S)-arrangement. In the molecules of **1**-**4**, and **8** the 2-spiro-cyclohexane moiety is in the canonical *chair* conformation. In the same molecules the plane of the heterocyclic component and the conventional plane of spiro-cyclohexane in the *chair* conformation (i.e. the plane formed by four atoms of this fragment) are nearly orthogonal. The respective dihedral angle is within 84.4-90°, with the conventional plane of the *chair*-like cyclohexane fragment being always oriented to the endocyclic oxygen atom of the furanone ring.

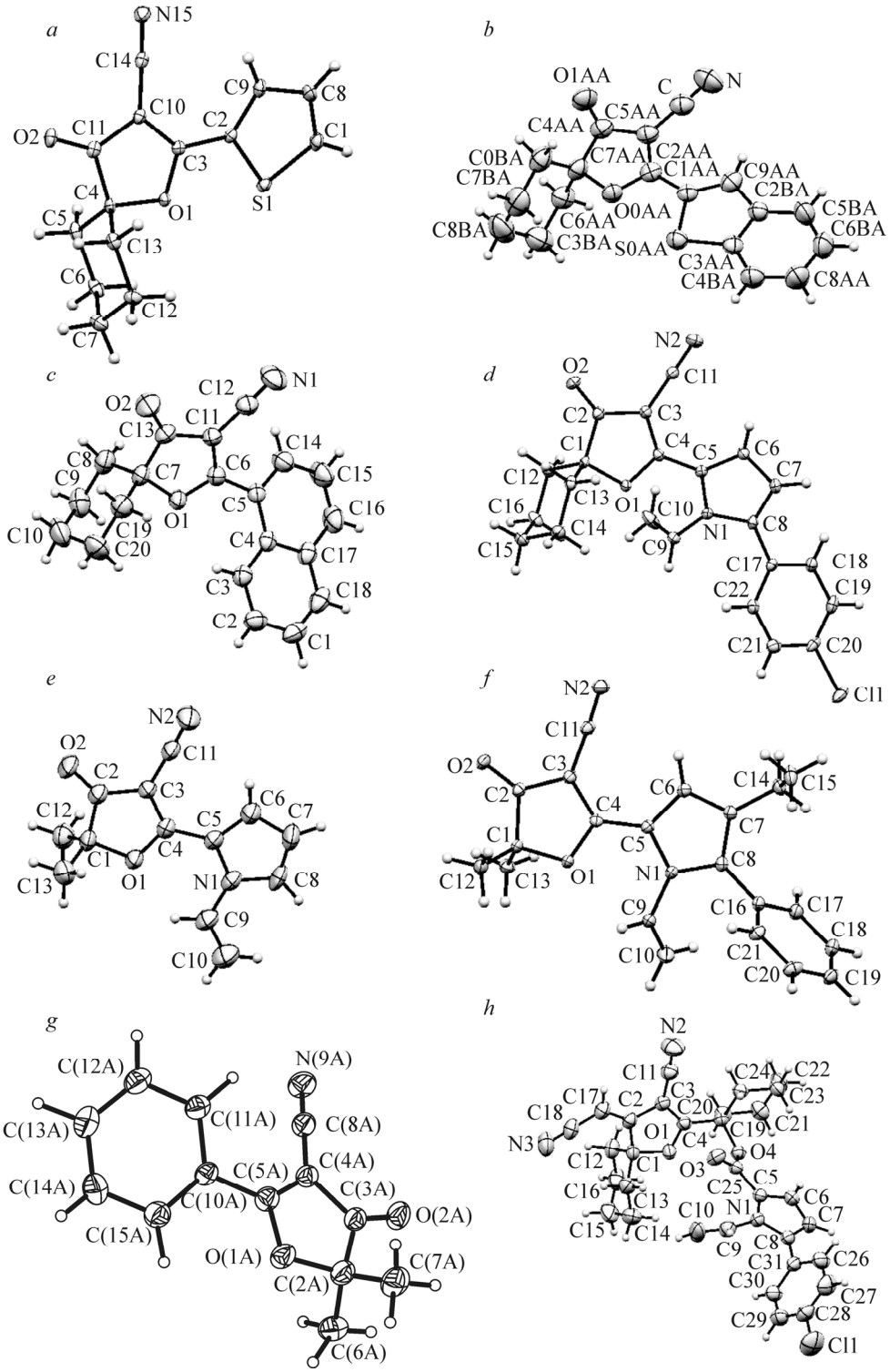
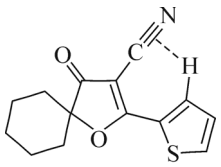


Fig. 1. ORTEP diagram of the molecular structure of 4-cyano-3(2*H*)-furanones **1** (*a*), **2** (*b*), **3** (*c*), **4** (*d*), **5** (*e*), **6** (*f*), **7** (*g*) and 3-cyanomethylene-4,5-dihydrofurane **8** (*h*) (50% probability thermal ellipsoids). ORTEP diagram of the molecular structure of **7** is taken from [25].

Methyl groups at position 2 of the furanone ring are non-equivalent in the molecules of **6** and **7**; differences in the C(C≡N)–C(O)–C(2)–CH_3 dihedral angles are 8.0° and 4.7° (7.7°)* respectively. At the same time, 2-methyl groups in the molecule of **5** are almost equivalent; the difference in the dihedral angles mentioned decreases to 0.5°.

In the crystal, the molecule of **5** is practically planar (except 2-methyl groups). The dihedral angles between the planes of the pyrrole and furanone rings as well as the pyrrole ring and the vinyl group are within 0.1-0.2°, which is facilitated by the *anti*(O)-orientation of the vinyl group relative to the furanone ring. The other molecules studied are more or less non-planar. Dihedral angles between the mean square planes of the furanone and thienyl (benzothienyl or phenyl) rings in the molecules of **1**, **2**, and **7** are 11.6° (5.7°)*, 7.7°, and 28.2° (26.0°)* respectively. In the molecule of **3** the dihedral angles between the mean square planes of the furanone ring and the naphthyl moiety increases to 40.3°, the latter having the *anti*(O)-orientation relative to the furanone ring.

It should be noted that there is a short contact between the H(9) and H(22) hydrogen atoms of the thiophene ring and centroids of the C≡N bond, Cg[C(14)N(15)] and Cg[C(27)N(1)], the 4-cyano-3(2*H*)-furanone component in the molecule of **1** [$r_{Cg\cdots H}$ = 2.679 Å (2.824 Å)*] (Scheme 2).



Scheme 2. Short contact of the hydrogen atom of the thiophene ring and the centroid of the C≡N bond in the molecule of **1**.

The cyano group is known to have substantial magnetic anisotropy manifested in the ^{1}H NMR spectra. Hydrogen atoms on the axis perpendicular to the –C≡N axis experience deshielding and their signal shifts to the lower field whereas the hydrogen atoms located along the –C≡N axis are shielded and their signal shifts to the strong field [28, 29]. A short distance Cg(C≡N)···H(9) [H(22)] explains the anomalous downfield shift of the signal from this hydrogen atom in the ^{1}H NMR spectrum of the **1** molecule relative to the signal from the neighboring hydrogen atom of the thiophene ring H(8)[H(23)] (8.29 ppm and 7.32 ppm respectively, [22]**) (Fig. 2*a*). In the absence of the anisotropy effect of the cyano group the difference between the chemical shifts of these hydrogen atoms of the thienyl ring is less than 0.1 ppm [30, 31]. A similar downfield shift of the signal from this hydrogen atom (~1 ppm) is observed for the entire series of synthesized 4-cyano-5-thienyl-3(2*H*)-furanones [22], indicating the *syn*(O,S)-orientation of heterocycles in the entire series of these compounds.

Since the naphthyl moiety has the *anti*(O)-orientation relative to the furanone ring in the molecule of **3**, there is a short contact between the H(4) hydrogen atom and the centroid of the C≡N bond, Cg[C(12)N(1)] ($r_{Cg\cdots H}$ = 2.792 Å). This enables the interpretation of a significant downfield shift of the H(4) signal in the ^{1}H NMR spectrum of the **3** molecule relative to the signal from the neighboring H(5) hydrogen atom of the naphthyl moiety (8.10 ppm and 7.63 ppm respectively, [23]**) as the anisotropy effect of the cyano group. Since in the **7** molecule there is a similar short contact between H(11A) and H(11B) hydrogen atoms of the aryl ring and centroids of the C≡N bond, Cg[C(8A)N(9A)] and Cg[C(8B)N(9B)],

* Value in parentheses corresponds to the second crystallographically independent molecule of **1** or **7**.

** in the part of [22] devoted to the spectra, the H(9)[H(22)] and H(8)[H(23)] atoms of the **1** molecule are designated as H-3′ and H-4′ respectively; two crystallographically independent molecules of **1** are identical in the solution; in [23] the H(4) and H(5) atoms of the **3** molecule are designated as H-2′ and H-3′; in [24] the H(6) and H(7) atoms of **4** and **5** molecules are designated as H-3′ and H-4′ respectively; in [25] the H(11A)[H(11B)] and H(12A)[H(12B)] atoms are designated as H_o and H_m respectively; two crystallographically independent molecules of **7** are identical in the solution.

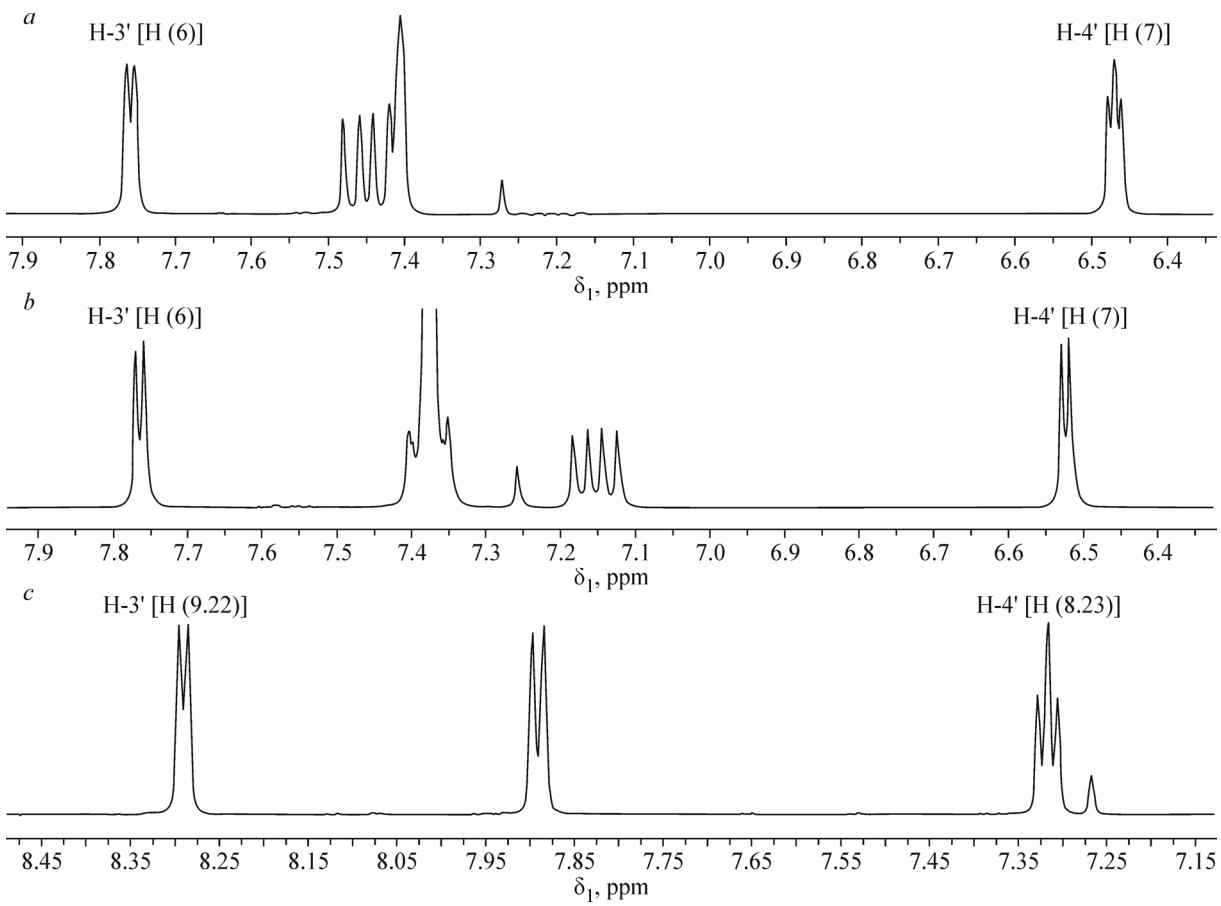


Fig. 2. Fragment of the ^{1}H NMR spectrum of molecules of **1** (*a*), **4** (*b*), **5** (*c*).

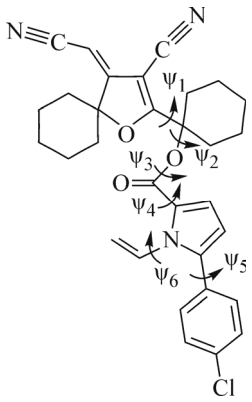
[$r_{Cg\cdots H}$ = 2.673 Å (2.701 Å)*]. Their signal in the ^{1}H NMR spectrum is also shifted to the lower field relative the signal from the neighboring H(12A) and H(12B) atoms (8.19 ppm and 7.69 ppm respectively [25]**).

In the molecules of **4** and **6** the dihedral angles between the mean square planes of the furanone and pyrrole rings, the pyrrole and aryl rings, and also the C(5)N(1)C(9)C(10) and C(8)C(7)C(14)C(15) torsion angles between the planes of the pyrrole ring and the vinyl group are 22.9° and 6.0°, 41.2° and 64.7°, 47.3° and 50.4° respectively. The vinyl group is in the *syn*(O)-position in the **4** molecule, but in the **6** molecule it has the *anti*(O)-orientation relative to the furanone ring (Fig. 1*d* and *f* respectively). The ethyl group in the **6** molecule is orthogonally oriented relative to the pyrrole ring (torsion angle C(8)C(7)C(14)C(15) = 86.4°, Fig. 1*f*).

Since in the molecules of **4** and **5** the pyrrole and furanone rings take the *syn*(O,N)-orientation, there is again a short contact between the H(6) hydrogen atom of the pyrrole ring and the centroid of the C≡N bond, Cg[C(11)N(2)], 4-cyano-3(2*H*)-furanone component ($r_{Cg\cdots H}$ = 2.836 Å and 2.588 Å respectively). Due to such a short contact an anomalous downfield shift of the H(6) hydrogen signal is also observed in the ^{1}H NMR spectra of the molecules of **4** and **5** relative to the signal from the neighboring H(7) hydrogen atom of the pyrrole ring (7.77 ppm, 7.77 ppm and 6.47 ppm, 6.52 ppm respectively, [24]**) (Fig. 2*b*, *c*). In the absence of the anisotropy effect of the cyano group the difference between the chemical shifts of these hydrogen atoms of the pyrrole ring are within 0.2-0.3 ppm [30, 31]. The downfield shift of this hydrogen atom signal is retained for the entire series of synthesized 1-vinyl-pyrrolyl- and 1*H*-pyrrolyl-4-cyano-3(2*H*)-furanones [24], indicating the *syn*(O,N)-orientation of heterocycles in the entire series of these compounds.

The molecule of **8** has the largest number of degrees of freedom associated with internal rotation (Scheme 3). First of all, it should be noted that this compound, according to the X-ray crystallographic data, is the *Z*-isomer. The cyclohexane ring in the side substituent, as well as the spiro-ring, has the *chair* conformation. Its spatial arrangement corresponds to the

syn(O,O)-arrangement of two ether oxygen atoms (torsion angle ψ_1 [O(1)C(4)C(19)O(4)] = 47.8°) and the *anti*-orientation of the carbonyl group (torsion angle ψ_2 [C(4)C(19)O(4)C(25)] = 53.0°).



Scheme 3. Structure of compound **8**.

The carbonyl group in turn has the *syn*(O,O)-orientation relative to the furan and pyrrole rings while the vinyl group has the *syn*(O)-orientation relative to the carbonyl one (torsion angles ψ_3 [C(19)O(4)C(25)O(3)], ψ_4 [O(3)C(25)C(5)N(1)], and ψ_6 [C(5)N(1)C(9)C(10)] are 10.4°, 17.0°, and 39.6° respectively). Finally, the dihedral angle ψ_5 between the mean square planes of the pyrrole and phenyl rings is **8** is 58.6° (Scheme 3).

The published X-ray crystallographic data on 3(2*H*)-furanones with the spiro-cyclohexane substituent at the second position are scarce. Nonetheless, for 6-acetoxy-2-(trifluoromethyl)-1-oxaspiro(4.5)dec-2-en-4-one [32] and methyl-4-(2-methyl-4-oxo-1-oxaspiro[4.5]dec-2-en-3-yl)benzoate [33] it is found that the structure of the heterocyclic and spiro-cyclohexane components are similar to that of the entire series of compounds **1**-**4**, **8**: the heterocyclic moiety is planar, the cyclohexane substituent has the *chair* conformation, and the conventional plane of the *chair* is almost orthogonal to the heterocycle plane and oriented to the endocyclic oxygen atom.

The X-ray crystallography data on 3(2*H*)-furanones with two methyl groups as substituents at the second position are more numerous. In 4-(4′,5′-bis(methoxy)-2′-(phenylthio)phenyl)-2,2-dimethyl-2,3-dihydrofuran-3-one [34], 7-(3-(4,5-dihydro-5,5-dimethyl-4-oxo-2-furanyl)-but-2-enyl)-oxy-(2*H*-1-benzopyran-2-one) [35], 4-acetyl-5-methoxy-2,2-dimethylfuran-3(2*H*)-one and methyl-2-(4-bromophenyl)-5,5-dimethyl-4-oxo-4,5-dihydrofuran-3-carboxylate [36], 6-(6-(5,5-dimethyl-4-oxo-4,5-dihydrofuran-2-yl)-1,2-dihydroxy-2-methylheptyl)-4-methyl-5,6-dihydro-2*H*-pyran-2-one [37], 3,4-dimethyl-7-[(3-(5,5-dimethyl-4-oxo-4,5-dihydro-2-furanyl)-2-butenyl)oxy]-2*H*-chromen-2-one [16] and 4-[(3-(4,5-dihydro-5,5-dimethyl-4-oxo-2-furanyl)-butyl)oxy]-7*H*-furo(3,2-g)(1)bensopyran-7-one [38] the furanone ring is planar and methyl groups are more or less non-equivalent. The maximum difference in =C–C(O)–C(2)–CH_3 torsion angles is 8.9° [35], and the minimum one is only 0.3° [36], which is consistent with the obtained data for compounds **5**-**7** studied.

The crystal packing of the molecules of **1**-**8** is diverse, which is caused by distinctions in the spatial structure of 4-cyano-3(2*H*)-furanone derivatives. The supramolecular architecture of the crystals under study is governed by several types of intermolecular interactions: intermolecular hydrogen bonds (ordinary and bifurcated), C–H···π interactions, and π,π-stacking interactions. Colored figures of the crystal packings in **1**–**8** are presented as the Supplementary Material (Fig. 1*a*–*h*_SM) published in the electronic form at the site of the Journal of Structural Chemistry (http://jsc.niic.nsc.ru) and at the site of the Springer Publishing Company (https://link.springer.com/journal/10947).

In the crystal of **1**, chains are formed along the (*b*–*c*) vector and layers along the *bc* plane with a width equal to the *a* lattice parameter (Fig. 1*a*_SM). The layered structure of the crystal is provided by the π,π-stacking interaction between the thienyl rings of the face-to-face type with a displacement [39] of molecules from different layers. The distance between the

centroids of thienyl rings of the neighboring molecules is Cg[C(1)S(1)C(2)C(9)C(8)]···Cg[C(21)–C(24)S(2)] = 3.739 Å, which satisfies the criterion for the appearance of the π,π-stacking interaction (the distance between the centroids of the interacting fragments ≤3.8 Å [40]). The layers are linked by weak intermolecular hydrogen bonds C(5)–H(5B)···N(15), C(29)–H(29A)···N(1), and C(18)–H(18A)···O(4) (intermolecular distances $r_{N(O)\cdots H}$ = 2.668 Å, 2.614 Å, and 2.614 Å respectively), and also intermolecular bifurcated hydrogen bonds C(13)–H(13A)···O(2)···H(24)–C(24) ($r_{O\cdots H}$ = 2.455 Å and 2.612 Å) which form the ring motif $R_2^2(5)$, and S(2)···H(13A)···O(2) ($r_{S\cdots H}$ = 2.994 Å). The distance H···X (X = N, O, S, Cl), which must be less than the sum of their van der Waals radii [41, 42], was used as a criterion for the formation of the hydrogen bond (H···N ≤ 2.75 Å, H···O ≤ 2.72 Å, H···S ≤ 3.00 Å, H···Cl ≤ 2.95 Å [43]).

The crystal structure of compound **2** is similar to that of **1** molecules (Fig. 1*b*_SM). In this case, layers are formed along the *c* and *b* axes with a layer width of 1/2*a*. This is promoted by the π,π-stacking interaction between the thienyl rings of the benzothienyl moieties of molecules from different layers. The distance between the respective centroids is Cg[C(1AA)C(9AA)C(2BA)C(3AA)S(0AA)]···Cg[C(1AA)C(9AA)C(2BA)C(3AA)S(0AA)] = 3.554 Å. The layers are linked by the intermolecular bifurcated hydrogen bond C(4BA)–H(4BA)···O(1AA)···H(6AB)–C(6AA) ($r_{O\cdots H}$ = 2.502 Å and 2.535 Å), forming the ring motif $R_2^2(10)$.

The crystal of **3** consists of zigzag molecular chains along the *b* axis due to which a parquet motif is formed in the plane parallel to crystallographic *b* and *c* axis (Fig. 1*c*_SM) [39]. This motif is provided by C–H···π intermolecular interactions between the phenyl rings of the edge-to-face type [44] C(15)–H(5)···Cg[C(1)–C(4)C(17)C(18)] ($r_{Cg\cdots C}$ = 3.739 Å, $r_{Cg\cdots H}$ = 2.945 Å) and C(16)–H(9)···Cg[C(4)C(5)C(14)–C(17)] ($r_{Cg\cdots C}$ = 4.179 Å, $r_{Cg\cdots H}$ = 3.429 Å), and also the C–H···π hydrogen bond between the α-C–H group of the cyclohexane moiety and the π system of the phenyl ring C(19)–H(10)···Cg[C(1)–C(4)C(17)C(18)] ($r_{Cg\cdots C}$ = 4.305 Å, $r_{Cg\cdots H}$ = 3.348 Å). The intermolecular distance between the carbon atom of the respective C–H bond and the centroid of the π-acceptor fragment was used as a criterion for the formation of the C–H···π hydrogen bond ($r_{Cg\cdots C}$ ≤ 4.5 Å [45, 46]). Moreover, the intermolecular C(18)–H(6)···N(1) hydrogen bond is found in this crystal ($r_{N\cdots H}$ = 2.741 Å).

The crystal of **4** has a layered structure along the crystallographic *c* axis with a layer width equal to the *a* cell parameter (Fig. 1*d*_SM). In this case, this structure is made by intermolecular hydrogen bonds C(12)–H(12A)···Cl(1) and C(10)–H(10B)···O(2) ($r_{Cl(O)\cdots H}$ = 2.922 Å and 2.598 Å respectively), the intermolecular bifurcated hydrogen bond C(9)–H(9)···N(2)···H(22)–C(22) ($r_{N\cdots H}$ = 2.605 Å and 2.691 Å), forming the ring motif $R_2^1(8)$, and also the intermolecular hydrogen bond C–H···π between the α-C–H group of the cyclohexane moiety and the π system of the phenyl ring C(13)–H(13B)···Cg[C(17)–C(22) ($r_{Cg\cdots C}$ = 4.367 Å, $r_{Cg\cdots H}$ = 3.493 Å).

In the crystal of **5** infinite chains are formed along the crystallographic *b* axis due to the formation of intermolecular hydrogen bonds C(8)–H(8)···O(2) ($r_{O\cdots H}$ = 2.334 Å), while the layers with a width equal to the *a* cell parameter are formed along the crystallographic *b* and *c* axes due to the π,π-stacking interaction between the pyrrole ligands (distance Cg[N(1)C(5)–C(8)]···Cg[N(1)C(5)–C(8)] = 3.945 Å) (Fig. 1*e*_SM). Similar infinite ribbons along the crystallographic *b* axis are found in the crystal of **6** whereas intermolecular bifurcated hydrogen bonds C(17)–H(17)···N(2)···H(18)–C(18) (ring motif $R_2^2(20)$, $r_{N\cdots H}$ = 2.719 Å and 2.709 Å) and C(10)–H(10A)···O(2)···H(15)–C(15B) ($r_{O\cdots H}$ = 2.578 Å and 2.633 Å) facilitate the formation of a molecular layer with a width equal to the *a* cell parameter along the *bc* plane (Fig. 1*f*_SM).

In the crystal of **7** it is possible to distinguish layers oriented along the *c* axis with a layer width of 1.2*a*. In the *ac* plane of this crystal the parquet motif is traced (Fig. 1*g*_SM) [39], which is stabilized by numerous intermolecular interactions: bifurcated hydrogen bond C(7B)–H(7B)···N(9A)···H(13A)–C(13A) ($r_{O\cdots H}$ = 2.719 Å and 2.648 Å), trifurcated hydrogen bond C(6B)–H(6B)···O(2B)···H(12A)–C(12A)[···H(14B)–C(14B)] ($r_{O\cdots H}$ = 2.655 Å, 2.688 Å, and 2.597 Å respectively) that generates ring motifs $R_2^2(9)$ and $R_3^2(10)$, and also intermolecular interactions C–H···π between the phenyl

rings of the edge-to-face type C(12B)–H(12B)···Cg[C(10A)–C(15A)] ($r_{Cg\cdots C}$ = 3.912 Å, $r_{Cg\cdots H}$ = 3.253 Å) and C(13B)–H(13B)···Cg[C(10A)–C(15A)] ($r_{Cg\cdots C}$ = 3.907 Å, $r_{Cg\cdots H}$ = 3.270 Å).

In the crystal of **8** it is possible to distinguish molecular ribbons along the (*c*–*a*) vector, which are located in orthogonal planes (Fig. 1*h*_SM). In the crystal under study the molecular ordering is generated by intermolecular hydrogen bonds C(10)–H(10A)···Cl(1) (ring motif $R_2^2(20)$ $r_{Cl\cdots H}$ = 2.940 Å), the C(17)–H(17)···O(3) ($r_{O\cdots H}$ = 2.604 Å) and C–H···π interaction of *T*-shaped stacking [47] between the aryl and pyrrol rings of the neighboring molecules C(30)–H(30)···Cg[N(1)C(5)–C(8)] ($r_{Cg\cdots C}$ = 3.519 Å, $r_{Cg\cdots H}$ = 2.716 Å).

CONCLUSIONS

By X-ray crystallography the molecular and crystal structures of a series of functionalized 4-cyano-3(2*H*)–furanones having a spiro-cyclohexane substituent or two methyl groups at position 2 of the furanone ring and also aryl or heteroaryl substituents at position 5 are studied. In all molecules the cyanofuranone component is planar. The spiro-cyclohexane moiety has the *chair* configuration; its conventional plane is almost orthogonal to the furanone ring plane and oriented to the endocyclic oxygen atom. Methyl groups at position 2 are more or less non-equivalent. The heterocyclic substituent at position 5 has the *syn*-orientation relative to the furanone ring. Unsaturated fragments are more or less out of the plane of the furanone ring, except the **5** molecule having a planar structure.

The molecular structure of the studied compounds generates the appearance of a short contact between hydrogen atoms at the α-position of the substituent at position 5 of the furanone ring and the centroid of the C≡N bond, which results in a downfield shift of the signal from this hydrogen atom in the ^{1}H NMR spectra relative to that of the hydrogen atom at the β-position. The shift may underlie the conformational analysis of functionalized 4-cyano-3(2*H*)-furanones in the solution.

The architecture of the crystals formed by the molecules of the series studied is governed by several types of intermolecular interactions: intermolecular hydrogen bonds (ordinary and bifurcated), C–H···π interaction, and π,π-stacking interactions that form supramolecular chain motifs and the layered structure.

CONFLICT OF INTERESTS

The authors declare that they have no conflict of interests.

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