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SYNTHESIS AND STRUCTURE OF BORANE COMPLEXES WITH 3-HYDROXYFLAVONE

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Conclusions have been made regarding the structure of the complexes formed between flavonol and boranes of different structures on the basis of the analysis of their ^{1}H, ^{13}C, and ^{11}B NMR spectra, IR and electronic spectra, and also from the results of quantum-chemical calculations. In all of the complexes, independently of the structure and acceptor properties of the boranes, it was found that the donor acceptor bond is formed between the boron atoms and the oxygen of the carbonyl group in the flavonol. Despite the lowered electron-donor ability of the carbonyl group oxygen atom after the formation of the bond to the boron atom it is likely that the hydrogen bond between the carbonyl and the 3-hydroxy group of the flavonol is retained. It was found that the carbonyl group of the flavonol has a lower electron-donor ability than the analogous group of aliphatic and aromatic ketones.

Keywords: boranes, flavonol complexes , flavonol, NMR spectra of flavones, IR and electronic spectra of flavonols.

3-Hydroxyflavone derivatives (flavonols) (Scheme 1) are used as analytical reagents for the determination of the concentrations of Sc^{3+}, Ga^{3+}, and Th^{3+} [1, 2] and are promising reagents for the analysis of alkaline earth metals. By a study of the interaction of flavonols with Mg^{2+}, Ca^{2+}, and Ba^{2+} ions we have found that, depending on the size of the latter, two types of complexes can be formed, i.e. chelates and the so called "outer" complexes [3, 4]. In the latter case, the donor acceptor bond is formed between the metal ion and the "outer" electron pair of the oxygen atom of the carbonyl group which is not bound by an intramolecular bond with the 3-hydroxy group.

The flavonol complexes have interesting spectroscopic properties but it has not been possible to study them in a series of compounds. This is because the metal complexes are present in solution only for quite high concentrations of the metal ions and they cannot be prepared in the crystalline state. In addition, the formation of these complexes is only possible in certain polar solvents in which the salts of the corresponding ion acceptors are soluble.

For the reasons given we have attempted to synthesize other flavonol complexes of similar structure using boranes as the acceptor molecules for the complexes. According to the literature, the given complexes with boron derivatives are more stable [5] than the metal complexes and can be separated in the crystalline state [6]. In addition the sizes of the acceptor molecule and the acceptor ability of the boron atoms can readily be varied by the use of a series of boranes with different substituents.

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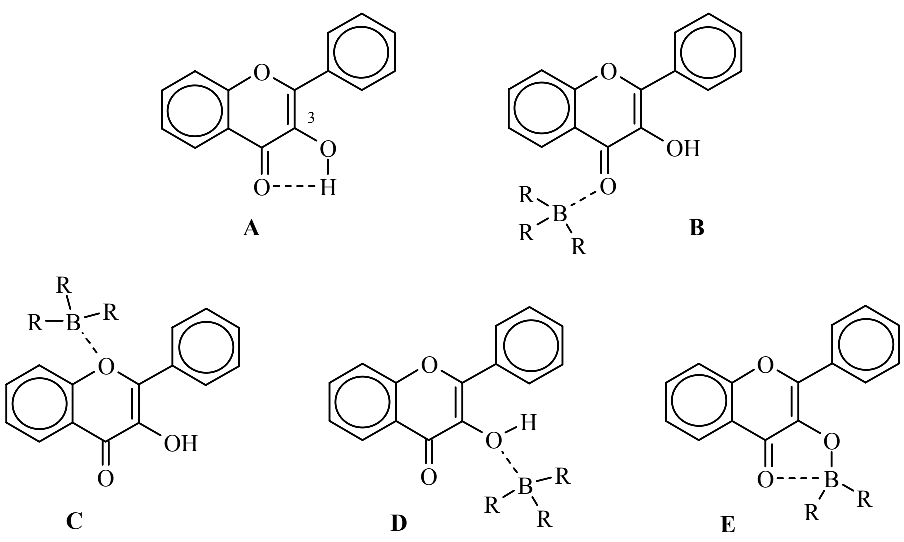
Scheme 1. Possible structures of the borane complexes with flavones



In the synthesis of the complexes we have used boranes which have both donor and also acceptor substituents of different sizes, *viz*. boron trifluoride and trichloride BF_3 and BCl_3, triphenylborane BPh_3, and triisopropylborate B(OPr-*i*)$_3$. The substances obtained are soluble in media of different polarity and are stable both in solvents and in the crystalline state. Since two different types of complex are formed by flavonols with metal ions the first problem in our investigation was the determination of the structure of the boron-containing complex compounds obtained.

In this work we report the preparation of the complexes of unsubstituted flavonol with boranes and also a study of the structure of these compounds using electronic, IR, and NMR spectroscopy and quantum-chemical methods.

DISCUSSION OF RESULTS

From the structure of flavonol **A** it follows that there are three different centers in the molecule capable of forming chemical bonds with boranes. These are the oxygen atoms in the carbonyl and hydroxyl groups and also the bridging oxygen in the pyrone ring. All of the oxygen atoms have vacant electron pairs and can potentially form a donor acceptor bond with the boron atom in **B**-**D**. In addition, substitution of the hydrogen atom in the hydroxyl group is possible to form cyclic complexes with an intramolecular donor acceptor bond (structure **E**).

Evidence for the compounds having the structure **B**-**D** is absent in the literature. The formation of complexes of type **E** with boron trifluoride at room temperature has been reported in the case of desoxybenzoin derivatives [7]. Substitution of hydrogen by a BX_2 fragment and formation of cyclic complexes is apparently observed when the BX_2 fragment closes a six-membered ring. This can explain reports of complexes of type **E** in the case of 2-hydroxychalcones, 5-hydroxyflavones [8], and acetylbenzoylmethane derivatives [9]. In cases where the substitution does not lead to the formation of a six-membered ring more rigid conditions are required for the substitution of a hydrogen atom in the reaction with boron trifluoride [10].

The structure of the obtained complexes was determined in two stages. In the first theoretical step a calculation was made of the optimum geometry of the molecules by localization of the electron density and the thermodynamic parameters of the compound complexes using quantum-chemical methods. The second step included the spectroscopic investigation of the synthesized products and a choice of the most likely structure of the complexes based on the analysis of the obtained experimental data.

TABLE 1. Calculated Enthalpy of Formation of Flavonol Complexes with Boranes for the Hypothetical Structures **B-E**

Complexes	ΔH_f, kcal/mol			
	B	**C**	**D**	**E**
BF_3	-315.14	-301.55	-298.50	-232.78
BCl_3	-132.53	-108.40	-124.75	-107.94
BPh_3	54.70	57.02	59.08	12.87
$B(OPr\text{-}i)_3$	-266.31	-247.10	-262.76	-205.87

As shown from calculation of the optimum geometry and thermodynamic parameters of the isomeric structures of type **B**, **C**, and **D** the lower value of the enthalpy of formation and thus the greatest stability is found in complexes of type **B**, in which the boranes form a donor acceptor bond with the oxygen atom of the carbonyl group (Table 1). A similar conclusion can be made based on an analysis of the values of the charges on the oxygen atoms of the flavonol molecule. The carbonyl oxygen atom has a higher negative charge (-0.319) than the bridging oxygen atom of the pyrone ring (-0.128) and the oxygen atom of the hydroxy group (-0.247), hence an electrophilic attack of the borane molecule at the carbonyl group is more likely.

Carrying out a theoretical analysis of the comparative stability of structures **B** and **E** did not prove possible due to the difference in their chemical composition so a final determination of the structure of the flavonol complexes with boranes needed the use of NMR, IR, and electronic spectroscopic methods.

Analysis of the ^{1}H NMR spectra of the flavonol complexes allowed us unambiguously to exclude the cyclic structure of type **E** from the discussion. The spectra of all the complexes show a peak for the hydrogen of the hydroxyl group which was displaced to low field relative to the peak in the analogous ligand (Table 2).

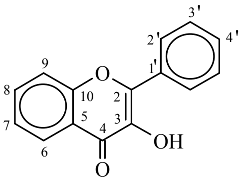
The hydroxy group bands are also seen in the IR spectra of the complexes. They are shifted to higher frequencies relative to the analogous bands of the unsubstituted flavonol. In our opinion, the small shift and marked broadening of the peaks points to a partial retention in the complexes of an intramolecular hydrogen bond between the carbonyl group and the hydroxyl.

Analysis of the spectroscopic data allows us to draw conclusions regarding the relative stability of structures of types **B**, **C**, and **D**. Thus indirect conclusions regarding the structure of the complexes formed can be made by comparison of the direction of the shift of the peaks in the ^{13}C NMR spectra with changes of the charges on the atoms of the pyrone ring in the process of complex formation. In the case of the formation of structure **C**, according to the calculations, there must occur an increase in the electron density at atom $C_{(2)}$ of the pyrone ring and a decrease in the electron density at atom $C_{(5)}$. Hence atom $C_{(2)}$ in a complex of type **C** must be more shielded than in the free ligand and, oppositely, $C_{(5)}$ must experience greater deshielding. In this case, with

TABLE 2. Spectroscopic Parameters for Flavonol Complexes with Boranes

Complex	^{1}H NMR spectrum, δ, ppm, 3-hydroxy group	IR spectrum, ν, cm^{-1}			
		>C=O	O–H	B→O	B–R in boranes
Flavonol	7.12	1628	3210	—	—
Complex of flavonol with					
BF_3	7.44	1622	3223	1432	1070, 1177 (B→F)
BCl_3	7.84	1618	3220	1431	754, 778, 790 (B→Cl)
BPh_3	7.34	1620	3243	1441	1470, 1194, 702 (B→Ar)
$B(OPr\text{-}i)_3$	7.62	1622	3222	1470	1194, 817 (B→O)

TABLE 3. Assignment of Peaks in the ^{13}C NMR Spectra of Flavonol and its Borane Complexes



	2	3	4	5	6	7
—	145.0	136.6	173.6	120.7	125.5	124.6
BF_3	156.1	144.9	173.5	114.3	132.9	124.7
BCl_3	156.4	142.8	173.1	114.3	133.8	125.0
BPh_3*	155.5	138.5	173.6	118.5	—	—
B(OPr-*i*)$_3$	156.1	143.5	173.7	114.6	131.2	124.7

	8	9	10	1'	2', 6'	3', 5'	4'
—	133.7	118.3	155.5	131.1	127.8	128.7	130.3
BF_3	136.4	118.9	150.0	128.7	129.3	127.3	128.5
BCl_3	137.3	119.2	152.0	128.0	129.6	129.0	128.0
BPh_3*	—	115.4	145.0	—	—	—	—
B(OPr-*i*)$_3$	133.8	114.6	145.1	129.4	129.2	128.3	125.6

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* The position of the peaks for carbon atoms C 6-8 and 1'-6' could not be determined due to superimposition of the benzene rings carbon peaks from the triphenylborane.

formation of the complex **C** the peak for the atom $C_{(2)}$ must be shifted to high field and the peak for $C_{(5)}$ to low field. Upon formation of the complexes of type **B** or **D** the change in electron density on these atoms must have an opposite nature and the shift of the corresponding peaks will be opposite to those predicted for structure **C**. As seen in Table 3 the peak for the $C_{(2)}$ atom is shifted to low field for all of the complexes and that for $C_{(5)}$ to high field and this is in agreement with the complexes of type **B** and **D**. Hence the comparative analysis of calculated and experimental data leads to a proposed structure of **B** or **D**.

A clearer conclusion can be made using vibrational and electronic spectroscopic methods. A comparison of the IR spectra of the free flavonol and the flavonol ligand shows that complex formation leads to a small shift of the carbonyl band to lower frequencies. This fact points to the participation of the carbonyl group in formation of a donor-acceptor bond with the boranes and, hence, confirms the proposal that the complexes have the structure **B**.

Differences in the electronic structure of the flavonol and the complexes **B**-**D** in the ground and excited states cause different spectroscopic features for the absorption spectra in the complex forming process. Thus the occurrence of a donor-acceptor bond between the boranes and the carbonyl group (complex **B**) leads to an increased shift of electron density from the substituent phenyl ring to the benzopyrone fragment *via* an $S_0 \rightarrow S_1$ transition and the appearance of a new electron transition with interfragmental charge transition. In the absorption spectra this is manifested as the formation of a new, long wavelength absorption band or an apparent shift of the long wavelength absorption band to the red region. The formation of a donor acceptor bond between the borane and the oxygen atom of the hydroxyl group (complex **D**) or the bridging oxygen atom in the pyrone ring (complex **C**) leads to a disturbance to the transfer of the conjugation effect into the phenyl-double bond-carbonyl chain in the pyrone fragment and, hence, to the opposite effect of a hypsochromic shift of the long wavelength absorption band. According to calculations of the electronic absorption spectra, the formation of the complex of type **B** must lead to a shift of the ligand band to the long-wavelength region of about 2570-2700 cm^{-1} and formation of the complexes **C** and **D** a hypsochromic shift of the band by 1200-2000 cm^{-1}. According to the experimental data given in Table 4 the complex formation with all of the boranes leads to a bathochromic shift and this unambiguously points to the formation of the complex **B**.

The electron-donor ability of the flavonol as a ligand was determined using ^{11}B NMR spectroscopy. Depending on the donor-acceptor properties of the substituent on the boron atom (σ-component) and on the presence of π-bonding between the boron atom and neighboring atoms, free boron atoms have peaks between 18 and 40 ppm. The formation of a complex leads to the disappearance of the planar structure for the boranes and a decreased π-component shielding effect as well as an additional shielding achieved through formation of the bond with the electron-donor carbonyl group. For the trifluorides and trichlorides, in which the boron atom has the most powerful electron-acceptor effects, the relative shift of the peak for the ^{11}B atom peak in the spectra upon complex formation with flavones reaches 33.8 and 26.6 ppm respectively. The shifts of the ^{11}B peaks in the spectra of the weaker acceptors triphenylborane and triisopropylborate are respectively 18.9 and 7.1 ppm. The greater differences in the Δδ ^{11}B suggests that the boranes with different electron acceptor ability give a different degree of change of electronic structure for the ligand and, in turn, this can be revealed in the electronic absorption and fluorescence spectra of the complex compounds. None the less, by contrast with complexes of boranes with diethyl ether (δ ^{11}B = -0.74 ppm for BF_3), saturated and chain unsaturated ketones (δ ^{11}B -0.9 to +1.8 ppm), and methanol (δ ^{11}B = -0.74 ppm for BF_3) [11], the ^{11}B peaks in the spectra of the flavonol complexes occur in the range of about 8-15 ppm (Table 4) and this suggests that the donor ability of the flavonol is lower than saturated alcohols, ketones, and ethers.

On the basis of the spectroscopic and theoretical discussions the following conclusions can be made. Independently of the size of the molecule and the acceptor properties of the boranes the complexes of the latter have a unique structure. The donor acceptor bond is formed between the boron atom and the oxygen atom of the carbonyl group in the flavone in such a way that the structure of the borane complexes corresponds to the "outer" type complexes of flavonols with alkaline earth metals. Despite the lowering of the electron donor ability of the oxygen atom of the carbonyl group after formation of the bond with the boron atom it is likely that the hydrogen bond between the carbonyl and the hydroxy group of the flavonol is retained. The flavonol possesses a lower electron donor ability than saturated or chain unsaturated ketones. Complex formation brings about a significant change in the electron shell of the ligand and this causes differences in the electronic spectra of the complex compounds.

TABLE 4. ^{11}B NMR Peaks of the Free Boranes and those Bound in the Flavonol Complexes. Absorption Spectroscopic Properties of Borane Complexes

	^{11}B NMR spectrum, δ, ppm			Absorption*, cm^{-1}	
	complex	free borane	Δδ*^{2}	ν_{abs}	$\Delta\nu_{abs}$
BF_3	8.0	41.8 [8]	33.8	26180	3220
BCl_3	15.3	41.9	26.6	25000	4400
BPh_3	11.1	30.0	18.9	24040	5360
$B(OPr\text{-}i)_3$	11.0	18.1	7.1	24670	4730

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* Absorption spectra were measured in acetonitrile, $\Delta\nu_{abs}$ is the shift of the long-wavelength band of the absorption complex when compared with the analogous band in the free flavonol.

*^{2} Δδ is the shift of the borane peak due to complex formation.

EXPERIMENTAL

^1H, ^{13}C, and ^{11}B NMR spectra were recorded on a Bruker 200 spectrometer (^1H 200, ^{13}C 50, and ^{11}B 64 MHz (relative to boron trifluoride etherate) respectively) using deuterated chloroform as solvent. IR spectra were obtained on a Perkin-Elmer 1760X Fourier spectrometer for KBr tablets and absorption spectra on a Hitachi U3210 spectrometer. Solvents, flavonol, and borane derivatives for the spectroscopy and the synthesis were used from the Aldrich company. The enthalpy of formation, charges on the atoms, and the theoretical absorption spectra were calculated using the AM1 method with the MOPAC 6.0 program [12, 13]. Configurational composition *via* 20*20 calculation of absorption spectra.

Complex of Flavonol with Trifluoroborane. Boron trifluoride etherate was added dropwise with stirring to an equimolar amount of a saturated solution of the flavonol (0.05 mol) in anhydrous dichloromethane. The solution became bright yellow in color. With gradual evaporation of solvent by two thirds of the volume, yellow crystals of the complex were precipitated. The precipitate was separated from the mother liquor, dried, and recrystallized from anhydrous dichloromethane. Yield 85%; mp 240-241°C (decomp.) Found, %: C 58.64; B 3.50. $C_{15}H_{10}O_3{\cdot}BF_3$. Calculated, %: C 58.87; B 3.53.

Complex of Flavonol with Trichloroborane. A solution of boron trichloride in dichloromethane (commercial product) was added to a saturated solution of flavonol. The volume of the borane solution was added so that the molar ratio of the boron trichloride to flavonol was 1.2:1. Bright yellow crystals were formed, even upon mixing the solutions. The mixture obtained was evaporated by two thirds and the crystals were filtered off and recrystallized from anhydrous dichloromethane. Yield 92%; mp <300°C. Found, %: C 50.55; B 3.11. $C_{15}H_{10}O_3{\cdot}BCl_3$. Calculated, %: C 50.69; B 3.04.

Complex of Flavonol with Triisopropoxyborane. Under an argon atmosphere, a saturated solution of flavonol in anhydrous dichloromethane (0.05 M) was treated with an equimolar amount of isopropylborate. The solution was evaporated to the onset of crystallization and then cooled The light yellow crystals were recrystallized from dichloromethane in 56% yield; mp 180-181°C (decomp.). Found, %: C 67.80; B 2.51. $C_{15}H_{10}O_3{\cdot}B(OPr\text{-}i)_3$. Calculated, %: C 67.62; B 2.54.

Complex of Flavonol with Triphenylborane. Under an argon atmosphere, a saturated solution of flavonol (0.05 M) in anhydrous dichloromethane was treated with an equimolar amount of triphenylborane and the solvent was evaporated off. The brown gum formed was extracted on a Soxhlet apparatus with cyclopentane (25 ml) under an argon atmosphere. The solution of the complex in cyclopentane was evaporated tenfold and the bright yellow precipitate was recrystallized from cyclopentane. Yield 86%; mp 242-244°C. Found, %: C 82.60; B 2.32. $C_{15}H_{10}O_3{\cdot}BPh_3$. Calculated, %: C 82.51; B 2.25.

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