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Bromination of 6-Dibromomethyl-6-methylcyclohexyl-2,4-dien-1-one

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Abstract—Bromination of 6-dibromomethyl-6-methylcyclohexyl-2,4-dien-1-one (**I**) with molecular bromine was studied at different ratios of reactants and varied reaction time. A number of tri-, tetra-, penta-, and hexabromo derivatives was obtained, which were characterized by ^{1}H, ^{13}C, IR, UV spectroscopy and elemental analysis. The molecular structure of (2*R*,3*R*,4*S*,5*S*,6*R*)-2-dibromomethyl-2-methyl-3,4,5,6-tetrabromocyclohexan-1-one (**V**) was revealed using XRD. It was shown that 2-bromo-6-dibromomethyl-6-methylcyclohexyl-2,4-dien-1-one (**III**) upon standing for six months at room temperature dimerized quantitatively via Diels–Alder reaction to form **IX**. Dimer **IX** was investigated by the methods of cyclic voltammetry (CVA) and rotating disk electrode (RDE) in a solution of DMF on glassy carbon electrode.

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A special structural feature of 6,6-disubstituted cyclohexa-2,4-dien-1-ones is the presence in the molecule of a conjugated system consisting of two double bonds in the cis conformation, and a carbonyl group.

The analysis of publications suggests that many naturally occurring organic molecules contain the specified structural fragment. Among them are a compound *sizigium* capable to inhibit the skin cancer [1], a fungicidal metabolite of the Japanese paper tree *spirobrouzonin A* [2], efficient repellent colupulone [3], stoloniferon E possessing an anticancer activity [4]. Bromine-substituted dienol fragments were found in metabolites possessing protection functions for sea animals [5–8].

The aim of this work was to study the reaction 6-dibromomethyl-6-methylcyclohexyl-2,4-dien-1-one (**I**) with molecular bromine.

The analysis of the literature shows that no such studies have been carried out on series of structurally similar compounds. To identify the possible pathways of bromination of dienone **I** we monitored the reaction by NMR spectroscopy and by the preparative isolation of the reaction products using column chromatography. The main reaction paths and the products of brominated of compound **I** are shown in Scheme 1.

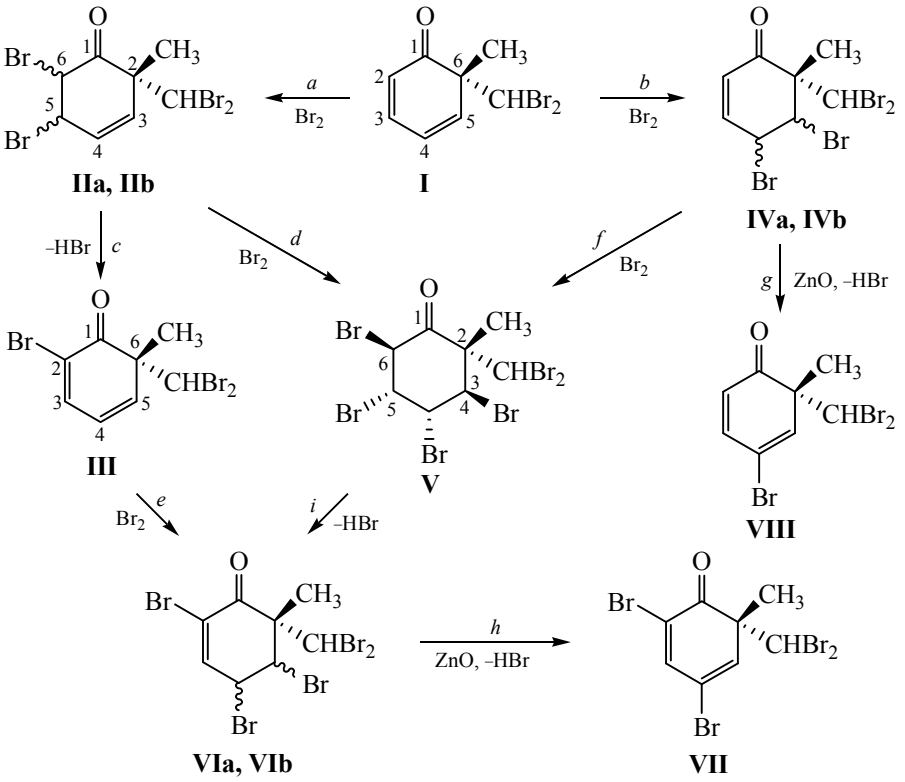
Compounds **III, IVa, V, VIa,** and **VII** were isolated and characterized by ^{1}H, ^{13}C NMR, IR, UV spectroscopy, elemental analysis; the molecular structure of the ketone **V** was investigated by XRD. Tetrabromo derivatives **II** and **IV**, as well as pentabromide **VI** are formed as a mixture of two stereoisomers: main (**a**) and minor (**b**). The structure of the other bromo derivatives, which failed to be isolated in an individual state, was established on the basis of the analysis of the ^{1}H and ^{13}C NMR spectra of the reaction mixtures as well as mixtures of compounds after chromatography.

In addition to the compounds shown in the Scheme 1, in the NMR spectra of the reaction mixture at a ratio of reactants Br_2:**I** $\geq$ 2:1 minor signals of unidentified compounds appear whose total content does not exceed 10%.

Structure of the products of dienone I bromination. Numbering of atoms in the resulting bromo derivatives is shown in Scheme. 1. For compounds **II** and **V** the numbering is opposite to that of the other compounds and coincides with the crystallographic numbering.

Compound **V**, formed at exhaustive bromination of **I**, according to the XRD crystallizes in a *chair*

Scheme 1.



conformation with the equatorial positions occupied by the dibromomethyl substituents and two neighboring atoms Br^3 and Br^4 (Fig. 1). The $CHBr_2$–Br^3–Br^4 triad has a *trans-trans* configuration. Axial atoms Br^5 and Br^6 are also located in the *trans* position to each other.

The pairwise assignment of the proton signals of $H^{3,4}$ and $H^{5,6}$ in the ^1H NMR spectrum of **V** was made by comparing $^3J_{HH}$ values and the dihedral angles obtained from the XRD data. For the axial protons $H^{3,4}$ (179.5°) $^3J_{HH}$ = 9.3 Hz, while for the equatorial protons $H^{5,6}$ (68.1°) $^3J_{HH}$ = 4.4 Hz.

The *transoid* arrangement of the atoms in the positions 3,4 and 5,6 of hexabromoketone **V** indicates the *trans*-addition of Br both to the initial dienone, and to the dibromides **IIa, IIb** and **IVa, IVb** formed in the reaction mixture and also to tribromide **III**. The presence of two isomers of the compounds **II, IV, VI** is due to two possible orientations of substituents CH_3 and $CHBr_2$ at the C^6 atom with respect to the CHBr-CHBr bond. In the minor isomer the Br atom nearest to C^6, in all probability, is in the *cis* position to the bulky dibrommethyl substituent. Compounds **IVa, IVb, VIa, Vb**, and **V** show a delayed conformational dynamics at 23°C, as seen from the broadening of the signals in the ^1H and ^{13}C NMR spectra at this temperature (see Experimental). In the case of compounds **VIa, VIb** raising the temperature to 50°C leads to narrowing of the signal of $CHBr_2$ in the ^1H NMR spectrum, indicating the acceleration of the interconversion of cyclic conformations.

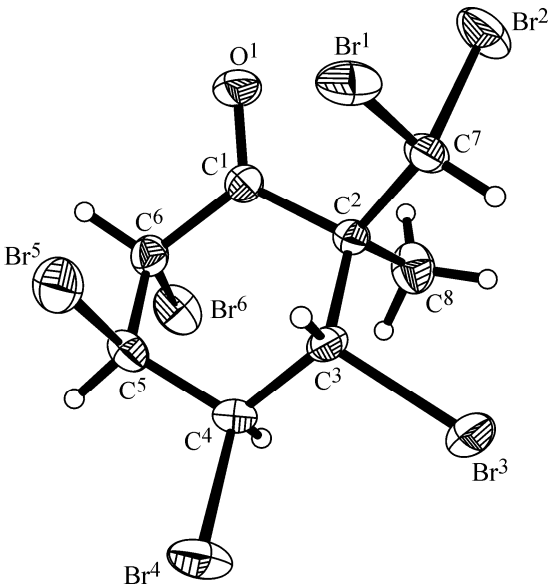


Fig. 1. The molecular structure of the compound **V**.

Table 1. Product yield in the bromination reaction of dienone **I**, depending on the ratio of reactants and reaction time according to ^{1}H NMR spectroscopy of the reaction mixtures[a]

Dienone:Br_2 ratio	Reaction time	Yield, %					**II**:**IV**	**IIa**:**IIb**	**IVa**:**IVb**
		II	**III**	**IV**	**V**	**VI**			
1:1	1 h	87.5	–	12.5	–	–	87.5:12.5	75:25	94.7:5.3
	24 h	87.5	[b]	12.5	–	–	87.5:12.5	75:25	94.7:5.3
	5 days	4.4	83.1	12.4	–	[b]		28.6:71.4	94.7:5.3
1:10	1 h	–	–	–	100	–	–	–	–
	2 h	–	–	–	100	–	–	–	–
	5 days	–	–	–	90	10	–	–	–

[a] Monitoring solutions in $CDCl_3$ in the NMR ampules. [b] Trace amount.

Some observations may be noted that facilitate the interpretation of the spectra of the compounds and the assignment of signals. These include, in particular, almost complete coinciding of spectral fragments for the structurally related parts of different compounds. For example, in the ^{1}H NMR spectra the parameters of the signals corresponding to substituents at C^4, C^5, and C^6 in **IVa, IVb**, and **VIa, VIb**, are almost identical for the main (**a**) and minor (**b**) isomers. The chemical shift of the carbonyl group carbon in ^{13}C NMR spectra is very sensitive to the presence of the conjugated double bond, which reduces the chemical shift of C=O group by ~10 ppm, as well as to the presence of bromine atom in the α-position (upfield shift of the signal of C=O groups by ~7 ppm). For γ-bromo substitution the upfield shift is significantly smaller (~2 ppm).

Pathways of the products formation of dienone (I) bromination. To determine the pathways of formation of the products shown in Scheme 1, we carried out a series of experiments with monitoring the reaction mixtures in $CDCl_3$ directly in NMR ampules. The results are listed in Table 1. The ^{1}H and ^{13}C NMR spectra of the reaction mixture at the 1:1 ratio of the reactants in an hour after the start of the reaction indicates that its initial stage consists in the competitive addition of bromine to the C^2=C^3 and C^4=C^5 bonds of ketone **I** leading to the formation of products **IIa, IIb** (path *a*) and **IVa**, **IVb** (path *b*) in Scheme 1, respectively. Isomeric ratio of tetrabromides **IIa**:**IIb** = 3:1, and the isomers **IVa**:**IVb** = 18:1. The relative content in the mixture of compounds **II** and **IV** is 7:1. During the first day this ratio remained almost unchanged, but in the mixture appears a product of dehydrobromination of ketone **II**, the dienone **III** (path *c*). Its content increased gradually, and 5 days later it becomes the predominant product. The ratio of isomeric products **IIa, IIb** equal to 3:1 in the initial moment of the reaction was reduced to 0.4:1 in 5 days, indicating a higher rate of dehydrobromination of 2,3-*trans*-isomer **IIa** compared with 2,3-*cis*-isomer **IIb**. The content of tetrabromide **IV** in the reaction mixture remained constant and the ratio of isomers **IVa**:**IVb** also did not change, which indicates their dynamic stability. In order to demonstrate the possibility of further bromination of enones **II**, **III**, and **IV**, we performed their reactions as individual compounds with Br_2. In the ^{1}H and ^{13}C NMR spectra of the reaction mixtures no signals occur of compounds **II, III, IV**, but we have found the presence of bromides **V** and **VI**. The amount of compound **IV** decreases with time, therewith the 4,5-*trans*-isomer **IVa** reacted with Br_2 faster than the 4,5-*cis*-isomer **IVb**. In addition to these compounds, pentabromide **VI** was found in the mixture originating obviously from the bromination of ketone **III** (path *e*) and dehydrobromination of ketone **V** (path *i*). In separate experiments, we showed that the reaction of individual bromide **III** with an equimolar amount of Br_2 gives pentabromides **VIa**, **VIb** in a ratio of 6:1, and dienone **I** reacts with a 10-fold excess Br_2 almost instantly, forming quantitatively the polybromide **V**. NMR spectra of the reaction mixture after standing for a few days contained the signals of enone **VI**, which indicate the dehydrobromination of ketone **V** in the solution (path *i*).

Note that we have not detected the products of 1,4-addition of molecular bromine to the diene system of ketone **I** in the reaction mixtures.

The preparative separation of the products by column chromatography on SiO_2 was performed after treatment with $Na_2S_2O_3$ and the subsequent storage over ZnO to remove from the reaction mixtures in CCl_4 HBr formed at the dehydrobromination,. The spectral analysis of the reaction mixtures before and after treatment with a solution of $Na_2S_2O_3$ indicated that the treatment did not affect the mixture composition. Intermediate fractions that could not be divided into individual substances were investigated by ^1H and ^{13}C NMR spectroscopy. The results are summarized in Table 2.

At a ratio of reactants 1:1, from the mixture kept for a day were isolated compounds **III** (28%), **IVa** (31%), and **VIa** (1%). After 48 hours the yields of the same compounds were 44%, 36%, and 9% respectively. These results suggest that the increase in the reaction time does not change the reaction direction and does not lead to new products. The growth in the yield of ketone **VIa** can be attributed to the reaction of ketone **III** with the residual bromine (path *e*).

The spectral analysis of the reaction mixture at a ratio of reactants 1:10 on the next day after treating it with $Na_2S_2O_3$ indicated the presence in it of ketones **V** (35%), **IVa, IVb** (35%), and **VIa, VIb**) 24 % (the ratio of **IVa**:**IVb** = 18:1, the ratio of **VIa**:**VIb** = 6:1). After processing with ZnO and the chromatographic separation on a column, from the mixture the same products were isolated: **V** (34%), **IVa** (33%), and **VIa** (21%), and after 48 h only two of these products, **V** (46%) and **VIa** (19%), and also compound **VII** (12%). The lack of enone **IVa** is due to its conversion to ketone **V** by the reaction with Br_2 (path *f*), and the presence of ketone **VII,** by the dehydrohalogenation of **V** and **VI** at the processing with ZnO and chromatographic separation (paths *i* and *h*). We failed to isolate ketone **VIII** in an individual state, it was spectrally detected in one of the chromatographic fractions of the reaction mixture (1:1 ratio of reagents). The presence of **VIII** and ketone **VII** is due to the dehydrohalogenation of compound **IV** at the processing the mixture with ZnO and the subsequent chromatographic separation (path *g*).

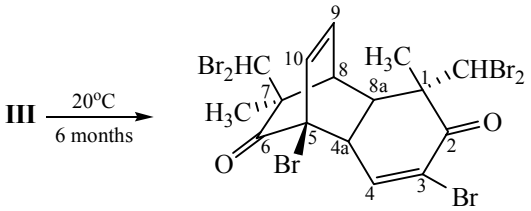
Ketone **III** when stored for six months at room temperature dimerized quantitatively through the Diels–Alder reaction to form **IX.**

The structure of diketone **IX** is established on the basis of spectral data and elemental analysis. The values of the spectral parameters of **IX** are in very good agreement with the respective values for the compound close to it by structure, previously obtained by us 3-bomo-1,7-dimethyl-1,7-di(dichloromethyl)-5,8-ethenodecalin-3-ene-2,6-dione whose molecular structure was established by XRD [9]. They differ only by the presence of the Br atom in 5 position in **IX** and by the dihalomethyl groups. In particular, the close values of $^3J_{HH}$ indicate the similarity of the preferential conformation of the rings in the decalinedione fragment of the two compounds in the solution.

Table 2. Preparative yield of reaction products of dienone **I** bromination depending on the ratio of reactants and reaction time (after separation by column chromatography on SiO_2)

Dienone:Br_2 ratio	Reaction time, h	Yield, %				
		III	**IVa**	**V**	**VIa**	**VII**
1:1	24	28	31	–	1[a]	–
1:1	48	44	36	–	9	–
1:10	24	–	33	34	21	–
1:10	48	–	–	46	19	12

[a] Detected by the ^1H NMR spectra.



IX

The mechanism of dienone I reaction with bromine. The structural features of dienone **I** include a carbonyl group conjugated with the double bond system, a built-in six-membered ring, in which next to the carbonyl group is a geminal site containing a methyl and a bulky dibrommethyl groups. The electrophilic agent Br_2 can attack the dienone **I** molecule either at the $C^2=C^3$ or $C^4=C^5$ bond (Scheme 2). The geometry optimization and the calculation of the atomic charges in the dienone **I** by the semiempirical PM3 method [18] (HyperChem software package, HyperCube Inc., FL, USA) showed that the maximum electron density is concentrated on the atoms C^2 and C^4. The calculated charges, C^2 –0.239, C^3 +0.008, C^4 –0.139, C^5 –0.089, are consistent with the data of ^1H and ^{13}C NMR spectra. It can be assumed that the initial attack of Br_2 occurs mainly at the $C^2=C^3$ bond, because

the steric hindrance caused by dibromomethyl group is less than at the attack on the C^4=C^5 bond, so the obtained ratio of **II**:**IV** is 7:1. The attack of the C^2=C^3 by the Br_2 electrophile obviously occurs from the plane of the ring opposite to the bulky $CHBr_2$ group (Scheme 2). Furthermore, the possibility of delocalization of the positive charge in the carbocation **A** is higher than in the carbocation **B**, as the donor properties of the C^4=C^5 are higher than those of the C^2=C^3 bond due to the conjugation of the latter with an electron pair of the carbonyl group. The resulting bromonium intermediate is opened by the bromide anion, preferably to form a product of *trans*-dibromination, in correspondence to the general laws of electrophilic addition. As a result, the *trans*-product of Br_2 addition to the C^2=C^3 bond of dienone **I** dominantes in the mixture**,** the tetrabromide **II**, and the ratio of **IIa**:**IIb** = 3:1.

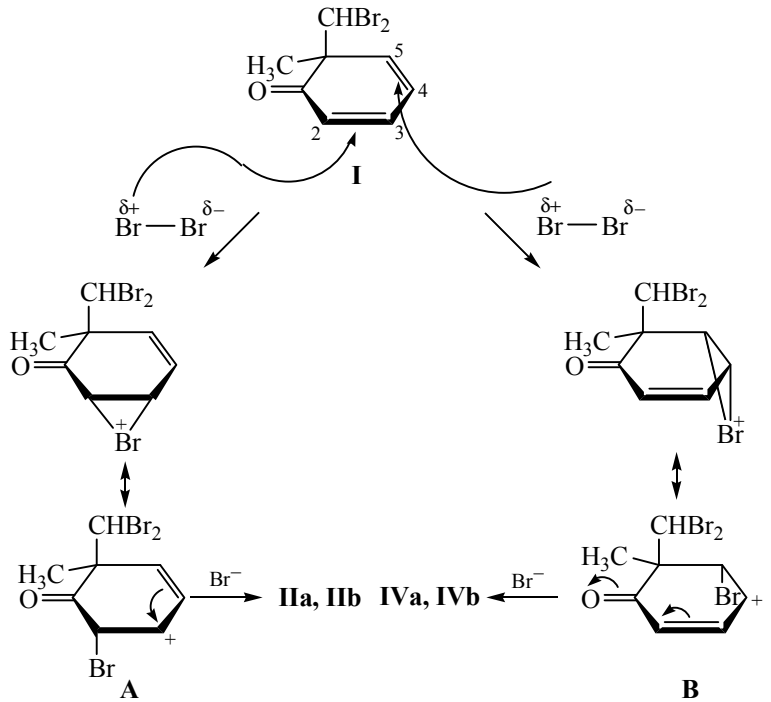
At the addition of the bromine molecule to the C^4=C^5 bond of dienone **I** the electrophilic attack, as for the C^2=C^3 bond, occurs on the side opposite to dibromomethyl substituent. The ratio of *trans*-*cis*-isomers **IVa**:**IVb** = 18:1, indicating that the critical factors affecting the stereochemistry of bromine addition at the C^4=C^5 bond are both steric barriers created by dibromomethyl group and stabilization of the cation **B** due to the conjugation with the double bond C^2=C^3 and the carbonyl group.

The proposed scheme of the reaction mechanism is supported by the results of the reactions in solution with monitoring by NMR, where the ratio of **IIa, IIb**:**IVa, IVb** = 7:1 (Table 1). However, in the preparative experiment the replacement of the more polar solvent $CDCl_3$ (ε = 4.806 at 20°C) by the less polar CCl_4 (ε = 2.238 at 20°C) the ratio of **III**:**IVa,IVb** = 1:1 (Table 2) where **III** is the product of conversion of **IIa**, **IIb**). Perhaps a more polar solvent contributes to the additional stabilization of the onium intermediate or of the open carbocation **A** thus increasing the relative yield of the products **IIa, IIb**.

XRD data for hexabromide **V**, namely, *trans* arrangement of $CHBr_2$ group relative to the bromine atoms in the positions 2 and 5 of the cyclohexane fragment (Fig. 1) also points to the decisive influence of steric hindrances created by bulky dibromomethyl group on the stereochemistry of addition.

The presence of the bromine atom at C^2 in dienone **III** leads to a change in the stereochemistry of bromination of the C^4=C^5 bond. The ratio of *trans*-*cis*-isomers **VIa**:**VIb** = 6:1 shows that the decrease in electron-donor properties of the bromovinyl group of

Scheme 2.



ketone **III** compared to the vinyl group of the parent compound **I** results in the formation of a more symmetric bromonium cation and in the increase in favorable conditions to attack it both from the front and the rear. In addition, an increase in contribution of the open form of the cation intermediate promotes less stereoselective reaction course.

These examples clearly show the influence of electronic and steric factors on the process of *cis,trans*-addition of bromine molecules to conjugated double bonds of dienone **I**.

Electrochemical study of compound IX. Dimer **IX** was investigated by cyclic voltammetry (CV) and rotating disk electrode (RDE) methods in a solution of DMF on glassy carbon electrode in order to compare its electrochemical characteristics with the earlier obtained for the structurally close 3-bromo-1,7-dimethyl-1,7-di-(dichloromethyl)-5,8-ethenodecalin-3-en-2,6-dione. Cyclic voltammogram of compound **IX** is shown in Fig. 2.

Compound **IX**, like the previously studied analog containing two dichlormethyl groups [9], is not oxidized at the potential below +1.5 V, making it possible to conclude on the elimination of the bromine atoms during the electrochemical studies from the reoxidation peak of the bromide ions, as observed in the anode region at the reversed sweep of potential after the corresponding cathodic peaks.

Cathode branch of the CVA curve of compund **IX** containing two bromine atoms in the 3 and 5 positions and two dibromomethyl groups at the carbon atoms C^1 and C^7 has three peaks corresponding to reductive cleavage of the bromide ions, and a low-intensity peak in the cathode region (Fig. 2). The first reduction peak E_{pc} = –1.02 V corresponds to a two-electron reductive elimination of a bromide anion, which is confirmed by the oxidation peak of Br^- (E = 0.82 V) at the reverse sweep of potential after reaching the potential of the first cathode peak. At this point, obviously, the elimination of carbonylvinyl bromine atom occurs from the position 3 with the formation of intermediate **C**, as the potential of the peak coincides with that of bromine reductive cleavage at this provision in the previously described similar dione with two dichlormethyl groups [9].

The second stage of the four-electron reduction at E_{pc} = –1.26 V corresponds to the simultaneous elimination of four bromide ions. At the reverse potential

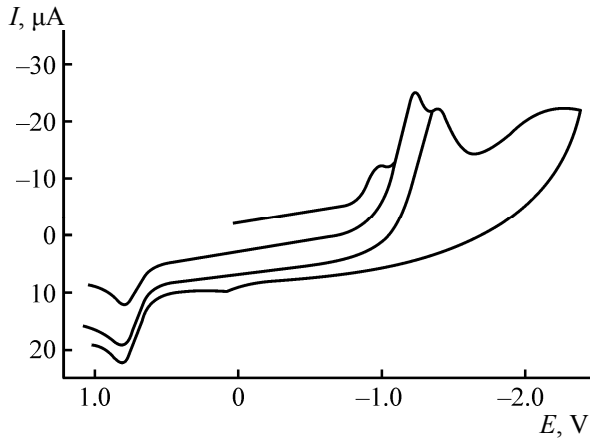


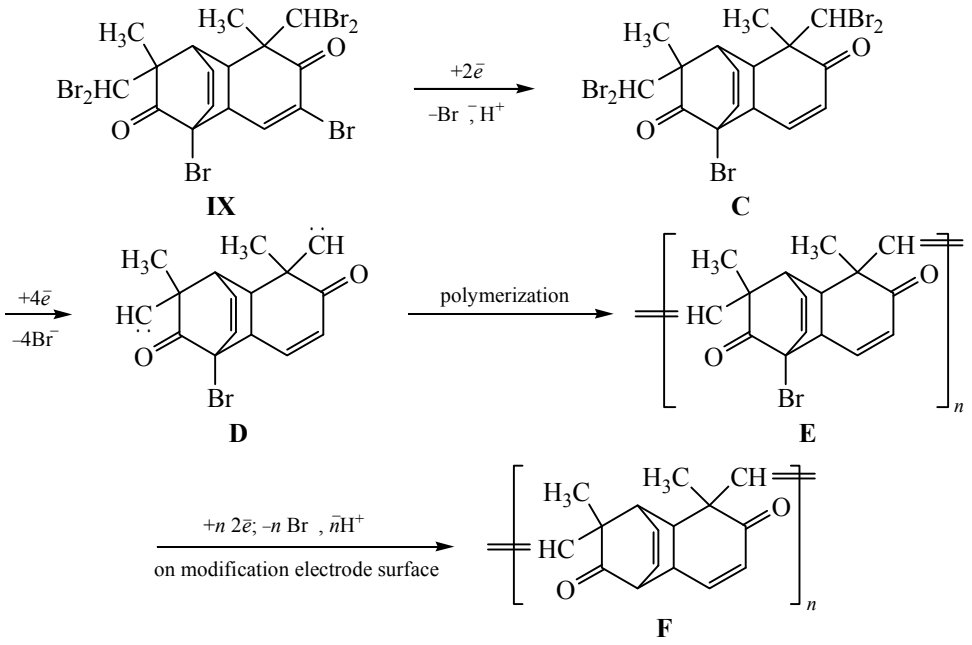
Fig. 2. Cyclic voltammogram of compound **IX**. Concentration 10^{-3} M, carbon glass electrode, DMF, 0.1 M Bu_4NClO_4.

sweep in the anodic region there is an intense peak of reoxidation of bromide ions (E = 0.82 V). Apparently, both dibromomethyl groups of compound **IX** are reduced simultaneously involving four electrons and forming an intermediate containing two carbenoid sites **D** [9]. This intermediate then polymerizes (Scheme 3), and the polymer product **E** is deposited on the electrode forming a visually observed low-conductive film on the surface, thus effectively modifying the electrode. This leads to a reduction of the wave current in this stage of RDE experiment and a decrease in the intensity of the subsequent cathodic peaks.

The reductive cleavage of the bromine atom from the 5 position occurs at a cathodic potential E_{pc} = –1.40 V, because this halogen atom is in the bridgehead position of the frame of a polycyclic structure, and due to the fact that the process occurs on the electrode surface modified by the polymerization product of bis-carbene **E**. Thus forms a polymer product **F**, not containing bromine atoms. The subsequent reduction of the carbonyl groups of the polymer is shown by appearance of a gentle peak at –2.30 to –2.40 V, similar to that at the last stage of reduction of 3-bromo-1,7-dimethyl-1,7-bis(dichloromethyl)-5,8-ethenodecalin-3-en-2,6-dione [9].

Thus, the electroreduction of 3-bromo-1,7-dimethyl-1,7-bis(dibromomethyl)-5,8-ethenodecalin-3-en-2,6-dione **IX** proceeds initially as a reductive elimination of the bromine atom in position 3, and in the second stage as a simultaneous reductive cleavage of the four bromine atoms from two dibromomethyl groups. A carbenoid intermediate is formed, containing bromine in 5 position, which is polymerized on the

Scheme 3.



surface of the electrode. In the final stage of reduction the bridgehead bromine atom is eliminated.

EXPERIMENTAL

^{1}H and ^{13}C–{1H} NMR spectra were recorded on a Bruker Avance-400 spectrometer at 400 and 100 MHz, respectively, at 23°C in $CDCl_3$. Chemical shift values were measured relative to TMS (^{1}H) and $CDCl_3$ (δ_C = 77 ppm). IR spectra were recorded on a spectrophotometer UR 20 in mineral oil, UV spectra, on a spectrophotometer Specord M-40 in ethanol.

Monitoring the progress of the reaction was carried out by thin layer chromatography using Silufol UV 254 plates.

For the semiempirical quantum-chemical calculations the PM3 method was used included in the software package HyperChem (HyperCube Inc., FL, USA) [10]. The geometry optimization of the molecules was performed with a gradient of convergence set no more than 10 cal Å^{-1} mol^{-1}.

Electrochemical studies were carried out using a potentiostat IPC-Pro M. The working electrode was a glassy carbon disk (d = 2 mm), supporting electrolyte was 0.1 M solution of Bu_4NClO_4 in DMF, reference electrode Ag/AgCl/KCl (saturated), auxiliary electrode was platinum plate. Potentials are given with the *iR*-compensation. In the study by CVA the potential sweep rate was 200 mV s^{-1}, in the study by RDE, 20 mV s^{-1}. Potentials are given with the *iR*-compensation. The surface of the working electrode was polished with aluminum oxide powder with a particle size less than 10 μm (Sigma-Aldrich). All measurements were carried out in an atmosphere of dry argon, the samples were dissolved in a pre-deaerated solvent. DMF of pure grade was purified by stirring over freshly calcined K_2CO_3 for 4 days, followed by distillation in a vacuum first over P_2O_5 and then over anhydrous $CuSO_4$.

X-ray diffraction analysis of compound **V** was performed on an automatic diffractometer Bruker SMART APEX II at room temperature (MoK_α-radiation, λ = 0.71073 Å, graphite monochromator). Crystals of **V** ($C_8H_8Br_6O$, M = 599.60) are monoclinic, space group $P2_1/c$, a = 11.3973(9), b = 9.0594(8), c = 14.3801(12) Å, α = 112.340(1)°, V = 1373.3(2) Å^3, Z = 4, ρ_{calc} = 2.900 g cm^{-3}, μ(MoK_α) = 17.513 mm^{-1}, F(000) = 1096. The intensities of 11 233 reflections (of which 2994 independent, R_{int} = 0.0428) were measured by the ω-scan in the range of 1.93° < θ < 27.00° (–14 ≤ h ≤ 14, –11 ≤ k ≤ 11, –18 ≤ l ≤ 17). Corrections for extinction were introduced on the basis of measurements of the intensities of equivalent reflections [11]. The structure was solved by the direct method and all non-hydrogen atoms were refined by the full anisotropic least squares with respect to F^2 (SHELXTL [12]). All hydrogen atoms were placed in calculated positions and refined by using the *rider*

scheme. The final value of the divergence factor was $R_1 = 0.0262$ for 2472 reflections with $I > 2\sigma(I)$ and $wR_2 = 0.0617$ for the entire set of data using 138 refinement parameters. $GOF = 1.048$, $\Delta\rho_{min/max} = -0.737/0.779$.

General procedure for bromination of dienone I. A mixture of 0.140 g (0.5×10^{-3} mol) of 6-dibromomethyl-6-methylcyclohexyl-2,4-dien-1-one (**I**) in 5 ml of CCl_4, and the calculated amount of molecular bromine was kept at room temperature for different times (Table 2). The solvent was removed in vacuo, the residue was dissolved in ether, treated with 15% solution of $Na_2S_2O_3$, washed with water, dried over $MgSO_4$, evaporated, dissolved in CH_2Cl_2 and kept on ZnO during a day. ZnO was separated, the solvent was evaporated, the reaction products were separated by column chromatography on silica gel L 40/100. Column height 15 cm, diameter 2.5 cm, eluent a mixture benzene:hexane = 1:1.5.

To monitor the composition of mixture during the reaction, 0.030 g (1.03×10^{-4} mol) of dienone **I** in 0.5 ml of $CDCl_3$ and the calculated amount of bromine (Table 1) was placed in an NMR ampule, and ^1H, ^{13}C NMR spectra were recorded and at different time intervals.

6-Dibromomethyl-6-methylcyclohexyl-2,4-dien-1-one (I) was synthesized by the method [13]. ^1H NMR spectrum, δ, ppm: 1.32 s (3H, Me), 5.98 s (H, $CHBr_2$), 6.10 d (1H, H^2, ^3J 9.8 Hz), 6.51 d.d (1H, H4, ^3J 9.6, 5.8 Hz), 6.72 d (1H, H^5, ^3J 9.6 Hz), 7.10 d.d (1H, H^3, ^3J 9.8, 5.8 Hz). $^{13}C-\{^1H\}$ NMR spectrum, δ_C, ppm: 25.55 (Me), 50.06 ($CHBr_2$), 57.54 (C^6), 123.18, 125.47 ($C^{2,4}$), 141.77, 141.82 ($C^{3,5}$), 199.98 (C=O).

5,6-Dibromo-2-dibromomethyl-2-methylcyclohexyl-3-en-1-one (II). A mixture of steric isomers **IIa** and **IIb**. Isomer **IIa**, ^1H NMR spectrum, δ, ppm: 1.76 s (3H, Me), 4.80 d (1H, H^6, ^3J 2.8 Hz), 5.06 d.d (1H, H^5, ^3J 5.0, 2.8 Hz), 6.05 s (H, $CHBr_2$), 6.16 d (1H, H^3, ^3J 10.2 Hz), 6.28 d.d (1H, H^4, ^3J 10.2, 5.0 Hz). $^{13}C-\{^1H\}$ NMR spectrum, δ_C, ppm: 28.87 (Me), 45.27, 47.16, 49.60 ($C^{5,6}$, $CHBr_2$), 55.31 (C^2), 126.71, 131.49 ($C^{3,4}$), 199.30 (C=O). Isomer **IIb**, ^1H NMR spectrum, δ, ppm: 1.53 s (3H, Me), 4.82 d (1H, H^6, ^3J 5.0 Hz), 5.01 m (1H, H^5, ^3J 4.7 Hz), 6.13 s (1H, $CHBr_2$) , 6.20 d (1H, H^3, ^3J 10.3 Hz), 6.30 d.d (1H, H^4, ^3J 10.3, 4.4 Hz). $^{13}C-\{^1H\}$ NMR spectrum, δ_C, ppm: 25.08 (Me), 46.88, 50.20, 50.40 ($C^{5,6}$, $CHBr_2$), 55.62 (C^2), 127.97, 132.01 ($C^{3,4}$), the signal C=O is not observed due to the low concentration of the isomer.

2-Bromo-6-dibromomethyl-6-methylcyclohexyl-2,4-dien-1-one (III). Pale yellow oil. $R_f = 0.35$. ^1H NMR spectrum, δ, ppm: 1.38 s (3H, Me), 5.97 s (1H, $CHBr_2$), 6.39 d.d (1H, H^4, ^3J 9.5, 6.5 Hz), 6.73 d.d (1H, H^5, ^3J 9.5 Hz, ^4J 1.4 Hz), 7.55 d.d (1H, H^3, ^3J 6.5 Hz, ^4J 1.4 Hz). $^{13}C-\{^1H\}$ NMR spectrum, δ_C, ppm: 25.92 (Me), 49.15 ($CHBr_2$), 59.49 (C^6), 122.56 (C^2), 123.15 (C^4), 141.79, 143.50 ($C^{3,5}$), 193.08 (C=O). IR spectrum, ν, cm^{-1} : 1640, 1675. UV spectrum: λ_{max} 322 nm (log ε 3.40). Found, %: C 26.96, H 2.13. $C_8H_7Br_3O$. Calculated, %: C 26.74, H 1.94.

4,5-Dibromo-6-dibromomethyl-6-methylcyclohexyl-2-en-1-one (IV). Isolated as a mixture of steric isomers **IVa** and **IVb**. Yellow oil, $R_f = 0.11$. IR spectrum, ν, cm^{-1}: 1650, 1730. UV spectrum: λ_{max} 227 nm (log ε 3.76). Found, %: C 22.00, H 1.96. $C_8H_8Br_4O$. Calculated, %: C 21.81, H 1.81. Isomer **IVa,** ^1H NMR spectrum, δ, ppm: 1.59 s (3H, Me), 5.00 d (1H, H^5, ^3J 4.7 Hz), 5.18 br.t (1H, H^4), 6.11 d (1H, H^2, ^3J 10.2 Hz), 6.40 br (1H, $CHBr_2$), 6.89 d.d (1H, H^3, ^3J 10.2, 3.5 Hz). $^{13}C-\{^1H\}$ NMR spectrum, δ_C, ppm: 20.04 (Me), 45.7, 56.1, both br ($C^{4,5}$), 46.56 ($CHBr_2$), 57.65 (C^6), 127.46 (C^2), 142.5 br (C^3), 191.89 (C=O). Isomer **IVb**, ^1H NMR spectrum, δ, ppm: 1.94 s (3H, Me), 5.00 d.d (1H, H^5, ^3J 3.0 Hz, ^4J 1.5 Hz), 5.44 d.d.d (1H, H^4, ^3J 4.2 , 3.0 Hz, ^4J 1.1 Hz), 6.11 d.d (1H, H^2, ^3J 10.1 Hz, ^4J 1.1 Hz), 6.16 s (1H, $CHBr_2$), 6.75 d.d.d (1H, H^3, ^3J 4.2, 10.1 Hz, ^4J 1.5 Hz).

(2*R*,3*R*,4*S*,5*S*,6*R*)-2-Dibromomethyl-2-methyl-3,4,5,6-tetrabromocyclohexane-1-one (V). White crystals, mp 141°C (reprecipitation from CH_2Cl_2 to hexane). ^1H NMR spectrum, δ, ppm: 1.92 s (3H, Me), 4.87 m (2H, $H^{5,6}$), 5.10 d.d (1H, H^4, ^3J 9.3, 2.5 Hz), 5.24 d (1H, H^3, ^3J 9.3 Hz), 6.18 br (1H, $CHBr_2$). ^1H NMR spectrum (in CD_2Cl_2), δ, ppm: 1.92 s (3H, Me), 4.87 d (1H, H^6, ^3J 4.4 Hz), 4.93 d.d (1H, H^5, ^3J 4.4, 2.7 Hz), 5.14 d.d (1H, H^4, ^3J 9.3, 2.7 Hz), 5.24 d (1H, H^3, ^3J 9.3 Hz), 6.20 br (1H, $CHBr_2$). $^{13}C-\{^1H\}$ NMR spectrum (in CD_2Cl_2), δ_C, ppm: 28.50 (Me), 47.00 ($CHBr_2$), 47.2, 51.3, 54.8, 57.7 all broad (C^{3-6}), 60.83 (C^2), 194.38 (C=O). IR spectrum, ν, cm^{-1}: 1755. Found, %: C 15.92, H 1.40. $C_8H_8Br_6O$. Calculated, %: C 16.02, H 1.33.

6-Dibromomethyl-6-methyl-2,4,5-tribromocyclohexa-2-en-1-one (VI). Isolated as a mixture of steic isomers **VIa** and **VIb**. Yellow oil, $R_f = 0.15$. IR spectrum, ν, cm^{-1}: 1610, 1715. UV spectrum: λ_{max} 265 nm (log ε 3.78), 331 nm (log ε 2.92). Found, %: C 18.69, H 1.52. $C_8H_7Br_5O$. Calculated, %: C 18.49, H 1.34. Isomer **VIa,** ^1H NMR spectrum, δ, ppm: 1.65 s (3H, Me), 4.96 d (1H, H^5, ^3J 4.2 Hz), 5.17 br. t (1H, H^4), 6.41 br (1H, $CHBr_2$), 7.28 d (1H, H^3, ^3J 3.9 Hz). $^{13}C-$

{^{1}H} NMR spectrum, δ_C, ppm: 20.46 br.s (Me), 45.6, 54.9, both broad. ($CHBr_2$, $C^{4,5}$), 58.70 (C^6), 122.96 (C^2), 142.0 br (C^3), 185.55 (C=O). Isomer **VIb**, ^{1}H NMR spectrum, δ, ppm: 1.98 s (3H, Me), 5.00 br.d.d (1H, H^5), 5.40 d.d (1H, H^4, ^3J 4.6, 2.9 Hz), 6.16 s (1H, $CHBr_2$), 7.16 d.d (1H, H^3, ^3J 4.6 Hz, ^4J 1.4 Hz).

2,4-Dibromo-6-dibromomethyl-6-methylcyclohexyl-2,4-dien-1-one (VII). White crystals, mp 92–93°C (reprecipitation from CH_2Cl_2 to hexane). ^{1}H NMR spectrum, δ, ppm: 1.40 s (3H, Me), 5.90 s (1H, $CHBr_2$), 6.93 d (1H, H^5, ^4J 2.0 Hz), 7.57 d (1H, H^3, ^4J 2.0 Hz) . ^{13}C–{^{1}H} NMR spectrum, δ_C, ppm: 25.86 (Me), 48.35 ($CHBr_2$), 61.14 (C^6), 114.78, 123.44 ($C^{2,4}$), 140.20, 146.61 ($C^{3,5}$), 191.08 (C=O). IR spectrum, ν, cm^{-1}: 1625, 1680. UV spectrum, λ_{max} 329 nm (lgε 3.74). Found, %: C 22.10, H 1.32. $C_8H_6Br_4O$. Calculated, %: C 21.91, H 1.36.

4-Bromo-6-dibromomethyl-6-methylcyclohexyl-2,4-dien-1-one (VIII). ^{1}H NMR spectrum, δ, ppm: 1.35 s (3H, Me), 5.89 s (1H, $CHBr_2$), 6.04 d (1H, H^2, ^3J 10.1 Hz), 6.93 d (1H, H^5, ^4J 2.3 Hz) , 8.7 d.d (1H, H^3, ^3J 10.1 Hz, ^4J 2.3 Hz). ^{13}C–{^{1}H} NMR spectrum, δ_C, ppm: 25.53 (Me), 49.04 ($CHBr_2$), 59.94 (C^6), 123.43 (C^4), 126.76 (C^2), 140.48, 145.73 ($C^{3,5}$), 197.64 (C=O).

3,5-Dibromo-1,7-di(dibromomethyl)-1,7-dimethyl-5,8-ethenodecaline-2,6-dione (IX). Ketone **III** was held for six months at room temperature, and the pale yellow oil crystallized. Yield quantitative, mp 183°C (reprecipitation from CH_2Cl_2 to hexane). ^{1}H NMR spectrum, δ, ppm: 1.51, 1.59, both broad (3H, 1,7-Me), 3.18 d.d (1H, H^{8a}, ^3J 8.3, 1.5 Hz), 3.22 d.d.d (1H , H^8, ^3J 6.5, 1.5 Hz, ^4J 1.8 Hz), 3.36 d.d.d (1H, H^{4a}, ^3J 8.3, 4.3 Hz, ^4J 0.8 Hz), 5.73, 5.77, both broad (1H, 1,7-$CHBr_2$) , 6.22 d.d.d (1H, H^{10}, ^3J 8.4 Hz, ^4J 1.8, 0.8 Hz), 6.36 d.d (1H, H^9, ^3J 8.4, 6.5 Hz), 7.26 d (1H, H^4, ^3J 4.3 Hz) . ^{13}C–{^{1}H} NMR spectrum, δ_C, ppm: 16.93, 18.36 (1,7-Me), 42.88, 44.86, 48.58, 49.79, 53.00 ($C^{4a,8,8a}$, 1,7-$CHBr_2$), 54.16 , 57.13 (C^1, 7), 70.35 (C^5), 123.28 (C^3), 132.92, 135.16, 142.75 (C^4, 9,10), 189.73 (2-C=O), 197.78 (6-C=O). IR spectrum, ν, cm^{-1}: 1620, 1710, 1745. UV spectrum, λ_{max} 205 nm (log ε 4.29), 263 nm (log ε 4.02). Found, %: C 26.90, H 2.10. $C_{16}H_{14}Br_6O_2$. Calculated, %: C 26.74, H 1.94.

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