## Nitro derivatives of *N*-alkylbenzoaza-15-crown-5: synthesis, structures, and complexation with metal and ammonium cations\*

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A number of *N*-alkylnitrobenzoaza-15-crown-5 with the macrocycle N atom conjugated with the benzene ring were obtained. The structural and complexing properties of these compounds were compared with those of model nitrobenzo- and *N*-(4-nitrophenyl)aza-15-crown-5 using X-ray diffraction, <sup>1</sup>H NMR spectroscopy, and DFT calculations. The macrocyclic N atom of benzoazacrown ethers are characterized by a considerable contribution of the sp<sup>3</sup>-hybridized state and a pronounced pyramidal geometry; the crownlike conformation of the macrocycle is preorganized for cation binding, which facilitates complexation. The stability constants of the complexes of crown ethers with the  $NH_4^+$ ,  $EtNH_3^+$ ,  $Na^+$ ,  $K^+$ ,  $Ca^{2+}$ , and  $Ba^{2+}$  ions were determined by <sup>1</sup>H NMR titration in MeCN-d<sub>3</sub>. The most stable complexes were obtained with alkaline-earth metal cations, which is due to the higher charge density at these cations. The characteristics of the complexing ability of *N*-alkyl-nitrobenzoaza-15-crown-5 toward alkaline earth metal cations are comparable with analogous characteristics of nitrobenzo-15-crown-5 and are much better than those of *N*-(4-nitrophenyl)aza-15-crown-5.

**Key words:** benzoazacrown ethers, synthesis, structures, complexation, metal cations, ammonium ions, stability constants, X-ray diffraction analysis, <sup>1</sup>H NMR spectroscopy, quantum chemical calculations, density functional theory.

The most important property of crown compounds is their ability to form stable complexes with metal ions, organic cations, and neutral polar molecules. Because of this ability, crown compounds are employed as selective ligands for metal cations (also in extraction processes), ion-selective electrodes, photosensitive systems, *etc*.

The synthesis of azacrown compounds with various combinations of the N and O atoms in the macrocycle is still of relentless interest.<sup>1-3</sup> Of particular interest from the viewpoint of using azacrown fragments as part of photosensitive ligands are those in which the N atom is conjugated with a chromophore. Such azacrown compounds absorb at much longer wavelengths than crown ether de-

rivatives, which is essential in photometric and fluorescence analyses, photocontrolled extraction, photocontrolled ion transportation across membranes, as well as for the design of photosensitive molecular devices. At present, substituted phenylazacrown ethers are most commonly used for these purposes; however, they have an essential drawback: their constants of complexation with metal ions are low. In this respect, benzoannulated derivatives of azacrown ethers can enjoy considerable advantages. Despite their simple structures, 1-aza-2,3-benzocrown ethers are poorly studied because most of their functional derivatives are scarcely accessible.<sup>3</sup> Earlier,<sup>4</sup> we have obtained formyl and nitro derivatives of N-methylbenzoazacrown compounds by stepwise transformation of the macrocycles of benzocrown ethers. This new strategy of the synthesis of functionalized azacrown ethers seems to be a promising

\* Dedicated to Academician I. L. Eremenko on his 60th birthday.

Published in Russian in Izvestiya Akademii Nauk. Seriya Khimicheskaya, No. 6, pp. 1167–1181, June, 2010.

1066-5285/10/5906-1192 © 2010 Springer Science+Business Media, Inc.

alternative to the currently existing routes to 1-aza-2,3benzocrown ethers.<sup>4</sup>

In the present work, we obtained *N*-alkylnitrobenzoazacrown ethers **1b**—**d** and compared the structural and complexing characteristics of azacrown ethers **1a**—**d** and the model compounds nitrobenzo- (2) and *N*-(4-nitrophenyl)aza-15-crown-5 (3) using X-ray diffraction, <sup>1</sup>H NMR spectroscopy, and DFT calculations. The stability constants of complexes of these crown ethers with alkali metal, alkaline-earth metal, and ammonium ions were determined using <sup>1</sup>H NMR titration.



1: R = Me (a), Et (b), Pr (c), CH<sub>2</sub>Ph (d)

## **Results and Discussion**

**Synthesis of nitrobenzoazacrown ethers.** Earlier, <sup>5,6</sup> we have found that nitrobenzocrown ethers undergo nucleophilic opening of the macrocycle in the presence of alkyl-

amines containing hydrocarbon radicals with different lengths and branching degrees. The resulting nitrogencontaining podands have been employed for the synthesis of *N*-methylbenzoazacrown ethers (*e.g.*, **1a**) in which the macrocycle N atom is conjugated with the benzene ring.<sup>7–9</sup> Here we extended this approach to the synthesis of *N*-alkylnitrobenzoaza-15-crown-5 **1** (Scheme 1).

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By heating nitrobenzocrown ether 2 with alcoholic solutions of alkylamines according to a modified procedure,<sup>6</sup> we obtained nitrogen-containing podands 4b-f. The presence of the secondary amino group and the terminal hydroxy group in their molecules allows intramolecular cyclization into previously unknown N-alkylnitrobenzoazacrown ethers. For successful cyclization of azapodands 4b-f into benzoazacrown ethers, first we should modify their hydroxy group by exchanging it for a good leaving group. To do this, we treated podands **4b**-**f** with SOCl<sub>2</sub> in the presence of pyridine to give chlorides 5b-f in 88–94% yields. Then the Cl atom in compounds 5b-f was replaced by an iodine atom; the yields of iodides 6b-fwere 88–98%. Cyclization of the latter under the action of NaH produced the target N-alkylnitrobenzoazacrown ethers 1. The yields of azacrown ethers 1b-f are given in Table 1. For comparison, the yield of N-methylbenzoazacrown ether **1a** obtained earlier<sup>9</sup> is also included. The vinyl ethers, which are formed via HI elimination<sup>9</sup> as by-products in the cyclization of the iodides, were not isolated in this work.

We found that an increase in the length and bulkiness of the substituent at the N atom of iodine-containing podands **6** lowers the yields of benzoazacrown ethers **1** and, on the whole, increases the cyclization time of iodides **6**. For instance, the maximum yield (53%) was achieved for

Ŗ Ŗ Cl HO RNH<sub>2</sub> SOC1<sub>2</sub>, Py CHC13  $O_2N$ O<sub>2</sub>N  $O_2N$ 2 5a—f 4a—1 R R NaI NaH THF Me<sub>2</sub>CO  $O_2N$ O<sub>2</sub>N 6a-f 1a-f

Scheme 1

R = Me(a), Et(b), Pr(c), PhCH<sub>2</sub>(d), Pr<sup>i</sup>(e), PhMeCH(f)

Table 1. Conditions for the cyclization of iodides 6a-funder the action of NaH in THF and the yields of the corresponding nitrobenzoazacrown ethers 1a-f

Iodide	R	<i>t/</i> h	<i>T</i> /°C	Yield of <b>1</b> (%)
6a	Me	0.5	64	80
		2.5	25	74
6b	Et	10	64	53
6c	Pr	2.5	64	48
		125	25	44
6d	PhCH <sub>2</sub>	8	64	46
	-	95	25	41
6e	Pr <sup>i</sup>	17	64	0
		170	25	0
6f	PhMeCH	70	25	0

*Note. t* is the reaction time; *T* is the temperature.

*N*-ethylnitrobenzoazacrown ether **1b**, which is much lower than the yield of *N*-methylnitrobenzoazacrown ether **1a** (80%). The yields of nitrobenzoazacrown ethers **1b**—**d** with the substituents Et, Pr, and CH<sub>2</sub>Ph differ insignificantly (53, 48, and 46%, respectively). Podands **6e**,**f** containing the bulkiest substituents (isopropyl and  $\alpha$ -phenylethyl) at the N atom did not undergo cyclization into products **1e**,**f**. The cyclization at room temperature results in slightly lower yields of the target nitrobenzoazacrown ethers **1** compared to the cyclization in boiling THF, the reaction time being substantially longer (TLC).

Apparently, the mechanism of the cyclization of iodides **6** into nitrobenzoazacrown ethers **1** can be described as follows: a strong base such as NaH abstracts the proton from iodide **6** to form reactive arylamide anion **7**, which undergoes cyclization into the final product unless a bulky N-substituent presents considerable steric hindrances at the reactive site (Scheme 2).

Model *N*-(4-nitrophenyl)aza-15-crown-5 **3** was obtained in 86% yield by a reaction of aza-15-crown-5 with an excess of 1-fluoro-4-nitrobenzene in the presence of triethylamine according to a modified procedure.<sup>10</sup>

The structures of the compounds obtained were determined by <sup>1</sup>H and <sup>13</sup>C NMR spectroscopy, IR spectroscopy, and mass spectrometry (including high-resolution mass spectrometry) and confirmed by elemental analysis data (Tables 2-4).

Com- pound	Yield (%)	[M] <sup>+</sup> , <i>m/z</i> <u>Found</u> Calculated	Molecular formula
1 <b>b</b> <sup><i>a</i></sup>	53	<u>340.1628</u> 340.1635	$C_{16}H_{24}N_2O_6$
1c	48	<u>354.1783</u> 354.1791	$C_{17}H_{26}N_2O_6$
1d	46	<u>402.1787</u> 402.1791	$C_{21}H_{26}N_2O_6$
5b	94	<u>376.1403</u> 376.1401 <sup>b</sup>	C <sub>16</sub> H <sub>25</sub> ClN <sub>2</sub> O <sub>6</sub>
5c	92	<u>390.1550</u> 390.1557 <sup>b</sup>	C <sub>17</sub> H <sub>27</sub> ClN <sub>2</sub> O <sub>6</sub>
5d	94	$\frac{438.1550}{438.1557^b}$	$C_{21}H_{27}CIN_2O_6$
5e	91	390.1550 390.1557 <sup>b</sup>	C <sub>17</sub> H <sub>27</sub> ClN <sub>2</sub> O <sub>6</sub>
5f	88	$\frac{452.1718}{452.1714^b}$	C <sub>22</sub> H <sub>29</sub> ClN <sub>2</sub> O <sub>6</sub>
6b	98	<u>468.0755</u> 468.0757	$C_{16}H_{25}IN_2O_6$
6c	95	<u>482.0912</u> 482.0914	C <sub>17</sub> H <sub>27</sub> IN <sub>2</sub> O <sub>6</sub>
6d	95	<u>530.0919</u> 530.0914	$C_{21}H_{27}IN_2O_6$
6e	92	<u>482.0913</u> 482.0914	$C_{17}H_{27}IN_2O_6$
6f	88	<u>544.1070</u> 544.1071	$C_{22}H_{29}IN_2O_6$

Table 2. Yields and high-resolution mass spectra of

compounds 1b-d, 5b-f, and 6b-f

<sup>*a*</sup> Found (%): C, 56.41; H, 7.21; N, 8.19.  $C_{16}H_{24}N_2O_6$ . Calculated (%): C, 56.46; H, 7.11; N, 8.23.

<sup>b</sup> For the ion with <sup>35</sup>Cl.

X-ray diffraction study. Single crystals of model crown ethers 2 and 3 and a complex of benzoazacrown ether 1a with barium perchlorate were studied; the structures of these compounds are shown in Fig. 1. The structure of free azacrown ether 1a has been examined earlier.<sup>9</sup> In the present work, we compared the conformational features of these compounds; for convenience, we used the same numbering of atoms in the benzocrown ether system that is different from the IUPAC rules. It is worth noting that the crystal structure of compound 2 has been loosely deter-



Table 3. IR and	<sup>1</sup> H NMR spectra of	compounds 1	b—d, 5b—1	f, and <b>6b—f</b>
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Com- pound	IR (KBr), $v/cm^{-1}$	<sup>1</sup> H NMR (CDCl <sub>3</sub> ), $\delta (J/Hz)$
1b	1498 (NO <sub>2</sub> )	1.20 (t, 3 H, Me, $J = 7.1$ ); 3.41 (q, 2 H, CH <sub>2</sub> N, $J = 7.1$ ); 3.56 (t, 2 H, NCH <sub>2</sub> CH <sub>2</sub> O, $J = 7.0$ ); 3.68, 3.71 (both m, 4 H each, 4 CH <sub>2</sub> O); 3.87 (t, 2 H, NCH <sub>2</sub> CH <sub>2</sub> O, $J = 7.0$ ); 3.93 (m, 2 H, CH <sub>2</sub> CH <sub>2</sub> OAr); 4.20 (m, 2 H, CH <sub>2</sub> OAr); 6.73 (d, 1 H, H(14), $J = 9.2$ ); 7.65 (d, 1 H, H(17), J = 2.5); 7.80 (dd, 1 H, H(15), $J = 9.2$ , $J = 2.5$ )
1c	1510 (NO <sub>2</sub> )	0.91 (t, 3 H, Me, $J = 7.3$ ); 1.61 (m, 2 H, CH <sub>2</sub> ); 3.30 (t, 2 H, CH <sub>2</sub> N, $J = 7.6$ ); 3.56 (t, 2 H, NCH <sub>2</sub> CH <sub>2</sub> O, $J = 7.2$ ); 3.67, 3.70 (both s, 4 H each, 4 CH <sub>2</sub> O); 3.86 (t, 2 H, NCH <sub>2</sub> CH <sub>2</sub> O, $J = 7.2$ ); 3.92 (m, 2 H, CH <sub>2</sub> CH <sub>2</sub> OAr); 4.20 (m, 2 H, CH <sub>2</sub> OAr); 6.70 (d, 1 H, H(14), $J = 8.6$ ); 7.65 (d, 1 H, H(17), $J = 1.9$ ); 7.79 (dd, 1 H, H(15), $J = 8.9$ , $J = 1.9$ )
1d	1494 (NO <sub>2</sub> )	3.65 (t, 2 H, NC $\underline{H}_2$ CH <sub>2</sub> O, $J = 6.9$ ); 3.67, 3.74 (both m, 4 H each, 4 CH <sub>2</sub> O); 3.97 (t, 2 H, NCH <sub>2</sub> C $\underline{H}_2$ O, $J = 6.9$ ); 3.98 (m, 2 H, 2 C $\underline{H}_2$ CH <sub>2</sub> OAr); 4.27 (m, 2 H, C $\underline{H}_2$ OAr); 4.64 (s, 2 H, NC $\underline{H}_2$ Ph); 6.66 (d, 1 H, H(14), $J = 9.2$ ); 7.23 (m, 3 H, H(2'), H(4'), H(6')); 7.31 (m, 2 H, H(3'), H(5')); 7.69 (d, 1 H, H(17), $J = 2$ 3); 7.71 (dd 1 H, H(15), $J = 9.2$ , $J = 2$ 3)
5b	3414 (NH); 1497 (NO <sub>2</sub> )	1.31 (t, 3 H, Me, $J = 7.4$ ); 3.28 (q, 2 H, CH <sub>2</sub> N, $J = 7.3$ ); 3.61 (t, 2 H, CH <sub>2</sub> Cl, $J = 5.8$ ); 3.66 (s, 4 H, 2 CH <sub>2</sub> O); 3.70 (m, 4 H, 2 CH <sub>2</sub> O); 3.74 (t, 2 H, CH <sub>2</sub> CH <sub>2</sub> Cl, $J = 5.8$ ); 3.88 (m, 2 H, CH <sub>2</sub> CH <sub>2</sub> OAr); 4.22 (m, 2 H, CH <sub>2</sub> OAr); 5.18 (br.s, 1 H, NH); 6.48 (d, 1 H, H(6), $J = 8.9$ ); 7.65 (d, 1 H, H(3), $J = 2.4$ ); 7.89 (dd, 1 H, H(5), $J = 8.9$ , $J = 2.5$ )
5c	3413 (NH); 1497 (NO <sub>2</sub> )	1.02 (t, 3 H, Me, $J = 7.4$ ); 1.70 (m, 2 H, CH <sub>2</sub> ); 3.20 (t, 2 H, CH <sub>2</sub> N, $J = 7.1$ ); 3.61 (t, 2 H, CH <sub>2</sub> Cl, $J = 5.9$ ); 3.66, 3.70 (both m, 4 H each, 4 CH <sub>2</sub> O); 3.74 (t, 2 H, CH <sub>2</sub> CH <sub>2</sub> Cl, $J = 5.9$ ); 3.88 (m, 2 H, CH <sub>2</sub> CH <sub>2</sub> OAr); 4.22 (m, 2 H, CH <sub>2</sub> OAr); 5.24 (br.s, 1 H, NH); 6.48 (d, 1 H, H(6), $J = 9.1$ ); 7.65 (d, 1 H, H(3), $J = 2.1$ ); 7.89 (dd, 1 H, H(5), $J = 9.1$ , $J = 2.1$ )
5d	3410 (NH, OH); 1494 (NO <sub>2</sub> )	3.59 (t, 2 H, CH <sub>2</sub> Cl, $J = 5.8$ ); 3.63 (s, 4 H, 2 CH <sub>2</sub> O); 3.66, 3.69 (both m, 2 H each, 2 CH <sub>2</sub> O); 3.72 (t, 2 H, CH <sub>2</sub> CH <sub>2</sub> Cl, $J = 5.8$ ); 3.89 (m, 2 H, CH <sub>2</sub> CH <sub>2</sub> OAr); 4.26 (m, 2 H, CH <sub>2</sub> OAr); 4.48 (br.s, 2 H, NCH <sub>2</sub> Ph); 6.47 (d, 1 H, H(6), $J = 8.9$ ); 7.26 (m, 1 H, H(4')); 7.31–7.38 (m, 4 H, H(2'), H(3'), H(5'), H(6')); 7.69 (d, 1 H, H(3), $J = 2.4$ ); 7.84 (dd, 1 H, H(5), J = 8.9, J = 2.4)
5e	3400 (NH); 1497 (NO <sub>2</sub> )	1.20 (d, 6 H, 2 Me, $J = 6.7$ ); 3.56 (m, 2 H, CH <sub>2</sub> Cl, $J = 5.8$ ); 3.61 (s, 4 H, 2 CH <sub>2</sub> O); 3.64 (m, 7 H, 3 CH <sub>2</sub> O, CHN); 3.82 (m, 2 H, CH <sub>2</sub> CH <sub>2</sub> OAr); 4.15 (m, 2 H, CH <sub>2</sub> OAr); 6.42 (d, 1 H, H(6), $J = 8.8$ ); 7.57 (d, 1 H, H(3), $J = 2.5$ ); 7.80 (dd, 1 H, H(5), $J = 8.8$ , $J = 2.5$ )
5f	3409 (NH); 1498 (NO <sub>2</sub> )	1.61 (d, 3 H, Me, $J = 7.0$ ); 3.61 (t, 2 H, CH <sub>2</sub> Cl, $J = 5.9$ ); 3.66 (m, 4 H, CH <sub>2</sub> O); 3.69–3.76 (m, 6 H, 3 CH <sub>2</sub> O); 3.94 (m, 2 H, C <u>H</u> <sub>2</sub> CH <sub>2</sub> OAr); 4.27 (m, 2 H, C <u>H</u> <sub>2</sub> OAr); 4.60 (q, 1 H, CHN, $J = 7.0$ ); 6.30 (d, 1 H, H(3), $J = 8.8$ ); 7.26 (m, 1 H, H(4')); 7.30–7.35 (m, 4 H, H(2'), H(3'), H(5'), H(6')); 7.67 (d, 1 H, H(6), $J = 2.1$ ); 7.71 (dd, 1 H, H(4), $J = 8.8, J = 2.1$ )
6b	3401 (NH); 1496 (NO <sub>2</sub> )	1.28 (t, 3 H, Me, $J = 7.0$ ); 3.24 (t, 2 H, CH <sub>2</sub> I, $J = 7.0$ ); 3.28 (q, 2 H, CH <sub>2</sub> N, $J = 7.0$ ); 3.65 (s, 4 H, 2 CH <sub>2</sub> O); 3.70 (m, 4 H, 2 CH <sub>2</sub> O); 3.73 (t, 2 H, CH <sub>2</sub> CH <sub>2</sub> I, $J = 7.0$ ); 3.89 (m, 2 H, CH <sub>2</sub> CH <sub>2</sub> OAr); 4.22 (m, 2 H, CH <sub>2</sub> OAr); 5.17 (br.s, 1 H, NH); 6.48 (d, 1 H, H(6), $J = 8.7$ ); 7.64 (d, 1 H, H(3), $J = 2.2$ ); 7.89 (dd, 1 H, H(5), $J = 8.7$ , $J = 2.2$ )
6с	3402 (NH); 1496 (NO <sub>2</sub> )	1.70 (m, 2 H, CH <sub>2</sub> ); 3.21 (t, 2 H, CH <sub>2</sub> I, $J = 7.3$ ); 3.25 (t, 2 H, CH <sub>2</sub> N, $J = 6.7$ ); 3.66, 3.71 (both m, 4 H each, 4 CH <sub>2</sub> O); 3.74 (t, 2 H, CH <sub>2</sub> CH <sub>2</sub> I, $J = 7.3$ ); 3.89 (m, 2 H, CH <sub>2</sub> CH <sub>2</sub> OAr); 4.23 (m, 2 H, CH <sub>2</sub> OAr); 5.23 (br.s, 1 H, NH); 6.49 (d, 1 H, H(6), $J = 8.7$ ); 7.65 (d, 1 H, H(3), $J = 2.2$ ); 7.90 (dd, 1 H, H(5), $J = 8.7$ , $J = 2.2$ )
6d	3415 (NH); 1496 (NO <sub>2</sub> )	3.23 (t, 2 H, CH <sub>2</sub> I, $J = 7.0$ ); 3.63 (s, 4 H, 2 CH <sub>2</sub> O); 3.66 (m, 2 H, CH <sub>2</sub> O); 3.70 (m, 2 H, CH <sub>2</sub> O); 3.72 (t, 2 H, CH <sub>2</sub> CH <sub>2</sub> I, $J = 7.0$ ); 3.90 (m, 2 H, CH <sub>2</sub> CH <sub>2</sub> OAr); 4.27 (m, 2 H, CH <sub>2</sub> OAr); 4.49 (s, 2 H, NCH <sub>2</sub> Ph); 5.71 (br.s, 1 H, NH); 6.48 (d, 1 H, H(6), $J = 9.0$ ); 7.27 (m, 1 H, H(4')); 7.31–7.36 (m, 4 H, H(2'), H(3'), H(5'), H(6')); 7.71 (d, 1 H, H(3), $J = 2.0$ ); 7.86 (dd, 1 H, H(5), $J = 9.0, J = 2.0$ )
6e	3399 (NH); 497 (NO <sub>2</sub> )	1.32 (d, 6 H, 2 Me, $J = 6.5$ ); 3.25 (t, 2 H, CH <sub>2</sub> I, $J = 7.1$ ); 3.66 (s, 4 H, 2 CH <sub>2</sub> O); 3.68–3.78 (m, 7 H, CHN, 3 CH <sub>2</sub> O); 3.91 (m, 2 H, CH <sub>2</sub> CH <sub>2</sub> OAr); 4.26 (m, 2 H, CH <sub>2</sub> OAr); 6.71 (d, 1 H, H(6), $J = 8.8$ ); 7.71 (d, 1 H, H(3), $J = 2.3$ ); 7.90 (dd, 1 H, H(5), $J = 8.8$ , $J = 2.3$ )
6f	3418 (NH); 1497 (NO <sub>2</sub> )	1.59 (d, 3 H, Me, $J = 6.7$ ); 3.21 (t, 2 H, CH <sub>2</sub> I, $J = 6.9$ ); 3.61 (m, 4 H, 2 CH <sub>2</sub> O); 3.63 (m, 6 H, 2 CH <sub>2</sub> O, CH <sub>2</sub> CH <sub>2</sub> I); 3.91 (m, 2 H, CH <sub>2</sub> CH <sub>2</sub> OAr); 4.26 (m, 2 H, CH <sub>2</sub> OAr); 4.58 (q, 1 H, CHN, J = 6.7); 6.29 (d, 1 H, H(6), $J = 8.9$ ); 7.22 (m, 1 H, H(4')); 7.26–7.32 (m, 4 H, H(2'), H(3'), H(5'), H(6')); 7.65 (d, 1 H, H(3), $J = 2.3$ ); 7.69 (dd, 1 H, H(5), $J = 8.9, J = 2.3$ )

Table 4.	<sup>13</sup> C NMR	and m	nass spectra	of compour	nds 1b—a	l, 5b—	f, and f	ób−f
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Com- pound	$\frac{^{13}\text{C NMR (CDCl}_3)}{\delta (J/\text{Hz})},$	$\frac{\text{MS},}{m/z  (I_{\text{rel}}(\%))^a}$
1b	12.10 (Me); 46.56 (CH <sub>2</sub> N); 52.18 (N <u>C</u> H <sub>2</sub> CH <sub>2</sub> O); 68.54 (CH <sub>2</sub> O); 69.21 (CH <sub>2</sub> O); 69.54 (CH <sub>2</sub> O); 70.02 (CH <sub>2</sub> O); 70.08 (CH <sub>2</sub> O); 70.15 (CH <sub>2</sub> O); 70.71 (CH <sub>2</sub> O); 107.68 (C(17)); 114.66 (C(14)); 118.36 (C(15)); 138.94 (C(16)); 146.25, 148.72 (C(13a), C(17a))	340 [M] <sup>+</sup> (81), 339 (100), 325 (20), 309 (12), 209 (11), 196 (11), 195 (54), 194 (18), 193 (37), 179 (13)
1c	11.36 (Me); 20.01 (CH <sub>2</sub> ); 53.01 (N $\subseteq$ H <sub>2</sub> CH <sub>2</sub> O); 54.24 (CH <sub>2</sub> N); 68.58 ( $\subseteq$ H <sub>2</sub> OAr); 69.27 ( $\subseteq$ H <sub>2</sub> CH <sub>2</sub> OAr); 69.51 (NCH <sub>2</sub> $\subseteq$ H <sub>2</sub> O); 70.05 (CH <sub>2</sub> O); 70.14 (CH <sub>2</sub> O); 70.22 (CH <sub>2</sub> O); 70.70 (CH <sub>2</sub> O); 107.76 (C(17)); 114.93 (C(14)); 118.32 (C(15)); 138.96 (C(16)); 146.35 (C(13a)); 148.77 (C(17a))	354 [M] <sup>+</sup> (57), 353 (49), 326 (26), 325 (100), 295 (12), 237 (14), 209 (19), 207 (13), 193 (19), 179 (20)
1d	52.82 (N $\subseteq$ H <sub>2</sub> CH <sub>2</sub> O); 56.00 (N $\subseteq$ H <sub>2</sub> Ph); 68.73 ( $\subseteq$ H <sub>2</sub> OAr); 69.29 (CH <sub>2</sub> O); 69.70 (CH <sub>2</sub> O); 70.01 (CH <sub>2</sub> O); 70.18 (2 CH <sub>2</sub> O); 70.92 (CH <sub>2</sub> O); 107.74 (C(17)); 115.94 (C(14)); 118.16 (C(15)); 126.99 (C(2 <sup>'</sup> ), C(6 <sup>'</sup> )); 127.10 (C(4 <sup>'</sup> )); 128.60 (C(3 <sup>'</sup> ), C(5 <sup>'</sup> )); 137.27 (C(1 <sup>'</sup> )); 139.49 (C(16)); 146.43 (C(13a)); 148.81 (C(17a))	402 [M] <sup>+</sup> (74), 372 (31), 165 (29), 147 (37), 120 (31), 106 (33), 105 (31), 92 (40), 91 (100), 65 (30)
5b	14.30 (Me); 37.50 (CH <sub>2</sub> N); 42.66 (CH <sub>2</sub> Cl); 68.60 (CH <sub>2</sub> O); 69.40 (CH <sub>2</sub> O); 70.57 (CH <sub>2</sub> O); 70.61 (CH <sub>2</sub> O); 70.66 (2 CH <sub>2</sub> O); 71.30 (CH <sub>2</sub> O); 106.61, 106.78 (C(3), C(6)); 120.46 (C(5)); 136.61 (C(4)); 144.04, 144.75 (C(1), C(2))	378 [M] <sup>+</sup> (2) <sup>b</sup> , 376 [M] <sup>+</sup> (16) <sup>c</sup> , 182 (20), 167 (16), 151 (17), 149 (23), 135 (21), 107 (42), 78 (12), 65 (32), 63 (100)
5c	11.66 (Me); 22.45 (CH <sub>2</sub> ); 42.95 (CH <sub>2</sub> Cl); 44.89 (CH <sub>2</sub> N); 68.84 (CH <sub>2</sub> O); 69.61 (CH <sub>2</sub> O); 70.74 (CH <sub>2</sub> O); 70.83 (3 CH <sub>2</sub> O); 71.50 (CH <sub>2</sub> O); 106.84, 106.95 (C(3), C(6)); 120.55 (C(5)); 136.59 (C(4)); 144.29, 145.20 (C(1), C(2))	392 [M] <sup>+</sup> (12) <sup>b</sup> , 390 [M] <sup>+</sup> (40) <sup>c</sup> , 361 (15), 196 (17), 195 (17), 193 (28), 167 (20), 109 (21), 107 (63), 65 (32), 63 (100)
5d	29.66 (MeN); 31.49 (CH <sub>2</sub> S); 31.63 (CH <sub>2</sub> S); 32.04 (CH <sub>2</sub> S); 35.99 (CH <sub>2</sub> S); 60.93 (CH <sub>2</sub> OH); 68.34 ( <u>C</u> H <sub>2</sub> OAr); 70.32 (2 CH <sub>2</sub> O); 71.18 (CH <sub>2</sub> O); 71.39 (CH <sub>2</sub> O); 106.02 (C(6)); 106.38 (C(3)); 120.36 (C(4)); 136.83 (C(5)); 143.96 (C(1)); 145.44 (C(2))	420 [M] <sup>+</sup> (12), 255 (25), 254 (28), 253 (100), 225 (93), 149 (44), 109 (27), 105 (94), 87 (49), 61 (92), 60 (29)
5e	42.91 (CH <sub>2</sub> Cl); 47.25 (N <u>C</u> H <sub>2</sub> Ph); 69.10 (CH <sub>2</sub> O); 69.64 (CH <sub>2</sub> O); 70.79 (CH <sub>2</sub> O); 70.89 (3 CH <sub>2</sub> O); 71.54 (CH <sub>2</sub> O); 107.37, 107.69 (C(3), C(6)); 120.43 (C(5)); 127.29 (C(2'), C(6')); 127.80 (C(4')); 129.04 (C(3'), C(5')); 137.47, 137.94 (C(1'), C(4)); 144.58, 144.84 (C(1), C(2))	392 [M] <sup>+</sup> (17) <sup>b</sup> , 390 [M] <sup>+</sup> (46) <sup>c</sup> , 375 (27), 207 (19), 196 (14), 195 (13), 181 (20), 109 (19), 107 (66), 64 (31), 63 (100)
5f	24.66 (Me); 42.95 (CH <sub>2</sub> Cl); 53.45 (CHN); 69.10 (CH <sub>2</sub> O); 69.67 (CH <sub>2</sub> O); 70.85 (CH <sub>2</sub> O); 70.95 (3 CH <sub>2</sub> O); 71.52 (CH <sub>2</sub> O); 107.26 (C(3)); 109.21 (C(6)); 120.12 (C(5)); 125.93 (C(2 <sup>'</sup> ), C(6 <sup>'</sup> )); 127.66 (C(4 <sup>'</sup> )); 129.09 (C(3 <sup>'</sup> ), C(5 <sup>'</sup> )); 137.56 (C(4)); 144.48 (C(1), C(1 <sup>'</sup> )); 144.57 (C(2))	454 [M] <sup>+</sup> (8) <sup>b</sup> , 452 [M] <sup>+</sup> (21) <sup>c</sup> , 439 (6), 437 (15), 107 (14), 106 (10), 105 (100), 79 (5), 77 (6), 65 (7), 63 (24)
6b	2.78 (CH <sub>2</sub> I); 14.32 (Me); 37.82 (CH <sub>2</sub> N); 68.58 (CH <sub>2</sub> O); 69.40 (CH <sub>2</sub> O); 70.14 (CH <sub>2</sub> O); 70.51 (CH <sub>2</sub> O); 70.65 (2 CH <sub>2</sub> O); 71.89 (CH <sub>2</sub> O); 106.59, 106.76 (C(3), C(6)); 120.35 (C(5)); 136.56 (C(4)); 144.00, 144.72 (C(1), C(2))	468 [M] <sup>+</sup> (53), 209 (7), 199 (20), 193 (6), 182 (22), 181 (14), 167 (11), 155 (100), 135 (12), 78 (10)
6c	2.74 (CH <sub>2</sub> I); 11.08 (Me); 21.83 (CH <sub>2</sub> ); 44.21 (CH <sub>2</sub> N); 68.27 (CH <sub>2</sub> O); 68.95 (CH <sub>2</sub> O); 69.69 (CH <sub>2</sub> O); 70.18 (3 CH <sub>2</sub> O); 71.41 (CH <sub>2</sub> O); 106.31, 106.16 (C(3), C(6)); 119.87 (C(5)); 135.88 (C(4)); 143.64, 144.56 (C(1), C(2))	482 [M] <sup>+</sup> (47), 452 (7), 199 (17), 196 (13), 195 (8), 193 (14), 167 (16), 155 (100), 149 (6), 119 (6)
6d	2.41 (CH <sub>2</sub> I); 46.44 (N $\subseteq$ H <sub>2</sub> Ph); 68.32 (CH <sub>2</sub> O); 68.85 (CH <sub>2</sub> O); 69.60 (CH <sub>2</sub> O); 70.01 (CH <sub>2</sub> O); 70.10 (2 CH <sub>2</sub> O); 71.33 (CH <sub>2</sub> O); 106.92, 106.56 (C(3), C(6)); 119.65 (C(5)); 126.50 (C(2'), C(6')); 127.00 (C(4')); 128.25 (C(3'), C(5')); 136.33, 137.21 (C(1'), C(4)); 143.82, 144.12 (C(1), C(2))	530 [M] <sup>+</sup> (21), 514 (3), 513 (12), 442 (3), 287 (3), 199 (8), 155 (52), 92 (11), 91 (100), 78 (3)
6e	2.77 (CH <sub>2</sub> I); 22.58 (2 Me); 43.87 (CHN); 68.66 (CH <sub>2</sub> O); 69.49 (CH <sub>2</sub> O); 70.22 (CH <sub>2</sub> O); 70.64 (CH <sub>2</sub> O); 70.74 (2 CH <sub>2</sub> O); 71.96 (CH <sub>2</sub> O); 107.01 (C(3), C(6)); 120.43 (C(5)); 136.37 (C(4)); 143.94, 143.99 (C(1), C(2))	482 [M] <sup>+</sup> (44), 467 (13), 199 (17), 196 (11), 195 (6), 181 (17), 165 (7), 155 (100), 153 (6), 78 (7)
6f	2.80 (CH <sub>2</sub> I); 24.40 (Me); 53.20 (CHN); 68.92 ( <u>C</u> H <sub>2</sub> OAr); 69.45 ( <u>C</u> H <sub>2</sub> CH <sub>2</sub> OAr); 70.18 (CH <sub>2</sub> O); 70.60 (CH <sub>2</sub> O); 70.73 (2 CH <sub>2</sub> O); 71.91 (CH <sub>2</sub> O); 107.12 (C(3)); 108.98 (C(6)); 119.86 (C(5)); 125.66 (C(2'), C(6')); 127.41 (C(4')); 128.84 (C(3'), C(5')); 137.39 (C(4)); 143.21 (C(1), C(1')); 144.43 (C(2))	544 [M] <sup>+</sup> (34), 530 (3), 529 (13), 269 (3), 199 (6), 165 (2), 155 (24), 106 (9), 105 (100), 79 (3)

<sup>&</sup>lt;sup>a</sup> The molecular ion peak and the ten most intense peaks are cited.
<sup>b</sup> For <sup>37</sup>Cl.
<sup>c</sup> For <sup>35</sup>Cl.



 $1a \cdot Ba(ClO_4)_2$ 

Fig. 1. Structures 2, 3 (two crystallographically independent molecules), and  $1a \cdot Ba(ClO_4)_2$  (two independent complexes). The hydrogen atoms in structure  $1a \cdot Ba(ClO_4)_2$  are omitted for simplicity; the minor components of the disordered fragments are indicated with unfilled lines. The atomic thermal displacement ellipsoids are given with 30% probability for  $1a \cdot Ba(ClO_4)_2$  and with 50% probability for the other structures. The coordination bonds are indicated with dashed lines.

mined earlier.<sup>11</sup> The low accuracy of that study was due, among other factors, to the disorder of the crown ether chain between the O(3) and O(4) atoms in room-temperature X-ray diffraction. To obtain more accurate data, we cooled single crystals to 120 K, thus eliminating the dynamic component of the above disorder of the polyether chain in compound **2**.

In structure **2**, the angles at the O(1) and O(5) atoms conjugated with the benzene fragment are  $117.8(1)^{\circ}$  and  $118.0(1)^{\circ}$ , respectively, which most likely corresponds to the sp<sup>2</sup>-hybridized state of these atoms. The shortened O(1)-C(2) and O(5)-C(7) bond lengths (1.353(2) Å either) compared to the other O-C bond lengths (1.415(2)-1.438(2) Å) and the near-zero or near-180° torsion angles  $C_{Ar}-C_{Ar}-O-C$  suggest the strong conjugation of the O(1) and O(5) atoms with the benzene ring. Unlike the other O atoms of the macrocycle, the O(3) atom is outside the cavity of the latter and its lone electron pairs (LEP) are oriented outward. Such a conformation of the macrocycle in the crystal is unfavorable for coordination of metal or ammonium cations to all heteroatoms of the macrocycle.

The independent part of the crystal cell of compound **3** contains two crystallographically independent molecules with different conformations of the polyether chain, which clearly demonstrates the high conformational flexibility of

azacrown ethers of this type. The independent molecules have similar geometrical parameters. The N atoms of the macrocycles are in planar configurations: the sums of their bond angles are  $359.5(3)^{\circ}$  and  $360.0(3)^{\circ}$ . These planes are virtually coplanar with the benzene rings: the corresponding dihedral angles are only  $4.6^{\circ}$  and  $2.6^{\circ}$ . Obviously, the LEP of the nitrogen atoms are efficiently conjugated with the  $\pi$ -system of the benzene ring, which is confirmed by the shortened C(1)-N(1) and C(1')-N(1') bond lengths (1.362(5) and 1.350(5) Å, respectively) and by the pronounced para-quinonoid distribution of the bond lengths in the benzene ring by analogy with that found in N,N-dimethyl-4-nitroaniline.<sup>12</sup> Thus, based on the planar geometry of the N atom of the macrocycle, the efficient conjugation of its LEP with the benzene ring, and the elongated conformation of the macrocycle, which precludes simultaneous coordination of all heteroatoms to metal cations, one can predict that complexes of phenylazacrown ether **3** would be unstable.

Interestingly, the N(1)–C(7) bond length in free nitrobenzoazacrown ether **1a** is only 1.386(6) Å,<sup>9</sup> although the N(1) atom has a pyramidal bond configuration (the sum of its bond angles is 349.4(3)°). This suggests that the sp<sup>2</sup>-hybridized state contributes relatively greatly to the N(1) atom in compound **1a**, probably because of the very efficient conjugation of its LEP with the strong electronwithdrawing nitro group in the *para*-position. This can make the aforesaid LEP less "switchable" to the coordination with a metal cation and, consequently, decrease the stabilities of the resulting complexes of this ligand (see below).

The poor quality of a single crystal of the complex  $1a \cdot Ba(ClO_4)_2$  leaves X-ray diffraction data highly inaccurate, which precludes correct comparison of the geometrical parameters of compound 1a in the individual state and in the complex. Nevertheless, the experimental accuracy suffices to reveal conformational changes in the macrocycle of 1a upon the complexation.

The complex  $1a \cdot Ba(CIO_4)_2$  is binuclear since the bridging anions  $CI(2)O_4$ ,  $CI(3)O_4$ , and  $CI(4)O_4$  form coordination bonds simultaneously to both independent metal cations. This is characteristic of barium perchlorate complexes with benzoaza-15-crown-5.<sup>13</sup> The anions  $CI(1)O_4$  and  $CI(4)O_4$  are disordered over two positions with populations of 0.72 : 0.38 and 0.57 : 0.43, respectively. That is why the coordination numbers of Ba(1) and Ba(2) vary from 10 to 12 and their coordination polyhedra are irregular. The polyether chains in both independent complexes are partly disordered over two positions with populations of 0.59 : 0.41 and 0.58 : 0.42. The nitro group in one complex is also disordered (0.55 : 0.45). Apparently, such a high degree of disorder of many components of the crystal is responsible for its poor quality.

The structures of two independent complexes  $1a \cdot Ba(ClO_4)_2$  in the binuclear complex are similar. The

barium cation is too large to completely penetrate into the cavity of the 15-membered macroheterocycle, so it is nearly above the center of the macrocyclic cavity of compound 1a ("bird-in-nest" model). The deviations of Ba(1) and Ba(2) from the mean-square plane passing through all heteroatoms of the nearest macrocycle are 1.78 and 1.67 Å, respectively. The distances Ba...O(macrocycle) are within 2.749(6) - 2.882(5) Å; the distances Ba...N are 3.154(7)and 3.000(7) Å. Thus, with allowance for the van der Waals radii of the O and N atoms ( $\sim$ 1.4 and 1.5 Å, respectively), all heteroatoms of macrocycle 1a can be regarded as almost equally coordinated to the barium cation. The angles Ba...O-C and Ba...N-C are 104.9(10)°-132.8(13)° and  $103.3(4)^{\circ}$ -111.8(6)°, respectively; this is not very favorable for coordination of the sp<sup>2</sup>- or sp<sup>3</sup>-hybridized heteroatoms of the macrocycle to the metal cation. Apparently, this is due to the limited possibility of conforming the 15-membered macroheterocycle to the coordination demands of a large metal cation.

The sums of the bond angles at the N(1) and N(1') atoms are 335.6(7)° and 337.0(6)°, respectively. Therefore, the nitrogen atoms in the complex are sp<sup>3</sup>-hybridized to a higher degree than those in free crown ether **1a** (349.4(3)°) and form stronger coordination bonds to the metal cation. This is also evident from the lengthened bonds N(1)–C(7) and N(1')–C(7') (1.410(10) and 1.438(9) Å, respectively) compared to those in free crown ether **1a** (1.386(6) Å). The bond angles at the O(1) and O(1') atoms conjugated with the benzene ring are 117.8(6)° and 117.0(5)°, which suggests their predominant sp<sup>2</sup>-hybridized state as in the free ligand (117.2(3)°).

It is interesting to compare the conformations of free and coordinated benzoazacrown ether **1a**. Superposition of structure **1a** and two independent complexes **1a**  $\cdot$  Ba(ClO<sub>4</sub>)<sub>2</sub> with complete coincidence of their benzene fragments is shown in Fig. 2. It can be seen that the conformation of the crown ether changes only slightly, thus suggesting preorganization of this ligand for binding metal cations.



Fig. 2. Molecules of free compound 1a (thick lines) and coordinated compound 1a in two independent complexes with  $Ba(ClO_4)_2$  (thin lines) when their benzene fragments are superposed. The atoms of the minor conformers of 1a and the per-chlorate anions are omitted.

**NMR studies.** Earlier,<sup>4,13</sup> we have demonstrated that benzomonoazacrown ethers and their derivatives containing the tertiary N atom conjugated with the benzene ring form sufficiently stable guest—host complexes with alkali, alkaline-earth, heavy metal, and ammonium ions, which will make them highly efficient as ionophores in promising optical chemosensory compounds. It was interesting to compare the quantitative stability parameters of complexes of nitrobenzoazacrown ethers with Groups I and II metal cations and ammonium ions, to reveal the structural features of the resulting complexes and their selectivity toward various ions, and to compare the complexing ability of nitrobenzoazacrown ethers containing various N-alkyl substituents with that of related compounds.

The NOESY spectra of free benzoazacrown ethers 1a-d exhibit intense cross peaks between the NCH<sub>2</sub> (NMe) protons of the substituents and the benzene H(3) proton, which is *ortho* to the N atom of the macrocycle (see, *e.g.*, Fig. 3). In contrast, the coupling of the H(3) proton with the NCH<sub>2</sub> protons of the macrocycle is insignificant. Apparently, in solution, the H(3) proton approaches the protons of the *N*-alkyl substituent; *i.e.*, the conformation of the 15-membered benzoazacrown ether in the vicinity of the N atom of the macrocycle is nearly identical with that

found earlier<sup>9</sup> for crystal structure **1a**. The data obtained suggest that the conjugation of the N atom of the macrocycle with the benzene ring in benzoazacrown ethers can be somewhat weakened and, consequently, its LEP can be donated for coordination bonding to a metal or ammonium cation.

The NMR study of nitrobenzoazacrown ethers 1a-dand model compounds 2 and 3 in MeCN-d<sub>3</sub> revealed substantial downfield shifts  $\Delta\delta_{\rm H}$  of the signals for most of the protons of these ligands upon the addition of an excess of metal (Na, K, Ca, or Ba) or (ethyl)ammonium perchlorate. Such a behavior is typical of inclusion complexes in which the  $M^{n+}$  ion is bound to all heteroatoms of the macrocycle by hydrogen bonds and/or ion—dipole interactions (Scheme 3), thus displacing the electron densities from all ligand atoms toward the cation (the electronwithdrawing effect of the cation). A general trend is the larger shifts  $\Delta\delta_{\rm H}$  (up to 0.7 ppm) for the complexes with doubly charged cations compared to those with singly charged cations, which is obviously due to the higher charge densities on the alkaline-earth metal cations.

Analysis of the NOESY spectra of benzoazacrown ethers 1a-d in the presence of excesses of calcium and barium cations showed that the conformation of the mac-



Fig. 3. Fragment of the NOESY spectrum of benzoazacrown ether 1a (MeCN-d<sub>3</sub>, 30 °C).



**Table 5.** Stability constants of the complexes of crown ethers 1-3 with ammonium, ethylammonium, and metal perchlorates<sup>*a*</sup>



 $M^{n+}$  is the metal or (ethyl)ammonium ion (n = 1, 2)

rocyclic fragment near the N atom remains virtually unchanged upon the complexation. This confirms the high preorganization of the macrocycles in the title compounds for binding the metal cations.

The abilities of nitrobenzoazacrown ethers to form complexes with metal and (ethyl)ammonium perchlorates were quantitatively estimated by <sup>1</sup>H NMR titration. The stability constants of the resulting complexes were calculated with the HYPNMR program<sup>14</sup> from experimental plots of the chemical shifts of the ligand protons vs. the added amount of the salt; these stability constants correspond to the formation of the complexes of the formula L  $\cdot$  M<sup>*n*+</sup>

$$L + M^{n+} \stackrel{K_1}{\longrightarrow} L \cdot M^{n+}, \tag{1}$$

where L is the crown compound,  $M^{n+}$  is the metal or (ethyl)ammonium cation (n = 1, 2), and  $K_1/L \mod^{-1}$  is the stability constant of the 1 : 1 complex. For metal cations with large ionic radii, we also considered possible formation of sandwich complexes of the formula  $L_2 \cdot M^{n+}$ 

$$\mathbf{L} \cdot \mathbf{M}^{n+} + \mathbf{L} \stackrel{\mathbf{K_2}}{\longrightarrow} \mathbf{L}_2 \cdot \mathbf{M}^{n+}, \tag{2}$$

where  $K_2/L \mod^{-1}$  is the stability constant of the 2 : 1 complex. For comparison, we studied the complexation between the aforementioned salts and the nearest structural analogs of nitrobenzoazacrown ethers, *viz.*, benzo-crown ether **2** and phenylazacrown ether **3** with the same size of the macrocycle. The results obtained are given in Table 5.

The presence of the electron-withdrawing nitro group in the compounds studied somewhat lowers the stability constants of their complexes compared to those of similar

Ligand	$\log K_1 (\log K_2)^b$					
	$\mathrm{NH_4}^+$	EtNH <sub>3</sub> <sup>+</sup>	Na <sup>+</sup>	$K^+$	Ca <sup>2+</sup>	Ba <sup>2+</sup>
1a	1.7	1.4	2.7	1.9	3.8	4.2 (1.6)
1b	1.6	1.5	2.7	1.7	3.8	3.2 (2.2)
1c	1.5	1.4	2.5	1.8	4.0	3.1
1d	1.5	1.3	2.3	1.9	3.4	2.7 (1.4)
2	2.1	1.7	3.4	2.7	4.2	4.1 (3.5)
3	1.8	1.2	2.6	0.7	2.3	1.4

<sup>*a*</sup> <sup>1</sup>H NMR titration in MeCN-d<sub>3</sub>, 30 °C.

<sup>b</sup>  $K_1/L \operatorname{mol}^{-1} = [L \cdot M^{n+}]/([L] \cdot [M^{n+}]), K_2/L \operatorname{mol}^{-1} = [L_2 \cdot M^{n+}]/([L] \cdot [L \cdot M^{n+}]);$  the constants were determined with an accuracy of  $\pm 20\%$ .

formylbenzene-containing crown ethers<sup>13</sup> (by ~0.3-0.5 order of magnitude). We also found that the complexing ability of these crown ethers depends on the cation nature, size, and charge, the substituent at the N atom of the macrocycle, and probably the degree of conjugation of this N atom with the benzene ring.

The crown ethers studied form more stable complexes with smaller cations of the alkaline and alkaline-earth metals and more stable complexes with the  $NH_4^+$  ion compared to the  $EtNH_3^+$  ion. The stability constants of the complexes with the doubly charged cations are substantially (up to 100 times) higher than the stability constants of the complexes with the singly charged cations. Obviously, the higher charge density on the smaller metal cations or on the doubly charged cations compared to the singly charged ones and the absence of electron-donating substituents in NH4<sup>+</sup> favor stronger ion-dipole interactions between the heteroatoms of the macrocycle and the cation in its cavity. The much higher stability constants of the complexes of all the ligands studied with Na<sup>+</sup> ions compared to  $K^+$  ions suggest that the cavity of the crown ether and the metal ion radius should match in size for the formation of stronger bonds between them.

We found that most of the nitrobenzocrown ethers studied form sandwich complexes with Ba<sup>2+</sup> ions of the formula  $L_2 \cdot Ba^{2+}$  because of the large size of the Ba<sup>2+</sup> cation (its ionic radius is 1.34 Å). The presumed sandwich complexes with potassium cations, whose ionic radius is also large (1.33 Å), seem to be very unstable (log $K_2 \le 0.5$ ) and cannot be detected by NMR titration.

For nitrobenzoazacrown ethers **1a,b,d**, the signals of the protons of all types in the <sup>1</sup>H NMR spectra of both the 1 : 1 and sandwich complexes are equally shifted downfield. Apparently, the steric hindrances presented by the *N*-alkyl group preclude two aromatic fragments from approaching each other and they are most likely oriented in opposite directions in complex  $\mathbf{1}_2 \cdot \mathbf{M}^{2+}$  (see Scheme 3). In contrast, the signals of the aromatic protons in sandwich complex  $2_2 \cdot Ba^{2+}$  are shifted upfield relative to the signals of the free ligand, thus suggesting that the benzene rings in this complex prefer to lie above one another.

With an increase in the length of the N-alkyl substituent in nitrobenzoazacrown ethers 1, the complexes with barium cations become somewhat less stable, while the complexes with the singly charged cations and the Ca<sup>2+</sup> ions are almost insensitive to the substituent length. Note that the complexes of crown ether 1 with singly charged cations are similar in stability with analogous complexes of the nearest structural analog (viz., phenylazacrown ether 3), while compound 2 forms appreciably more stable complexes with cations M<sup>+</sup>. In this respect, nitro derivatives 1 differ from benzene-unsubstituted benzoazacrown ethers and their formyl derivatives: their complexes with the cations in question are much more stable than similar complexes of related N-phenylaza-15-crown-5.13 This behavior of compounds 1 can be explained by two factors: first, the coordination bond N...M<sup>+</sup> is weakened because of the strong electron-withdrawing effect of the NO2 group and, second, the substituent at the N atom presents steric hindrances to its coordination to the large  $Ba^{2+}$  ion. The second reason is indirectly confirmed by the inability of crown ether 1c, which contains a bulky n-propyl substituent, to form stable sandwich complexes.

Nevertheless, the specific properties of the tertiary N atom in compounds 1, whose LEP is conjugated with the benzene ring not very efficiently, allow this atom to donate its LEP for coordination bonding to a doubly charged metal cation. In contrast, our X-ray diffraction experiments (see above) showed that the geometrical parameters of the N atom in phenylazacrown ether 3 suggest its  $sp^2$ -hybridized state and very strong conjugation with the benzene ring, which, in combination with a higher flexibility of the macrocycle, makes this compound less efficient as a macrocyclic ligand for  $M^{2+}$ . It should also be noted that compounds 1 are only slightly inferior to crown ether 2 in the complexing ability toward alkaline-earth metal cations.

Quantum chemical calculations. Quantum chemical calculations help to reveal the structural features of compounds for which X-ray diffraction data are lacking. For molecules in solution, indirect structural information can be obtained from 2D NMR spectra. In combination with quantum chemical calculations, this becomes a powerful tool for the examination of noncrystalline molecular structures.

Our previous DFT calculations of the structures of crown ethers and their complexes show<sup>15–19</sup> that the calculated structures agree well with X-ray diffraction data on the bond lengths, the bond angles, and the conformations of the macrocycle. Thus, we hope that the calculated structures of *N*-methylnitrobenzoaza-15-crown-5 **1a** and its aqua complexes with Ba<sup>2+</sup> (four to six water molecules coordinated, together with the cation, on one side of

the mean-square plane of the crown ether) and  $Ca^{2+}$  (three water molecules coordinated in the same way) will also be reliable. According to our calculations and analysis of numerous experimental data,<sup>20,21</sup> Ca<sup>2+</sup> and Ba<sup>2+</sup> ions in the cavities of various 15-crown-5 protrude from the mean-square plane of the macrocycle, forming half-sandwich structures. Additional ligands (solvent molecules or counterions) are coordinated by the cation in such a way that both the cation and these ligands are on the one side of the macrocycle.

The solvation shell of the cation in acetonitrile consists of not only solvent molecules and may include water (present as an impurity in the solvent) and counterions. In our models, we studied in detail the complexes with such additional ligands as water molecules, which fill vacancies in the inner coordination sphere of the cation, and performed special calculations for acetonitrile molecules. These calculations, as well as previous calculations for perchlorate anions,<sup>22,23</sup> showed that the presence of additional ligands substantially changes the conformation of the macrocycle in the complex compared to the cation-crown ether complex, regardless of the nature of the additional ligands. Aqua complexes enjoy a greater variety of conformations because many structures are stabilized by hydrogen bonds between water molecules and the O atoms of the crown ether. With acetonitrile and perchlorate anions, this is obviously not the case.

The most stable calculated structures of free crown ether 1a are consistent well with X-ray diffraction data.<sup>9</sup> The conformers selected by the energy criterion (relative conformation energy\* <3 kcal mol<sup>-1</sup>) can be conventionally broken down into two groups differing in the structure of the fragment ArNR<sub>2</sub>. The first group includes the conformers in which the distance between the H(3) proton of the benzene ring and the N-methyl group is  $\sim 2$  Å; the second group includes the conformers in which the H(3)proton approaches the N-methylene group of the macrocycle. Although all the conformers under consideration satisfy the energy range <3 kcal mol<sup>-1</sup>, the energies of the structures of the first group are lower. Therefore, they should dominate in equilibrium mixtures, which agrees well with the experimental NOESY data (see above). The structure of the most stable conformer of 1a is shown in Fig. 4, a. In this structure, the pyramidal character of the N atom of the macrocycle (defined as a deviation of the sum of the bond angles at the N atom from  $360^\circ$ ) is  $\sim 7^\circ$  (against  $\sim 10^\circ$ in the experimental structure). This suggests considerable conjugation of this N atom with the aromatic ring.

The conformers of the complexes of *N*-methylbenzoaza-15-crown-5 with  $Ca^{2+}$  and  $Ba^{2+}$  cations can be broken down into two groups also differing in the structure of the fragment ArNR<sub>2</sub>.

<sup>\*</sup> The energies of the conformers relative to the energy of the most stable structure.



**Fig. 4.** DFT-calculated most stable conformers of *N*-methylnitrobenzoaza-15-crown-5 **1a** (*a*) and its aqua complexes with  $Ca^{2+}(b)$  and  $Ba^{2+}(c)$ .



Here the difference is more distinct: the first group includes the conformers in which the cation and the N-methyl group are on the same side of the mean-square plane of the macrocycle, while the second group includes the conformers in which they are on the opposite sides. In the first group, the H(3) proton approach-

es the *N*-methyl group; in the second group, the H(3) proton approaches the *N*-methylene group of the macrocycle.

For the complexes cation—crown ether **1a** containing no additional ligands, the calculated structures are in conflict with NMR data. The most stable structure (close to that found from X-ray diffraction experiments) agrees best (though still insufficiently) with the experimental NOESY spectrum (H(3)...MeN, ~2.15 Å; H(3)...H<sub>2</sub>CN, ~2.9 Å). With these distances, the NOESY spectra would show not only the cross peak H(3)...MeN but also a weak cross peak H(3)...H<sub>2</sub>CN. However, the latter is absent from the spectra. In all the other calculated structures, the distance H(3)...H<sub>2</sub>CN is shorter than or equals H(3)...MeN, which would result in a noticeable cross peak H(3)...H<sub>2</sub>CN and probably in a weak cross peak H(3)...MeN.

Coordination of three (for  $Ca^{2+}$ ) or four to six water molecules (for  $Ba^{2+}$ ) to the cation changes the fragment RO-C<sub>6</sub>H<sub>3</sub>-NR<sub>2</sub> only slightly compared to waterfree structures; yet the conformation of the peripheral units of the macrocycle undergoes some changes. The structures with the lowest energies become consistent better with the NOESY spectrum (H(3)...MeN, ~2.2–2.4 Å; H(3)...H<sub>2</sub>CN,  $\sim$ 3.3–3.7 Å). Such structures agree better with X-ray diffraction data (when the anions are coordinated by the cation) than do the structures containing no additional ligands. Therefore, calcium and barium complexes with azacrown ethers in solution should necessarily include some additional ligands (usually solvent molecules). The most stable structures of the aqua complexes of crown ether **1a** with  $Ca^{2+}$  and  $Ba^{2+}$  are shown in Figs 4, b and c. The pyramidal character of the N atom of the macrocycle is ~26° in the complexes with Ca<sup>2+</sup> and ~21° or 24° in the complexes with Ba<sup>2+</sup>. This suggests a virtually complete loss of conjugation between this N atom and the benzene ring in the complexes.

To sum up, a stepwise transformation of the macrocycle of accessible nitrobenzo-15-crown-5 afforded a number of N-alkylnitrobenzoaza-15-crown-5 containing the N atom conjugated with the benzene ring. Using quantum chemical calculations, we obtained the 3D structures of benzoazacrown ethers and their complexes and demonstrated that the complex should necessarily contain additional ligands in the coordination sphere of the cation. Quantitative measurements clearly showed that N-alkylbenzoazacrown ethers easily form complexes with alkaline-earth metal cations and that these ligands are comparable in complexing ability with nitrobenzo-15-crown-5 and are vastly superior to N-(4-nitrophenyl)aza-15-crown-5. This can give impetus to the design, on the basis of nitrobenzoazacrown ethers, of promising chromoionophores with a great optical response to the complexation with the aforesaid metal cations.

<sup>1</sup>H NMR spectra were recorded on a Bruker DRX500 spectrometer (500.13 MHz) in CDCl<sub>3</sub> and MeCN-d<sub>3</sub> with the solvent signals ( $\delta$  7.27 and 1.96, respectively) as the internal standards. <sup>13</sup>C NMR spectra were recorded on a Bruker DRX500 spectrometer (125.76 MHz) in CDCl<sub>3</sub> with the solvent signal ( $\delta$  77.00) as the internal standard. Chemical shifts and coupling constants were measured to within 0.01 ppm and 0.1 Hz, respectively. To assign the signals of the protons and the C atoms, 2D homonuclear (<sup>1</sup>H–<sup>1</sup>H COSY, NOESY) and heteronuclear techniques (<sup>1</sup>H–<sup>13</sup>C COSY: HSQC, HMBC) were used. 2D Experiments were carried out with the standard parameters of the Bruker software. The mixing time in the NOESY experiment was 300 µs; the HMBC experiment was optimized for the constant  $J_{H,C} = 8$  Hz.

IR spectra were recorded on a Bruker IFS-113V spectrophotometer in thin films with KBr. Mass spectra were measured on Varian MAT-311A and Finnigan MAT-212 instruments; highresolution mass spectra were recorded on a Finnigan MAT-212 instrument with perfluorokerosene as a standard (ionizing energy 70 or 60 eV, direct inlet probe).

Elemental analysis of samples was carried out at the Microanalysis Laboratory of the A. N. Nesmeyanov Institute of Organoelement Compounds, Russian Academy of Sciences. Melting points were determined in capillaries on a MEL-Temp II instrument.

For column chromatography, SiO<sub>2</sub> (Kieselgel 60, 0.063-0.100 or 0.063-0.200 mm, Merck) was used. The course of the reactions was monitored by TLC on DC-Alufolien Kieselgel 60 F<sub>254</sub> plates (Merck).

4-Nitrobenzo-15-crown-5 (2) was purchased from the A. V. Bogatsky Physicochemical Institute, National Academy of Sciences of Ukraine (Odessa). Ethylamine (70% aqueous solution), 1-propylamine, isopropylamine, benzylamine, 1-phenylethylamine, and 4-nitrofluorobenzene (Aldrich) were used without further purification. The salts NH<sub>4</sub>ClO<sub>4</sub>, NaClO<sub>4</sub>, KClO<sub>4</sub>, Ca(ClO<sub>4</sub>)<sub>2</sub>, and Ba(ClO<sub>4</sub>)<sub>2</sub> (Aldrich) were dried *in vacuo* at 60 (NH<sub>4</sub>ClO<sub>4</sub>) or 200 °C (the other salts); EtNH<sub>3</sub>ClO<sub>4</sub> was prepared by neutralization of 70% aqueous ethylamine with 70% aqueous HClO<sub>4</sub> (Aldrich) and dried *in vacuo* at 60 °C.

Synthesis of azapodands 4b—f (general procedure). A mixture of crown ether 2 (313 mg, 1 mmol) and a 45% solution of an amine (0.04 mol) in dry EtOH was heated in a sealed tube at 130 °C (oil bath) for 100 (for 4b,c) or 300 h (for 4d—f). The tube was opened and the reaction mixture was concentrated *in vacuo*. The podands were isolated from the mixtures of reaction products in one of the following ways.

*A*. The residue containing compounds 4b-d was chromatographed on SiO<sub>2</sub> with AcOEt and then AcOEt-EtOH (5 : 1) as eluents.

**B**. The residue containing compounds **4e**,**f** was diluted with water (50 mL) and acidified dropwise with conc. HCl to pH 3. The product was extracted with CHCl<sub>3</sub>, the combined extracts were concentrated *in vacuo*, and the residue was purified as described in the method A.

Podands **4b**—**f** were isolated as yellow oils.

**2-(2-{2-[2-(2-Ethylamino-5-nitrophenoxy)ethoxy]ethoxy}-ethoxy)ethan-1-ol (4b).** Yield 97% (*cf.* Ref. 6: oil). <sup>13</sup>C NMR (CDCl<sub>3</sub>),  $\delta$ : 14.20 (Me); 37.45 (CH<sub>2</sub>N); 61.54 (CH<sub>2</sub>OH); 68.25

(2 CH<sub>2</sub>O); 69.36 (CH<sub>2</sub>O); 70.15 (CH<sub>2</sub>O); 70.42 (CH<sub>2</sub>O); 70.49 (CH<sub>2</sub>O); 70.53 (CH<sub>2</sub>O); 72.44 (CH<sub>2</sub>O); 106.48 (C(3), C(6)); 120.34 (C(4)); 136.36 (C(5)); 144.00, 144.27 (C(1), C(2)). High-resolution MS, found: m/z 358.1737 [M]<sup>+</sup>. C<sub>16</sub>H<sub>26</sub>N<sub>2</sub>O<sub>7</sub>. Calculated: M = 358.1740.

**2-(2-{2-[2-(5-Nitro-2-propylaminophenoxy)ethoxy]ethoxy} ethoxy)ethan-1-ol (4c).** Yield 98% (*cf.* Ref. 6: oil). <sup>13</sup>C NMR (CDCl<sub>3</sub>),  $\delta$ : 11.05 (Me); 21.79 (CH<sub>2</sub>); 44.26 (CH<sub>2</sub>N); 61.08 (CH<sub>2</sub>OH); 68.00 (CH<sub>2</sub>O); 68.94 (CH<sub>2</sub>O); 69.76 (CH<sub>2</sub>O); 70.08 (3 CH<sub>2</sub>O); 72.14 (CH<sub>2</sub>O); 106.11 (C(3), C(6)); 119.94 (C(4)); 135.75 (C(5)); 143.68, 144.69 (C(1), C(2)). High-resolution MS, found: *m/z* 372.1890 [M]<sup>+</sup>. C<sub>17</sub>H<sub>28</sub>N<sub>2</sub>O<sub>7</sub>. Calculated: M = = 372.1897.

**2-(2-{2-[2-(2-Benzylamino-5-nitrophenoxy)ethoxy]ethoxy} ethoxy)ethan-1-ol (4d).** Yield 81% (*cf.* Ref. 6: oil). <sup>13</sup>C NMR (CDCl<sub>3</sub>),  $\delta$ : 46.46 (NCH<sub>2</sub>Ph); 61.12 (CH<sub>2</sub>OH); 68.20 (CH<sub>2</sub>O); 68.97 (CH<sub>2</sub>O); 69.76 (CH<sub>2</sub>O); 70.04 (CH<sub>2</sub>O); 70.13 (CH<sub>2</sub>O); 70.17 (CH<sub>2</sub>O); 72.14 (CH<sub>2</sub>O); 106.32, 107.03 (C(3), C(6)); 119.82 (C(4)); 126.62 (C(2'), C(6')); 127.06 (C(4')); 128.37 (C(3'), C(5')); 136.46, 137.60 (C(1'), C(5)); 144.04, 144.45 (C(1), C(2)). High-resolution MS, found: *m/z* 420.1894 [M]<sup>+</sup>. C<sub>21</sub>H<sub>28</sub>N<sub>2</sub>O<sub>7</sub>. Calculated: M = 420.1896.

**2-(2-{2-[2-(2-Isopropylamino-5-nitrophenoxy)ethoxy]eth**oxy}ethoxy)ethan-1-ol (4e). Yield 96% (converted to the consumed compound 2, 81% conversion) (*cf.* Ref. 6: oil). <sup>13</sup>C NMR (CDCl<sub>3</sub>),  $\delta$ : 22.10 (2 Me); 43.61 (CHN); 61.19 (CH<sub>2</sub>OH); 68.23 (CH<sub>2</sub>O); 69.06 (CH<sub>2</sub>O); 69.92 (CH<sub>2</sub>O); 70.16 (CH<sub>2</sub>O); 70.21 (2 CH<sub>2</sub>O); 72.22 (CH<sub>2</sub>O); 106.52, 106.72 (C(3), C(6)); 120.03 (C(4)); 135.88 (C(5)); 143.71, 143.76 (C(1), C(2)). High-resolution MS, found: *m/z* 372.1891 [M]<sup>+</sup>. C<sub>17</sub>H<sub>28</sub>N<sub>2</sub>O<sub>7</sub>. Calculated: M = 372.1897.

2-[2-(2-{2-[5-Nitro-2-(1-phenylethyl)aminophenoxy]ethoxy}ethoxy)ethoxy]ethan-1-ol (4f). Yield 73% (converted to the consumed compound **2**, 36% conversion). <sup>1</sup>H NMR (CDCl<sub>3</sub>),  $\delta$ : 1.62 (d, 3 H, Me, J = 7.0 Hz); 3.58 (m, 2 H, CH<sub>2</sub>O); 3.66 (s, 4 H, 2 CH<sub>2</sub>O); 3.66-3.75 (m, 4 H, 2 CH<sub>2</sub>O); 3.92 (m, 2 H, CH<sub>2</sub>CH<sub>2</sub>OAr); 4.27 (m, 2 H, CH<sub>2</sub>OAr); 4.58 (br.q, 1 H, CHN); 5.73 (br.s, 1 H, NH); 6.25 (d, 1 H, H(3), J = 8.9 Hz); 7.24 (m, 1 H, H(4')); 7.30-7.34 (m, 4 H, H(2'), H(3'), H(5'), H(6')); 7.65 (d, 1 H, H(6), J = 2.4 Hz); 7.71 (dd, 1 H, H(4), J = 8.9 Hz)J = 2.5 Hz). <sup>13</sup>C NMR (CDCl<sub>3</sub>),  $\delta$ : 24.43 (Me); 52.93 (CHN); 61.52 (CH<sub>2</sub>OH); 68.51 (CH<sub>2</sub>OAr); 69.39 (CH<sub>2</sub>CH<sub>2</sub>OAr); 70.18 (CH<sub>2</sub>O); 70.45 (2 CH<sub>2</sub>O); 70.60 (CH<sub>2</sub>O); 72.46 (CH<sub>2</sub>O); 106.70 (C(3)); 108.35 (C(6)); 119.93 (C(4)); 125.56 (C(2'), C(6'));127.24 (C(4')); 128.76 (C(3'), C(5')); 136.86 (C(5)); 143.65 (C(1')); 143.57 (C(2)); 144.14 (C(1)). IR (KBr), v/cm<sup>-1</sup>: 3389 (NH, OH); 1489 (NO<sub>2</sub>). MS, m/z ( $I_{rel}$  (%)): 434 [M]<sup>+</sup> (17), 419 (13), 417 (5), 133 (3), 106 (9), 105 (100), 103 (4), 79 (19), 79 (7), 77 (5). High-resolution MS, found: *m*/*z* 434.2055 [M]<sup>+</sup>.  $C_{22}H_{30}N_2O_7$ . Calculated: M = 434.2053.

Synthesis of chlorides 5b—f (general procedure). A solution of SOCl<sub>2</sub> (3.2 mL, 43.9 mmol) in CHCl<sub>3</sub> (5 mL) was slowly added at 0 °C (ice bath) to a stirred solution of podand 4b—f (1.8 mmol) and dry pyridine (0.16 mL, 2 mmol) in CHCl<sub>3</sub> (15 mL). The reaction mixture was refluxed for 6—7 h and cooled. A 5% aqueous solution of HCl (50 mL) was added and the product was extracted with CHCl<sub>3</sub>. The combined extracts were washed with 5% aqueous Na<sub>2</sub>CO<sub>3</sub> and water and concentrated *in vacuo*. The residue was chromatographed on SiO<sub>2</sub> with benzene—AcOEt (1 : 1) as an eluent for 5b—f or with benzene—AcOEt (5 : 1 and then 1 : 1) as eluents for 5e,f. Chlorides 5b—f were isolated as

yellow oils. The yields and physicochemical characteristics of compounds 5b-f are given in Tables 2–4.

Synthesis of iodides 6b-f (general procedure). A solution of compounds 5b-f (1.6 mmol) and NaI (4.8 g, 32 mmol) in dry acetone (50 mL) was refluxed with stirring for 100 h. The reaction mixture was concentrated *in vacuo*, the residue was diluted with water (50 mL), and the product was extracted with benzene. The combined extracts were concentrated *in vacuo* and the residue was chromatographed on SiO<sub>2</sub> with benzene—AcOEt (1:1) as an eluent for 6b or with benzene—AcOEt (5:1 and then 1:1) as eluents for 6c-f. Iodides 6b-f were isolated as yellow oils. The yields and physicochemical characteristics of compounds 6b-f are given in Tables 2–4.

Synthesis of benzoazacrown ethers 1b-d (general procedure). *A.* A mixture of iodide 6b-d (0.35 mmol), dry THF (15 mL), and 60% NaH (0.14 g, 3.5 mmol) in paraffin was refluxed with stirring for 2.5–10 h. The reaction mixture was cooled and diluted with water. The product was extracted with benzene and CHCl<sub>3</sub>. The combined organic extracts were washed with water and concentrated *in vacuo*. The residue was chromatographed on SiO<sub>2</sub> with benzene—AcOEt (1 : 1) as an eluent for **1b** or with benzene—AcOEt (5 : 1 and then 1 : 1) as eluents for **1c**,d. Compound **1c** was isolated as yellow oil; compounds **1b**,d were isolated as yellow powders, m.p. 73—75 (**1b**) and 119—121 °C (**1d**). The yields and physicochemical characteristics of compounds **1b**—d are given in Tables 1—4.

**B.** A mixture of iodide 6c,d (0.35 mmol), dry THF (15 mL), and 60% NaH (0.28 g, 7.0 mmol) in paraffin was stirred at room temperature for 125 (for 6c) or 95 h (for 6d). The same workup of the reaction mixture as described in method A gave compound 1c as yellow oil and compound 1d as yellow powder. The yields of the compounds are given in Table 1.

13-(4-Nitrophenyl)-1,4,7,10-tetraoxa-13-azacyclopentadecane (3). A mixture of 1,4,7,10-tetraoxa-13-azacyclopentadecane (110 mg, 0.5 mmol), 1-fluoro-4-nitrobenzene (213 mg, 160  $\mu$ L, 1.5 mmol), triethylamine (153 mg, 210  $\mu$ L, 1.5 mmol), and MeOH (5 mL) was heated in a sealed tube at 120 °C (oil bath) for 40 h. The reaction mixture was concentrated *in vacuo* 

Table 6. Crystallographic parameters and the data collection and refinement statistics for compounds 2, 3, and  $1a \cdot Ba(ClO_4)_2$ 

Compound	2	3	$1a \cdot Ba(ClO_4)_2$
Molecular formula	C <sub>14</sub> H <sub>19</sub> NO <sub>7</sub>	C <sub>16</sub> H <sub>24</sub> N <sub>2</sub> O <sub>6</sub>	C15H22BaCl2N2O14
$M/g \text{ mol}^{-1}$	313.30	340.37	662.59
Crystal system	Orthorhombic	Monoclinic	Triclinic
Space group	$Pca2_1$	$P2_1/c$	$P\overline{1}$
a/Å	15.0965(9)	24.361(7)	10.5563(4)
b/Å	4.8500(3)	15.160(4)	13.4472(5)
c/Å	19.7472(11)	8.906(2)	16.1110(7)
α/deg	90	90	90.005(2)
β/deg	90	91.934(4)	97.529(2)
γ/deg	90	90	92.111(2)
$V/Å^3$	1445.85(15)	3287.1(15)	2265.72(16)
Ζ	4	8	4
$d_{\rm calc}/{ m g~cm^{-3}}$	1.439	1.376	1.942
<i>F</i> (000)	664	1456	1312
$\mu$ (Mo-K $\alpha$ )/mm <sup>-1</sup>	0.116	0.105	2.063
Crystal size/mm	$0.26 \times 0.23 \times 0.14$	$0.22 \times 0.18 \times 0.08$	0.26×0.24×0.22
Scan mode/ $\theta$ (deg) range	ω/2.06-29.00	ω/0.84—29.00	ω/2.42-27.00
Ranges of $h, k, l$ indices	$-20 \le h \le 20,$	$-33 \le h \le 33,$	$-13 \le h \le 13,$
	$-6 \le k \le 1,$	$-20 \le k \le 20,$	$-17 \le k \le 17,$
	$-25 \le l \le 25$	$-12 \le l \le 12$	$-20 \le l \le 20$
Number of measured reflections	6724	30888	17551
Number of independent	3545	8678	9458
reflections	$(R_{\rm int} = 0.0202)$	$(R_{\rm int} = 0.0671)$	$(R_{\rm int} = 0.0284)$
Number of reflections with $I > 2\sigma(I)$	3164	6005	7977
Number of parameters refined	275	625	771
<i>R</i> Factors for $I > 2\sigma(I)$	$R_1 = 0.0357$ ,	$R_1 = 0.1020$ ,	$R_1 = 0.0595$ ,
( ) ( )	$wR_2 = 0.0900$	$wR_2 = 0.2484$	$wR_2 = 0.1548$
for all reflections	$R_1 = 0.0421,$	$R_1 = 0.1346$ ,	$R_1 = 0.0698,$
	$w\dot{R}_2 = 0.0937$	$w\dot{R}_2 = 0.2603$	$w\dot{R}_2 = 0.1590$
GOOF on $F^2$	1.089	1.071	1.134
Residual electron	-0.205/0.284	-0.394/0.615	-1.203/1.982
density (min/max)/e $Å^{-3}$			

and the residue was chromatographed on SiO<sub>2</sub> (gradient elution with benzene—AcOEt up to 60% of AcOEt). The yield of compound **3** was 148 mg (86%), yellow powder, m.p. 126—128 °C (*cf.* Ref. 24: m.p. 127—130 °C).

X-ray diffraction experiments. Crystals of free crown ethers 2 and 3 were obtained by slow evaporation of their solutions in  $CH_2Cl_2$ —hexane at room temperature. Crystals of a complex of benzoazacrown ether 1a with barium perchlorate were obtained by slow saturation of a solution of an equimolar mixture of the ligand and Ba( $ClO_4$ )<sub>2</sub> in MeCN with the benzene vapor.

The single crystals of all compounds were mounted under cooled nitrogen (T = 120.0(2) K) on a Bruker SMART-CCD diffractometer and reflection intensities were measured (Mo-K $\alpha$ radiation,  $\lambda = 0.71073$  Å, graphite monochromator,  $\omega$  scan mode). The experimental data were processed with the SAINT program.<sup>25</sup> For the complex **1a** · Ba(ClO<sub>4</sub>)<sub>2</sub>, an absorption correction was applied with the SADABS program. All structures were solved by the direct methods and refined by the least-squares method in the full-matrix anisotropic approximation on  $F^2$  for non-hydrogen atoms. The H atoms at the C atoms were located geometrically and refined isotropically for compounds **2** and **3** and using a riding model for the complex **1a** · Ba(ClO<sub>4</sub>)<sub>2</sub>.

All calculations were performed with the SHELXTL-Plus program package<sup>26</sup> (Bruker). Crystallographic parameters and the data collection and refinement statistics are summarized in Table 6. Atomic coordinates and other structural parameters for the complex  $1a \cdot Ba(ClO_4)_2$  and compounds 2 and 3 have been deposited with the Cambridge Crystallographic Data Center\* (Nos. 733 455, 733 456, and 733 457, respectively).

<sup>1</sup>H NMR titration. Deuterated MeCN (water content <0.05%; FGUP RNTs Prikladnaya Khimiya, St.-Petersburg) was used as a solvent. The molecular formulas and stability constants of the complexes of the crown ethers with the salts  $M^{n+}(ClO_4^{-})_n$  were determined by plotting the shifts of the signals of the ligand (L) protons versus the concentration of the added salt. The total concentration of L was maintained constant (~5 · 10<sup>-3</sup> mol L<sup>-1</sup>); the salt concentration was varied beginning with zero (the maximum ratio  $M^{n+}/L$  was ~3). With NH<sub>4</sub>ClO<sub>4</sub> and KClO<sub>4</sub> as titrants, the total concentration of L was maintained at ~1 · 10<sup>-3</sup> mol L<sup>-1</sup> because of the limited solubilities of these salts. The  $\Delta\delta_{\rm H}$  values were measured to within 0.001 ppm. The stability constants of the complexes were calculated with the HYPNMR program.<sup>14</sup>

**Quantum chemical calculations.** Full geometrical optimization of free *N*-methylbenzoaza-15-crown-5, *N*-methylnitrobenzoaza-15-crown-5 **1a**, and their aqua complexes with  $Ca^{2+}$  and  $Ba^{2+}$  was carried out by the DFT method with the functional PBE<sup>27</sup> in the original three-exponen t basis 3z with the PRIRODA program.<sup>28</sup> The resulting structures (conformers) were rejected unless their relative conformation energies (with respect to the most stable conformer) were less than 3 kcal mol<sup>-1</sup>. A typical error of the DFT method was ~1–2 kcal mol<sup>-1</sup>. Nonspecific (van der Waals) interactions of the flexible macrocyclic molecule with its environment (*e.g.*, a crystalline or solvating one) produce effects of the same order of magnitude. That is the reason why the conformation energy alone does not suffice to specify the dominating structure among the conformers of the crown ethers and their complexes with relative energies no higher than 3 kcal mol<sup>-1</sup>. Comparison of the calculated structure with the NOESY spectrum allowed the conclusion that one or more conformers dominate in an equilibrium mixture.

This work was financially supported by the Russian Foundation for Basic Research (Project No. 09-03-00429), the Presidium of the Russian Academy of Sciences (Program No. 7), and the Royal Society of Chemistry of the United Kingdom (personal grants for L. G. Kuz'mina and J. A. K. Howard).

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Received June 3, 2009; in revised form March 10, 2010