Supramolecular Chemistry
Publication details, including instructions for authors and subscription information:
http://www.informaworld.com/smpp/title~content=t713649759

Improvement of selective d-cation binding by tetrathiacalix[4]arene hydrazides: synthesis and extraction properties

Sergey N. Podyachev[a]; Nadezda E. Burmakina[b]; Svetlana N. Sudakova[a]; Victor V. Syakaev[a]; Alexander I. Konovalov[a]
[a] A. E. Arbuzov Institute of Organic and Physical Chemistry, Kazan Scientific Center of the Russian Academy of Sciences, Kazan, Russia [b] Kazan State Technological University, Kazan, Russia

To cite this Article Podyachev, Sergey N. , Burmakina, Nadezda E. , Sudakova, Svetlana N. , Syakaev, Victor V. and Konovalov, Alexander I.(2010) 'Improvement of selective d-cation binding by tetrathiacalix[4]arene hydrazides: synthesis and extraction properties', Supramolecular Chemistry, 22: 6, 339 — 346

To link to this Article: DOI: 10.1080/10610270903531556

URL: http://dx.doi.org/10.1080/10610270903531556

Supramolecular Chemistry
Vol. 22, No. 6, June 2010, 339–346

Improvement of selective d-cation binding by tetrathiacalix[4]arene hydrazides: synthesis and extraction properties

Sergey N. Podyachev[a]*, Nadezda E. Burmakina[b], Svetlana N. Sudakova[a], Victor V. Syakaev[a] and Alexander I. Konovalov[a]

[a]*A. E. Arbuzov Institute of Organic and Physical Chemistry, Kazan Scientific Center of the Russian Academy of Sciences, Arbuzov Street 8, 420088 Kazan, Russia;* [b]*Kazan State Technological University, K. Marks Street 68, 420015 Kazan, Russia*

(*Received 23 September 2009; final version received 2 December 2009*)

New de-*tert*-butyltetrathiacalix[4]arenes with acetylhydrazide substituents in *cone* and 1,3-*alternate* conformations have been synthesised with good yield by the hydrazinolysis of calix[4]arene ester derivatives. The recognition ability of synthesised macrocycles towards transition and alkali metals has been investigated by the picrate extraction method. The stoichiometry of complexes and the extraction constants have been determined. It has been found that tetrahydrazides do not extract alkali metal ions, but show an excellent affinity towards transition and heavy metal cations. The 1,3-*alternate* conformer of de-*tert*-butyltetrathiacalix[4]arene has revealed a remarkable selectivity for Ni^{2+} and Ag^{+} in the row of d-elements and for Cd^{2+} ion among the toxic heavy metals. The experimental data show that the removal of *tert*-butyl groups from tetrathiacalix[4]arene framework leads to the drastic improvement of extraction efficiency and selectivity of new tetrahydrazides.

Keywords: calix[4]arene; hydrazide; transition metal ions; extraction

Introduction

The rational design of artificial receptors for recognition, extraction and recovery of different metal ions is one of the interesting directions in supramolecular chemistry. Since Gutsche and Miyano (*1–3*) first published an effective and accessible one-pot synthesis of calixarene-based macrocycles, the investigation of three-dimensional structures with unique functions has occupied a central place in supramolecular chemistry (*4–8*). Whereas the conventional calix[*n*]arenes have poor coordination ability towards metal ions, it is a common practice to improve their metal-recognition ability by the functionalisation of lower and upper rims (*9*, *10*).

Our aim is to continue the investigation of calix[4]-arenes functionalised by hydrazide groups actively started in the last few years. These compounds can be considered as promising objects for biological applications (*11*). They are key reagents for the synthesis of nitrogen-containing derivatives (*12–16*). The tetrahydrazides **1–3** (Figure 1) are effective extractants of transition metal ions, but they practically do not extract the alkali and alkaline-earth metal ions (*17*, *18*). The shift of selectivity in the hydrazides from alkali and alkaline-earth cations to transition metal ions as compared with the amide derivatives is attributed to the presence of additional 'soft' nitrogen binding sites in the former. It is noticeable that the absolute values of the extraction efficiency are of minor importance for metal ion separation, whereas the selectivity factor for ions is a valuable property from a practical standpoint.

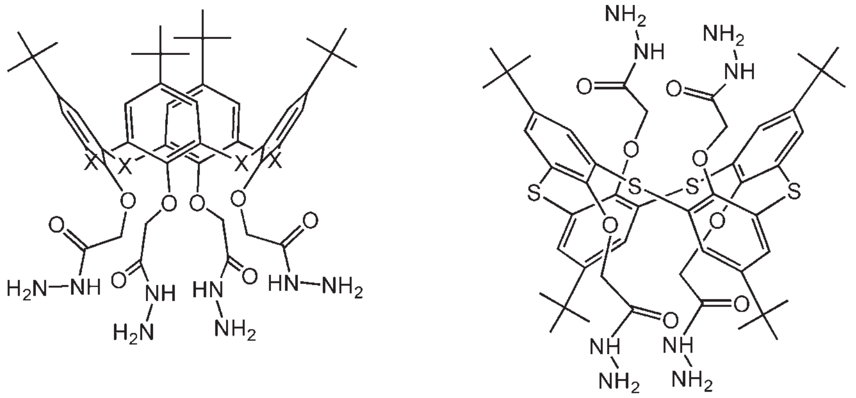
Generally, the extraction efficiency and selectivity of a lower rim functionalised calix[*n*]arenes can be controlled by several factors: the choice of a certain platform (calix[*n*]phenol or tetrathiacalix[*n*]phenol, etc.), the variation of the number of donor groups and phenyl fragments (*n*) in the calix[*n*]arene framework and the purposeful synthesis of desired conformers of calix[*n*]arene (*19*, *20*). In addition, the fine-tuning of binding properties of calix[*n*]arenes can be achieved by the variation of substituents located at the upper rim. The influence of the upper rim substitution on the metal complexation at the lower rim can be attributed to the differences in conformational mobility, solvation effect and distribution of electron density. The last factor could be important for the binding properties of amide derivatives of calix[*n*]arenes in which a determining role in coordination belongs to the phenolic oxygen atoms (*21*, *22*). In the case of acetylhydrazide derivatives, the carbonyl oxygen and amine nitrogen atoms, which promote the formation of a chelate-binding centre, are essentially distant from the phenyl rings. On the other hand, it was shown that the removal of *para*-alkyl substituents from the calix[*n*]arene skeleton leads to a significant change in the efficiency and selectivity of metal ion separation by the carboxamide calix[4]arenes (*9*, *21*, *23*). Although the bulky *para*-alkyl substituents

---

*Corresponding author. Email: spodyachev@iopc.knc.ru

ISSN 1061-0278 print/ISSN 1029-0478 online

DOI: 10.1080/10610270903531556
http://www.informaworld.com



1 X=CH$_2$
2 X=S

3

Figure 1. Structure of calix[4]arene **1**, tetrathiacalix[4]arenes **2** and **3** functionalisated by acetylhydrazide groups.

possess weak electron-donor properties, they considerably affect the macrocycle flexibility and lipophilicity. Therefore, the influence of these factors can be of crucial importance in the course of complexation by acetylhydrazide derivatives.

In this paper, the synthesis of new tetrathiacalix[4]arene hydrazides is reported. We study how the removal of *tert*-butyl groups from the upper rim of the calix[4]arene platform in different conformations affects its metal extraction properties.

Results and discussion

Synthesis

Tetrathiacalix[4]arene was chosen as a macrocyclic platform due to an easy synthetic procedure of its preparation (*3*). As illustrated in Figure 2, the parent calix[4]arene **4** was transformed into its de-*tert*-butylated analogue **5** by the previously described method (*24*). The tetraacetates, having the *cone* (**6**) or 1,3-*alternate* (**7**) conformations, were obtained by the alkylation of **5** with ethylbromoacetate under refluxing in dry acetone, using Na$_2$CO$_3$ or Cs$_2$CO$_3$ as a base, respectively, according to a well-known procedure (*20*). The corresponding hydrazides **8** (92%) and **9** (82%) have been prepared in good yields upon further treatment of calixarenyloxyacetic acid esters **6** and **7** with an excess of hydrazine hydrate. The synthesis of 1,3-*alternate* conformer **9** was carried out at higher temperature and longer time of reaction than for *cone* conformer **8** (35°C, 12 h for **8**; 50°C, 36 h for **9**). The same tendency was also observed in the synthesis of their *tert*-butyl analogues **2** and **3**. Obviously, the reaction centres in the 1,3-*alternate* conformer are blocked by phenyl rings, thus resulting in a decrease in the reaction rate.

The formation of tetrahydrazide derivatives of calix[4]arenes **8** and **9** has been confirmed by elemental analysis, mass spectra (MALDI-TOF), IR, ^{1}H and ^{13}C NMR data. The spectral characteristics of the obtained compounds are in agreement with their structures.

Extraction studies

The affinity between metal ions and compounds **8** and **9** was estimated by the extraction of metal picrates from an aqueous solution into chloroform with the use of the methodology described in our previous works (*13*, *18*). The concentrations of picric acid and metal cations in the aqueous phase were identical in all experiments. The extraction experiments were carried out with a buffer at pH 6.0. Under such conditions, the hydrolysis of metal ions (*25*) and the transfer of picric acid from the aqueous to the organic phase ($\alpha < 0.02$, Figure 3) are negligible. In this case, the extraction process can be described by Equation (1):

$$\mathrm{M}^{z+}_{\mathrm{aq}} + z\,\mathrm{Pic}^-_{\mathrm{aq}} + n\,\mathrm{L}_{\mathrm{org}} \rightleftarrows [\mathrm{M}^{z+}\mathrm{L}_n\mathrm{Pic}^-_z]_{\mathrm{org}}, \qquad (1)$$

where M^{z+}, Pic$^-$, L and $[\mathrm{M}^{z+}\mathrm{L}_n\mathrm{Pic}^-_z]$ denote the metal ion, picrate anion, ligand and ion-pair metal complex, respectively, and the subscripts aq and org mean that the species exist in the aqueous or organic phase. The equilibrium concentration of picrate in the aqueous phase was determined spectrophotometrically. The extraction constant (K_{ex}) is evaluated from Equation (2):

$$K_{\mathrm{ex}} = \frac{[\mathrm{M}^{z+}\mathrm{L}_n\mathrm{Pic}^-_z]_{\mathrm{org}}}{[\mathrm{M}^{z+}]_{\mathrm{aq}}[\mathrm{Pic}^-]^z_{\mathrm{aq}}[\mathrm{L}]^n_{\mathrm{org}}}. \qquad (2)$$

The results of extraction for **8** and **9** and the novel data for **2** and **3** are summarised in Figure 4.

The new macrocycle **8** reveals high extraction ability for d-elements (Figure 4(a)). A poor extraction is observed

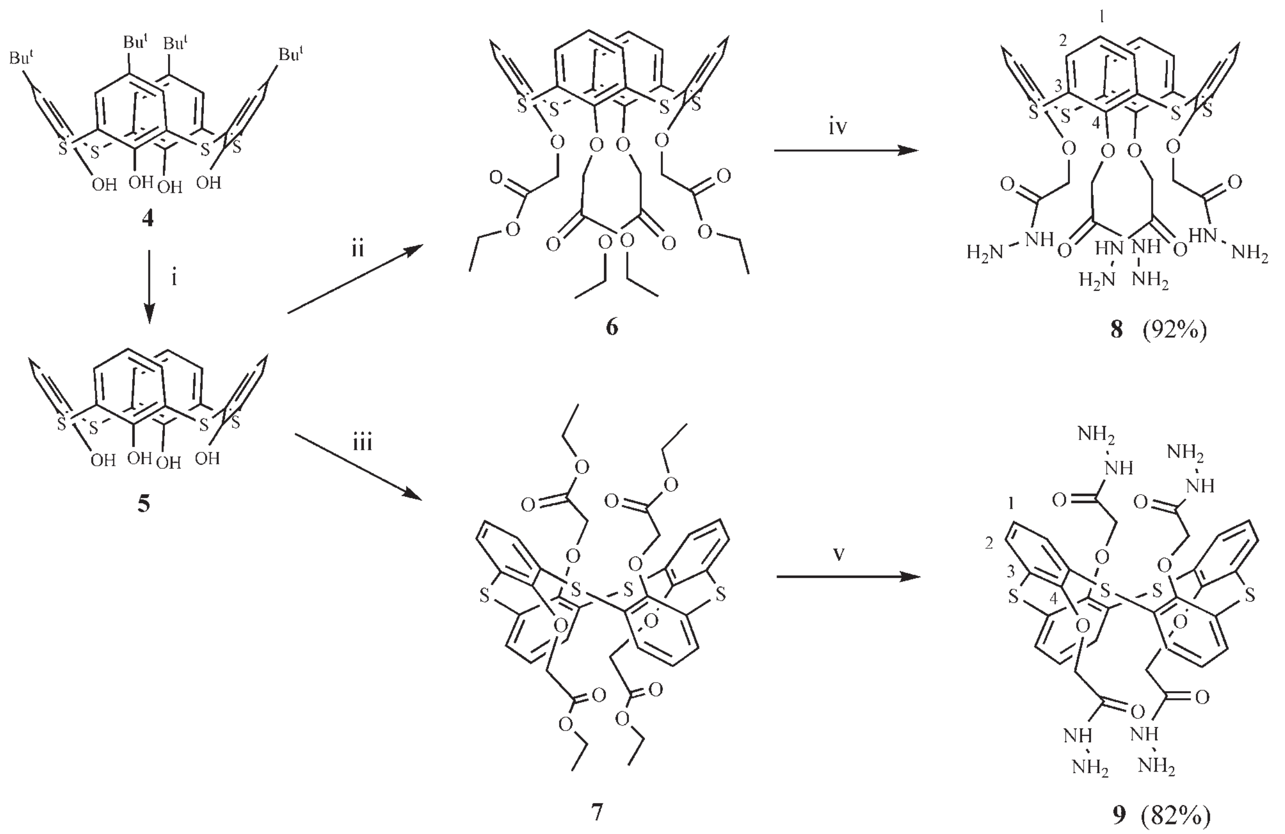


Figure 2. Synthesis of the hydrazides **8** and **9**, and atomic numbering scheme. Reagents and conditions: (i) $AlCl_3$, phenol, toluene, 60°C, 4 h; (ii) $BrCH_2COOEt$, Na_2CO_3, acetone, reflux, 100 h; (iii) $BrCH_2COOEt$, Cs_2CO_3, acetone, reflux, 100 h; (iv) $NH_2NH_2{\cdot}H_2O$, THF/MeOH, 35°C, 12 h; (v) $NH_2NH_2{\cdot}H_2O$, THF/EtOH, 50°C, 36 h.

for alkali ($E < 3\%$ for Li^+, Na^+, K^+ and Cs^+) and alkaline-earth ($E \sim 4\%$ for Ca^{2+}) ions. The recovery of d-metal ions (Co^{2+}, Ni^{2+}, Cu^{2+}, Zn^{2+} and Ag^+) by calix[4]arenes **2** and **8** is practically total at 1×10^{-3} M and the extraction percentage for calix[4]arenes **2** (*18*) and **8** is almost equal at this concentration. However, the maximum of extraction for heavy metal ions is shifted from Pb^{2+} (for **2** ~92% (*18*) and **8** ~40%) to Cd^{2+} (for **2** ~77% (*18*) and **8** ~88%). The calix[4]arene **8** does not practically extract f-ions (La^{3+}, Gd^{3+} and Lu^{3+}) in contrast to compound **2** (for **2** ~24–29% (*18*) and for **8** ~5–8%). With the decrease in extractant concentration up to 2.5×10^{-4} M, the difference in extraction yield becomes more apparent. The extraction efficiency of calix[4]arene **8** in comparison with **2** is increased for Co^{2+}, Ni^{2+}, Zn^{2+} and Ag^+ up to $E_8(Me^{n+})/E_2(Me^{n+}) \sim 1.35$–1.44 and achieves the values of 1.8 and 2.3 for Hg^{2+} and Cd^{2+} ions, respectively. Thus, the calix[4]arene **8** extracts d-ions more selectively and effectively than its more rigid *tert*-butyl analogue **2**.

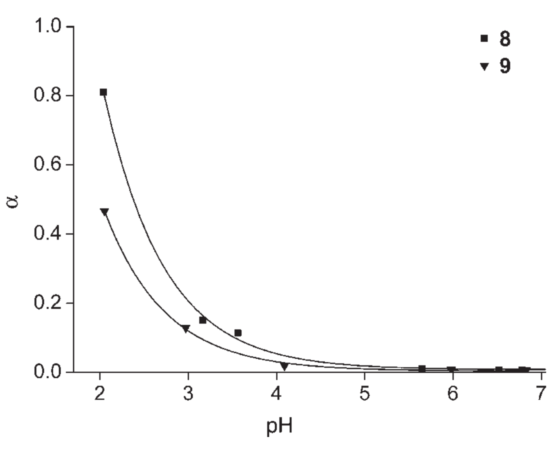


Figure 3. Effect of pH on a degree of transfer of HPic in the systems containing extractants **8** and **9**. $[HPic] = 2.5 \times 10^{-4}$ M; $[L_8] = 1 \times 10^{-3}$ M; $[L_9] = 2.5 \times 10^{-4}$ M.

The solubility of 1,3-*alternate* conformer **9** is substantially lower than that of *cone* conformer **8** or *tert*-butyl analogue **2**. Therefore, the liquid–liquid extraction experiments for **9** were carried out at the ligand concentration not exceeding 2.5×10^{-4} M (Figure 4(b)). Under such conditions, 1,3-*alternate* conformer **9** reveals the lower extraction efficiency compared to its *cone* analogue **8**. However, the extraction selectivity for **9** is dramatically increased. At the same time, the efficiency of extraction of d-ions by compound **9** is significantly higher

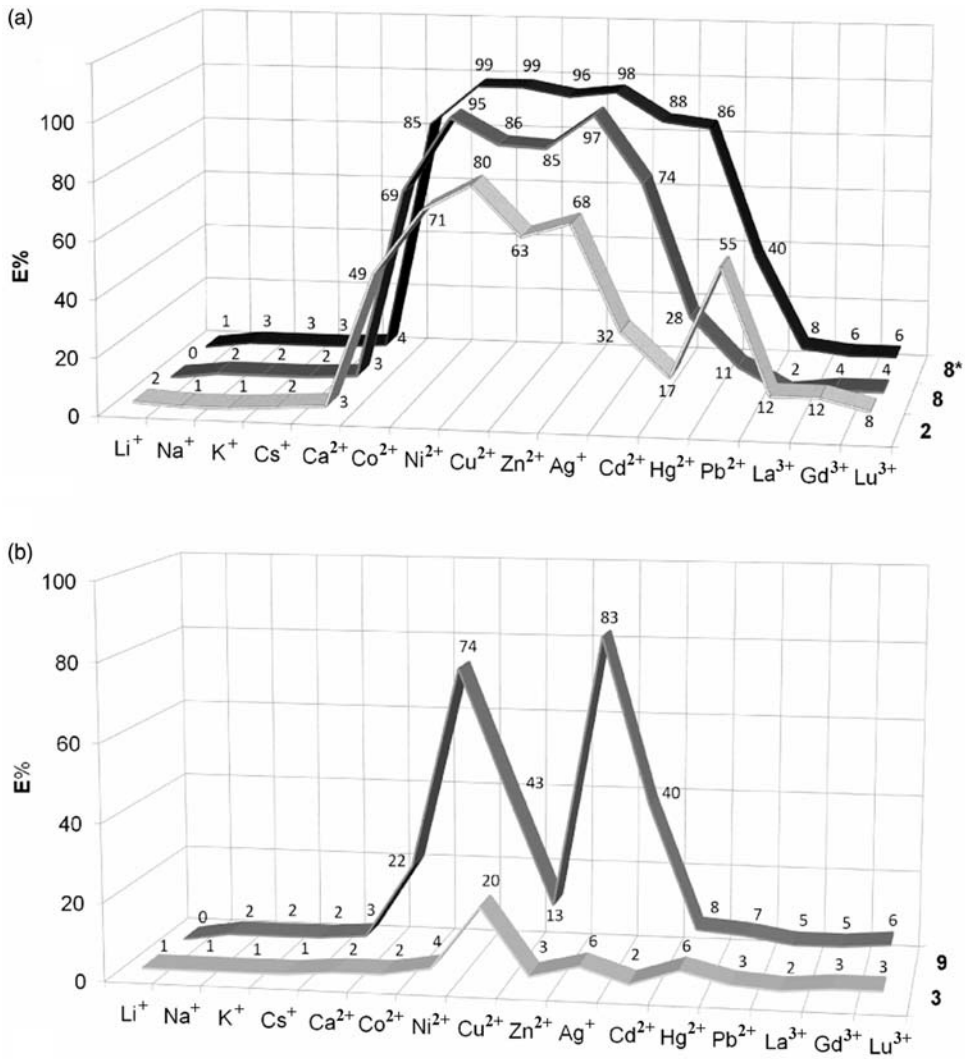


Figure 4. Extraction percentages (*E%*) of metal picrates from water into $CHCl_3$ at 25°C by (a) *cone*-**2**, *cone*-**8** and (b) 1,3-*alternate*-**3**, 1,3-*alternate*-**9**. pH = 6.0; [HPic] = 2.5×10^{-4} M, $[M^{z+}] = 1 \times 10^{-2}$ M, $[L_{\mathbf{2,3,8,9}}] = 2.5 \times 10^{-4}$ M, $^*[L_{\mathbf{8}}] = 1 \times 10^{-3}$ M.

than that for *tert*-butyl analogue **3**, in spite of the lower lipophilicity of the former. The maximum of extraction is shifted from Cu^{2+} to Ni^{2+} and from Hg^{2+} to Cd^{2+} for heavy metal ions. A considerable increase in extraction efficiency is observed for Ag^+ (for **3** $\sim$6% and **9** $\sim$83%). The values of extraction selectivity for Ag^+/Hg^{2+} and Ag^+/Pb^{2+} are 10.1 and 11.8, respectively. These values are higher than those reported earlier (*26–30*).

The regularity ($Co^{2+} < Ni^{2+} > Cu^{2+} > Zn^{2+}$) of extraction efficiency for compounds **8** and **9** is disturbed as compared to the Irving–Williams (*31*) order for the relative stability of complexes formed by metal ions of the first transition series. The Ni^{2+} ion is extracted essentially better than Cu^{2+}, particularly by compound **9**.

Usually calix[4]arenes form 1:1 complexes with guest molecules, but various types of complexation were observed depending on the calix ring size and the functional groups introduced in the macrocycle. Due to the existence of four hydrazide metal-binding sites, several possibilities may be realised for the metal complexation mode. We have estimated the percentage of metal picrate recovery at various concentrations of the ligand. The stoichiometry of the extracted complexes and the extraction constants have been determined from $\log Q$ vs. $\log [L]_{org}$ plots (see the Experimental section). The extraction dependence on the final concentration of 'free' ligand has been taken into account. The results of extraction experiments for compounds **8** and **9** with some transition metal ions are presented in Figure 5 and Table 1.

All graphs of extraction dependences for *cone* conformer **8** with different metal ions have an equal slope ($n = 2$) independently of excess or insufficiency of ligand (Figure 5(a)). This indicates the 1:2 (M^{z+}/L) stoichiometry of the extracted complexes in a wide

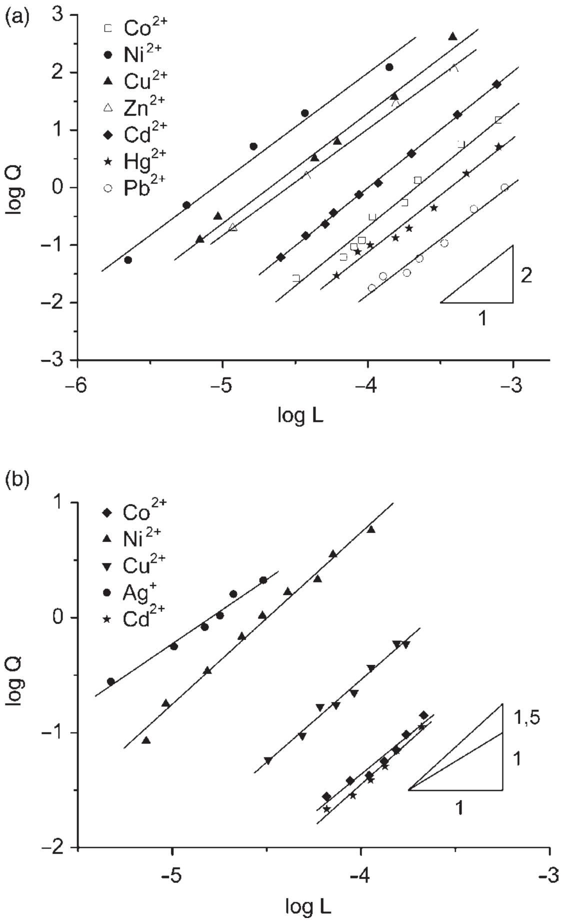


Figure 5. Log Q vs. $\log[\mathrm{L}]_{\mathrm{org}}$ for some metal ions extracted by (a) *cone*-**8** and (b) 1,3-*alternate*-**9** in $CHCl_3$. $[\mathrm{HPic}] = 2.5 \times 10^{-4}$ M, $[\mathrm{M}^{z+}] = 1 \times 10^{-2}$ M, pH = 6.0.

concentration range. In the case of the 1,3-*alternate* conformer **9**, the plots have a slope $n = 1.5$ for all metal ions, except for Ag^{+} ($n = 1$) (Figure 5(b)). One can suppose that compound **9** forms 2:3 and 1:1 (M^{z+}/L) complexes, respectively.

The selectivity in the series of d-elements (Co^{2+}, Ni^{2+}, Cu^{2+} and Zn^{2+}) and heavy toxic metals for compound **8** achieves two orders of magnitude: $K_{\mathrm{ex}}(\mathrm{Ni}^{2+})/K_{\mathrm{ex}}(\mathrm{Co}^{2+}) = 10^{1.9}$ and $K_{\mathrm{ex}}(\mathrm{Cd}^{2+})/K_{\mathrm{ex}}(\mathrm{Pb}^{2+}) = 10^{2.3}$ (Table 1). On going to 1,3-*alternate* conformer **9**, the selectivity of extraction in the series of d-elements is increased up to four orders ($K_{\mathrm{ex}}(\mathrm{Ni}^{2+})/K_{\mathrm{ex}}(\mathrm{Co}^{2+}) = 10^{3.0}$ and $K_{\mathrm{ex}}(\mathrm{Ni}^{2+})/K_{\mathrm{ex}}(\mathrm{Zn}^{2+}) = 10^{4.4}$) and for heavy toxic metals equals almost three orders of magnitude ($K_{\mathrm{ex}}(\mathrm{Cd}^{2+})/K_{\mathrm{ex}}(\mathrm{Hg}^{2+}) = 10^{2.7}$ and $K_{\mathrm{ex}}(\mathrm{Cd}^{2+})/K_{\mathrm{ex}}(\mathrm{Pb}^{2+}) = 10^{2.8}$).

The high extraction efficiency of Ag^{+} ion recovery by compounds **8** and **9** along with the visible precipitation during the extraction experiment have not allowed us to obtain the accurate values of the constants and stoichiometry. The precise definition of stoichiometry of formed Ag^{+} complexes with *cone*-**2**, *cone*-**8** and 1,3-*alternate*-**9** was carried out in $H_2O/CHCl_3$ phases by the Job plots. The extraction yields reached the maxima at 0.4 mole fraction for **2** and 0.5 mole fraction for **8** and **9** (Figure 6). This fact clearly indicates that Ag^{+} forms the complexes of 2:3 and 1:1 (M^{z+}/L) stoichiometry for **2**, and **8** and **9** compounds, respectively. The obtained result for **9** is in accordance with the data for complex stoichiometry determined from $\log Q$ vs. $\log[\mathrm{L}]_{\mathrm{org}}$ plot dependences (Figure 5(b)). However, the coordination of *cone*-**8** and 1,3-*alternate*-**9** with Ag^{+} may lead to the formation of

Table 1. The extraction constants and stoichiometry of metal complexes with compounds **8** and **9**.

Cation	Metal:ligand stoichiometry	Log K_{ex}	
		cone-**8**	1,3-*alternate*-**9**
Co^{2+}	1:2	13.2 ± 0.5	–
	2:3	–	9.6 ± 0.2
Ni^{2+}	1:2	15.1 ± 0.4	–
	2:3	–	12.6 ± 0.3
Cu^{2+}	1:2	14.6 ± 0.2	–
	2:3	–	10.9 ± 0.3
Zn^{2+}	1:2	13.9 ± 0.3	–
	2:3	–	8.2[a]
Ag^{+}	1:1	7.5[b]	7.3 ± 0.3
Cd^{2+}	1:2	13.7 ± 0.1	–
	2:3	–	10.6 ± 0.3
Hg^{2+}	1:2	12.6 ± 0.5	–
	2:3	–	7.9[a]
Pb^{2+}	1:2	11.4 ± 0.2	–
	2:3	–	7.8[a]

[a] The extraction constant was evaluated from extraction yield for proposed complex stoichiometry 2:3.

[b] The extraction constant was evaluated from extraction yield for complex stoichiometry 1:1.

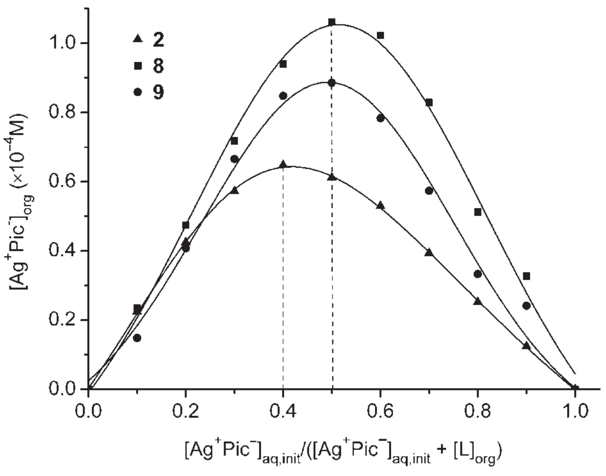


Figure 6. Job plots for $Ag^{+}Pic^{-}$ extracted by *cone*-**2**, *cone*-**8** and 1,3-*alternate*-**9**. $[\mathrm{HPic}]_{\mathrm{aq}} + [\mathrm{L}]_{\mathrm{org}} = 2.5 \times 10^{-4}$ M, $[\mathrm{M}^{z+}] = 1 \times 10^{-2}$ M, pH = 6.0.

polymer chains with 'an effective or formal' 1:1 complex stoichiometry, in which Ag^+ ion acts as a 'bead' between hydrazide fragments of two neighbouring calix[4]arene molecules. Although the reason for precipitation in the case of **8** and **9** is not still clear, this fact can indirectly indicate the polymer character of complexes formed.

Therefore, even in the case of calix[4]arene **9**, four hydrazide groups can participate in a coordination. It is noticeable that, in this situation, a number of donor centres (8) excessive for binding of d-ions are available. The high dentation of tetrahydrazides **8** and **9** and their tendency to form intra- and intermolecular hydrogen bonds can be a reason for steric hindrances arising from coordination with metal ions. All these factors lead to the deviation from the Irving–Williams order.

It was assumed earlier that the decrease in pre-organisation effect following the removal of *tert*-butyl groups from the tetrathiacalix[4]arene framework is the main reason for a poor extraction of alkali metal ions by de-*tert*-butyl ester derivatives of 'classical' calix[4]arene (*32*). Similar experimental data were obtained for ester, amide and phenylcarbonyl derivatives of tetrathiacalix[4]-arene in different conformations (*33*). However, the extraction ability of hydrazide derivatives of calix[4]-arenes **2**, **3** and **8**, **9** studied here has revealed an opposite effect of the removal of *tert*-butyl groups.

We have shown earlier (*18*) that the bis-ligand coordination with transition metal ions was obtained with only an excess of *cone* conformer **2**. The 1,3-*alternate* conformer **3** formed mono-ligand complexes in all investigated cases. In contrast to the *tert*-butylcalix[4]-arenes **2** and **3**, the non-substituted derivatives **8** and **9** participate in bis-ligand coordination with metal ions. This fact is probably a consequence of an increased flexibility of calix[4]arene macrocycle and the decrease in steric hindrances. The introduction of several ligand molecules into the structure provides the formation of coordinatively saturated complexes with higher lipophilicity. As a result, the drastic increase in extraction efficiency for tetrahydrazides **8** and **9** as compared with their *tert*-butyl analogues **2** and **3** is observed.

Conclusion

In summary, we have synthesised new tetrahydrazide derivatives of tetrathiacalix[4]arene in *cone* (**8**) and 1,3-*alternate* (**9**) conformations. The liquid–liquid extraction experiments with metal cations have shown that both calix[4]arene tetrahydrazide derivatives **8** and **9** are excellent phase transfer agents for d-cations and can separate them from alkali, alkaline-earth and f-metal ions more selectively than their *tert*-butyl analogues **2** and **3**. On going from *cone* **8** to 1,3-*alternate* conformer **9**, the extraction selectivity in the series of d-elements dramatically increases for Ni^{2+}, Ag^+ and Cd^{2+}. The abnormally low extraction efficiency of Ag^+ ion by 1,3-*alternate* conformer **3** compared to its de-*tert*-butyl analogue **9** is observed.

The stoichiometry and the extraction constants of investigated complexes have been determined using the ligand concentration dependences. The *cone* conformer **8** and 1,3-*alternate* conformer **9** form 1:2 and 2:3 (M^{z+}/L) metal complexes in a wide range of ligand concentration. Unlike the other metal ions, the Ag^+ ion forms with **8** and **9** the complexes of 1:1 stoichiometry.

The removal of *tert*-butyl groups from the tetrathiacalix[4]arene framework dramatically changes the extraction efficiency and selectivity of new tetrahydrazides **8** and **9**. The increased flexibility of macrocycle and the decreased steric hindrances promote the bis-ligand coordination of metal ions and lead to a drastic improvement of cation-binding properties of investigated compounds. Therefore, the fine-tuning of the structure can play an important role in the design of the calix[4]arene derivatives and should be mostly considered for the optimisation of metal ion affinity.

Experimental

Reagents

All chemicals were used as commercially received without further purification. $CHCl_3$ was distilled over P_2O_5. $CDCl_3$ (99.8% isotopic purity) and DMSO-d_6 (99.5% isotopic purity) from Aldrich were used for NMR spectroscopy. The metal salts for extraction experiments were the following chlorides and nitrates: LiCl, NaCl, KCl, CsCl, $CaCl_2$, $CoCl_2 \cdot 6H_2O$, $NiCl_2$, $CuCl_2$, $ZnCl_2$, $CdCl_2 \cdot 2.5H_2O$, $Hg(NO_3)_2 \cdot H_2O$, $Pb(NO_3)_2$, $LaCl_3 \cdot 7H_2O$, $Gd(NO_3)_3 \cdot 6H_2O$ and $LuCl_3 \cdot 6H_2O$.

Synthesis

The tetrahydrazide derivatives of calix[4]arenes **2** and **3** were obtained as described earlier (*17*, *18*). Figure 2 illustrates the successive synthetic steps for compounds **8** and **9**.

*25,26,27,28-Tetrakis[hydrazinocarbonylmethyl]-2,8,14,20-tetrathiacalix[4]arene (*cone-***8***)*

To the *cone* conformer of tetrathiacalix[4]arenyloxyacetic acid ethyl ester **6** (1.0 g; 1.2 mmol) in the mixture of THF (8 ml) and MeOH (4 ml) under stirring, an excess of $NH_2NH_2 \cdot H_2O$ (98%, 1.8 ml; 37 mmol) was added. The reaction mixture was heated at 35°C for 12 h. The solvent was removed from the reaction mixture by distillation and the solid remainder was washed twice by MeOH and diethyl ether. Yield: 0.86 g (92%) as a white powder. Mp 218–220°C. ^1H NMR (600.0 MHz, DMSO-d_6, 30°C) δ: 4.4 (br s, 8H, NH_2), 4.63 (s, 8H, $O—CH_2$), 6.91 (t, 4H,

$J = 7.8$ Hz, H-Ph), 7.00 (br d, 8H, H-Ph), 9.3 (s, 4H, NH); ^{13}C NMR (150.9 MHz, DMSO-d_6, 30°C) δ: 74.3 (t, $J = 148.5$ Hz, O—CH$_2$), 125.7 (d, $J = 166.2$ Hz, C(1) in Ar), 130.3 (d, $J = 9.9$ Hz, C(3) in Ar), 135.6 (d, $J = 148.5$ Hz, C(2) in Ar), 158.8 (C(4) in Ar), 167.0 (d, $J = 9.2$ Hz; t, $J = 4.1$ Hz, C═O). IR (ν/cm^{-1}, KBr): 3340, 3202 (νNH), 1673 (νC═O), 1616 (δNH$_2$), 1520 (δNH). Elemental analysis Calc. for $C_{32}H_{32}N_8O_8S_4$ (784.89): C, 48.97; H, 4.11; N, 14.29; S, 16.31. Found: C, 48.92; H, 3.74; N, 14.55; S, 15.94. Mass spectrum (MALDI-TOF): $m/z = 785$ [M+H]$^+$; 807 [M+Na]$^+$; 823 [M+K]$^+$.

*25,26,27,28-Tetrakis[hydrazinocarbonylmethyl]-2,8,14,20-tetrathiacalix[4]arene (1,3-*alternate-***9***)*

To the 1,3-*alternate* conformer of tetrathiacalix[4]arenyloxyacetic acid ethyl ester **7** (1.0 g; 1.2 mmol) in the mixture of THF (20 ml) and EtOH (8 ml) under stirring, an excess of $NH_2NH_2{\cdot}H_2O$ (98%, 1.8 ml; 37 mmol) was added. The reaction mixture was heated at 50°C for 36 h. The solvent was removed from the reaction mixture by distillation and the solid remainder was washed twice by MeOH and diethyl ether. Yield: 0.76 g (82%) as a white powder. Mp 253–255°C. ^{1}H NMR (600.0 MHz, DMSO-d_6, 30°C) δ: 4.06 (br s, 8H, NH$_2$), 4.42 (s, 8H, O—CH$_2$), 7.05 (t, 4H, $J = 8.1$ Hz, H-Ph), 7.22 (br s, 4H, NH), 7.44 (d, 8H, $J = 8.1$ Hz, H-Ph); ^{13}C NMR (150.9 MHz, DMSO-d_6, 30°C) δ: 67.9 (t, $J = 148.2$ Hz, O—CH$_2$), 125.2 (d, $J = 126.0$ Hz, C(1) in Ar), 128.1 (d, $J = 9.8$ Hz, C(3) in Ar), 133.0 (d, $J = 163.0$ Hz, C(2) in Ar), 157.5 (C(4) in Ar), 165.7 (d, $J = 8.7$ Hz; t, $J = 4.4$ Hz, C═O). IR (ν/cm^{-1}, KBr): 3430, 3318, 3209 (νNH), 1670 (νC═O), 1620 (δNH$_2$), 1520 (δNH). Elemental analysis Calc. for $C_{32}H_{32}N_8O_8S_4$ (784.89): C, 48.97; H, 4.11; N, 14.29; S, 16.31. Found: C, 49.31; H, 3.80; N, 14.39; S, 16.04. Mass spectrum (MALDI-TOF): $m/z = 785$ [M+H]$^+$; 807 [M+Na]$^+$; 823 [M+K]$^+$.

Apparatus

Microanalyses of C, H and N were carried out with a CHN-3 analyser. Melting points of compounds were measured with a Boetius hot-stage apparatus. IR absorption spectra of Nujol emulsions, KBr pellets and CHCl$_3$ solutions (0.25 mmol) of compounds were recorded on a Vector-22 Bruker FTIR spectrophotometer with a resolution of 4 cm^{-1}. Mass spectra (MALDI) were detected on a Bruker Ultraflex III MALDI-TOF/TOF mass spectrometer. NMR experiments were performed on a Bruker AVANCE-600 spectrometer at 303 K equipped with a 5 mm diameter broadband probe head working at 600.13 MHz in ^{1}H and 150.864 MHz in ^{13}C experiments. Chemical shifts in ^{1}H and ^{13}C spectra were reported relative to the solvent as an internal standard (DMSO δ(^{1}H) 2.50 ppm, δ(^{13}C) 39.5 ppm).

Picrate extraction experiments

Aqueous metal picrate solution (5 ml), which was buffered at pH 6.0, and the solution of extractant (5 ml, 2.5×10^{-5} to 1×10^{-3} M) in CHCl$_3$ were magnetically stirred in a flask. The extraction equilibrium was reached after vigorous stirring for 1.5 h at 20°C. Then, two phases were allowed to settle for 1 h. The absorbances A_1 of the aqueous phase after extraction and A_0 of the aqueous phase before extraction were measured at $\lambda_{max} = 355$ nm (the wavelength of maximum absorption of the picrate ion). All data were obtained from the three independent experiments. Aqueous metal picrate solutions ([metal salt] $= 1 \times 10^{-2}$ M; [picric acid] $= 2.5 \times 10^{-4}$ M) were prepared by stepwise addition of 2.5×10^{-4} M aqueous picric acid solution to the calculated amounts of metal salts. The obtained solutions were stirred at pH 6.0 with acetic–acetate buffer for 1 h. For alkaline ions, the tris(hydroxymethyl)aminomethane–HCl (0.05 M) was used as a buffer. The per cent of extraction was calculated as ratio $E\% = \alpha \times 100\% = 100 \times (A_0 - A_1)/A_0$. $E\%$ uncertainties are generally $\leq 2\%$. The $\log K_{ex}$ and n values were determined from the plot of $\log Q$ vs. $\log [L]_{org}$, where $Q = \alpha/z(1 - \alpha)^z$ as described elsewhere (*13*, *18*).

Acknowledgement

This work was supported by the Russian Foundation for Basic Research (grant 07-03-00325-a).

References

(1) Gutsche, C.D.; Dhawan, B.; No, K.; Muthukrishnan, R. *J. Am. Chem. Soc.* **1981**, *103*, 3782–3792.

(2) Gutsche, C.D.; Iqbal, M.; Stewart, D. *J. Org. Chem.* **1986**, *51*, 742–745.

(3) Kumagai, H.; Hasegawa, M.; Miyanari, S.; Sugawa, Y.; Sato, Y.; Hori, T.; Ueda, S.; Kamiyama, H.; Miyano, S. *Tetrahedron Lett.* **1997**, *38*, 3971–3972.

(4) Gutsche, C.D. In *Calixarenes Revisited: Monographs in Supramolecular Chemistry*; Stoddart, J.F., Ed.; The Royal Society of Chemistry: Cambridge, 1998.

(5) Steed, J.W.; Atwood, J.L. *Supramolecular Chemistry*; Wiley: Chichester, 2000.

(6) Asfary, Z., Böhmer, V., Harrowfield, J., Vicens, J., Eds. *Calixarenes 2001*; Kluwer Academic: Dordrecht, 2001.

(7) Vicens, J.; Harrowfield, J. *Calixarenes in the Nanoworld*; Springer: The Netherlands, 2007.

(8) Diederich, F., Stang, P.J., Tykwinski, R.R., Eds. *Modern Supramolecular Chemistry: Strategies for Macrocycle Synthesis*; Wiley-VCH: Weinheim, 2008.

(9) Creaven, B.S.; Donlon, D.F.; McGinley, J. *Coord. Chem. Rev.* **2009**, *253*, 893–962.

(10) Morohashi, N.; Narumi, F.; Iki, N.; Hattori, T.; Miyano, S. *Chem. Rev.* **2006**, *106*, 5291–5316.

(11) Pires, V.S.; Gaboriau, F.; Guillon, J.; da Nascimento, S.; Dassonville, A.; Lescoat, G.; Desplat, V.; Rochette, J.; Jarry, C.; Sonnet, P.J. *Enzyme Inhib. Med. Chem.* **2006**, *21*, 261–270.

(12) Podyachev, S.N.; Sudakova, S.N.; Syakaev, V.V.; Shagidullin, R.R.; Galiev, A.K.; Konovalov, A.I. *Mendeleev Commun.* **2006**, *6*, 297–299.

(13) Podyachev, S.N.; Burmakina, N.E.; Syakaev, V.V.; Sudakova, S.N.; Shagidullin, R.R.; Konovalov, A.I. *Tetrahedron* **2009**, *65*, 408–417.

(14) Quinlan, E.; Matthews, S.E.; Gunnlaugsson, T. *Tetrahedron Lett.* **2006**, *47*, 9333–9338.

(15) Quinlan, E.; Matthews, S.E.; Gunnlaugsson, T. *J. Org. Chem.* **2007**, *72*, 7497–7503.

(16) Yang, F.; Ji, Y.; Zheng, L.; Guo, H.; Lin, J. *Supramol. Chem.* **2006**, *18*, 177–181.

(17) Podyachev, S.N.; Syakaev, V.V.; Sudakova, S.N.; Shagidullin, R.R.; Osyanina, D.V.; Avvakumova, L.V.; Buzykin, B.I.; Latypov, Sh.K.; Habicher, V.D.; Konovalov, A.I. *J. Inclusion Phenom. Macrocyclic Chem.* **2007**, *58*, 55–61.

(18) Podyachev, S.N.; Sudakova, S.N.; Syakaev, V.V.; Galiev, A.K.; Shagidullin, R.R.; Konovalov, A.I. *Supramol. Chem.* **2008**, *20*, 479–486.

(19) Iki, N.; Narumi, F.; Fujimoto, T.; Morohashi, N.; Miyano, S. *J. Chem. Soc. Perkin Trans. 2* **1998**, 2745–2750.

(20) Lhotak, P.; Stastny, V.; Zlatuskova, P.; Stibor, I.; Michlova, V.; Tkadlecova, M.; Havlicek, J.; Sykora, J. *Collect. Czech. Chem. Commun.* **2000**, *65*, 757–771.

(21) Schuhle, D.T.; Klimosch, S.; Schatz, J. *Tetrahedron Lett.* **2008**, *49*, 5800–5803.

(22) Arnaud-Neu, F.; Barboso, S.; Berny, F.; Casnati, A.; Muzet, N.; Pinalli, A.; Ungaro, R.; Schwing-Weill, M.-J.; Wipff, G. *J. Chem. Soc. Perkin Trans. 2* **1999**, 1727–1738.

(23) Talanova, G.G.; Talanov, V.S.; Gorbunova, M.G.; Hwang, H.-S.; Bartsch, R.A. *J. Chem. Soc. Perkin Trans. 2* **2002**, 2072–2077.

(24) Higuchi, Y.; Narita, M.; Niimi, T.; Ogawa, N.; Hamada, F.; Kumagai, H.; Iki, N.; Miyano, S.; Kabutod, C. *Tetrahedron* **2000**, *56*, 4659–4666.

(25) Morrow, J.I. *J. Chem. Educ.* **1972**, *49*, 748–749.

(26) Marcos, P.M.; Ascenso, J.R.; Segurado, M.A.P.; Pereira, J.L.C. *J. Inclusion Phenom. Macrocyclic Chem.* **2002**, *42*, 281–288.

(27) Xie, J.; Zheng, Q.-Y.; Zheng, Y.S.; Chen, C.-F.; Huang, Z.-T. *J. Inclusion Phenom. Macrocyclic Chem.* **2001**, *40*, 125–130.

(28) No, K.; Lee, J.H.; Yang, S.H.; Noh, K.H.; Lee, S.W.; Kimd, J.S. *Tetrahedron* **2003**, *59*, 2403–2407.

(29) Yang, F.; Huang, C.; Guo, H.; Lin, J.; Peng, Q. *J. Inclusion Phenom. Macrocyclic Chem.* **2007**, *58*, 169–172.

(30) Bouhroum, S.; Arnaud-Neu, F.; Asfari, Z.; Vicens, J. *Supramol. Chem.* **2005**, *17*, 629–635.

(31) Irving, H.; Williams, R.J.P. *J. Chem. Soc.* **1953**, *10*, 3192–3210.

(32) Ivamoto, K.; Shinkai, S. *J. Org. Chem.* **1992**, *57*, 7066–7073.

(33) Solovieva, S.E.; Kleshnina, S.R.; Kozlova, M.N.; Galiullina, L.F.; Gubaidullin, A.T.; Latypo, S.K.; Antipin, I.S.; Konovalov, A.I. *Russ. Chem. Bull.* **2008**, *57*, 1477–1485.