

RECENT ADVANCES IN CALIX[4]RESORCINARENE CHEMISTRY

© M. Pietraszkiewicz,¹ O. Pietraszkiewicz,¹ E. Uzig,¹ P. Prus,¹ Z. Brzózka,² K. Woźniak,³
R. Bilewicz,³ T. Borowiak,⁴ and M. Mączyński⁴

¹ Institute of Physical Chemistry Polish Academy of Sciences. 01224 Warsaw. Kasprzaka 44/52. Poland. E-mail: pietrasz@ichf.edu.pl

² Department of Analytical Chemistry. Warsaw University of Technology. 00-664 Warsaw. Noakowskiego 3. Poland.

³ Department of Chemistry. University of Warsaw. 02093 Warsaw. Pasteura 1. Poland.

⁴ Department of Chemistry. A. Mickiewicz University. Grunwaldzka 6. 60-780 Poznan. Poland.

Keywords: calix[4]resorcinarenes, thermogravimetry, CP/MAS NMR, transport/extraction, HPLC, X-ray, Langmuir, electrochemical methods.

Abstract

Calix[4]resorcinarenes bearing lipophilic and amino functions were investigated as potential receptors for ions and neutral molecules by means of thermogravimetric, CP/MAS NMR, transport/extraction, HPLC, X-ray, Langmuir, and electrochemical methods. Chiral Mannich-base calix[4]resorcinarenes forming Langmuir films were found to differentiate amino acids in water subphase.

Introduction

Calix[4]resorcinarenes deliver a versatile molecular platform for the elaboration of more complicated molecular host systems. Most of reactions with these compounds consists on electrophilic substitution of hydrogen atom between two hydroxyls, or substitutions on hydroxyl groups. One of the easiest reactions is the Mannich-type reaction with different amino components. We have dealt with a number of lipophilic *C*-tetraundecylcalix[4]resorcinarenes bearing four amino functions of different type, of which the general formula is presented below:

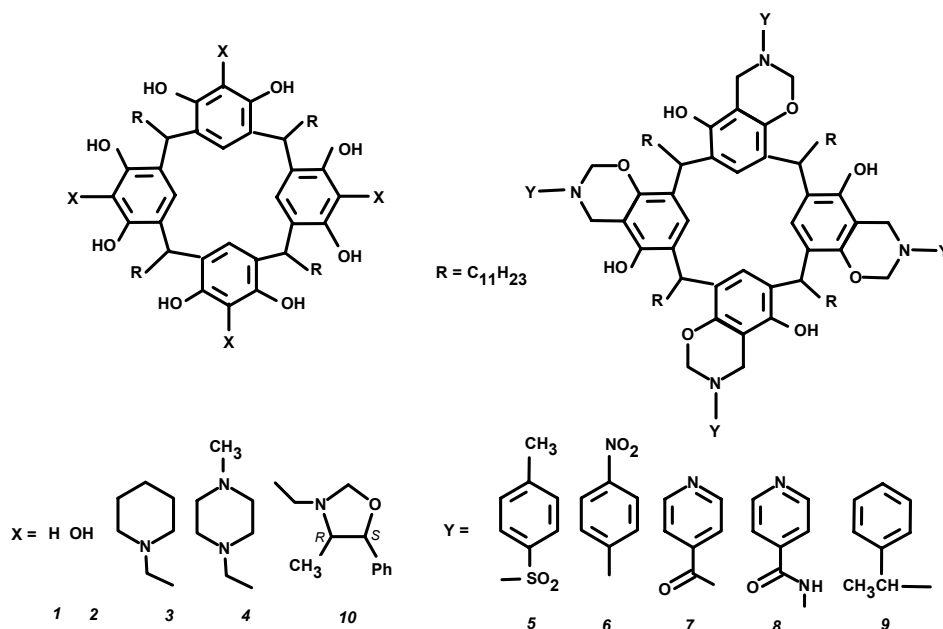


Fig. 1. Structural formulas of investigated calix[4]resorcinarenes.

The initial nonderivatised resorcinarene and its solvates was studied by X-ray analysis, TGA, H-1 CP/MAS NMR, and its derivatives by transport across liquid membranes, extraction, HPLC experiments, and electrochemistry. Chiral recognition studies were performed on chiral Mannich bases using Langmuir technique as a sensitive means to distinguish enantiomers.

Calix[4]resorcinarenes form a relatively shallow conical cavity that can be extended by suitable substitution and functionalised further. Calix[4]resorcinarenes form a variety of complexes with organic/inorganic ions, neutral molecules, transition metal complexes and organometallics by means of noncovalent interactions. This capability makes them particularly attractive as multifunctional receptors to be used in molecular recognition studies. Many monograph books about calixarenes appeared to date [1].

Results and Discussion

I. Solvate Formation.

a. Thermogravimetry.

Practically all calix[4]resorcinarenes form solvates with the solvents from which they crystallize. Often the removal of solvent molecules can be achieved in high vacuum at elevated temperature. This strong interaction of calix[4]resorcinarenes with organic solvents is a competing mechanism with inclusion phenomena in solution. Thus, the solvation is an important factor affecting significantly the strength and the selectivity of complexation of selected guest species.

One of convenient methods to follow the stability of solvates is thermogravimetry. We have done an extensive thermogravimetric studies on selected solvates with unsubstituted *C*-tetra-*n*-undecylcalix[4]resorcinarene [2]. Several TG and DTG curves are collected to demonstrate that various crystalline solvates decomposed in different manner. The decomposition of the solvate with acetone displayed three distinct steps, and with dioxane and dimethoxybenzene - two steps (Figure 2).

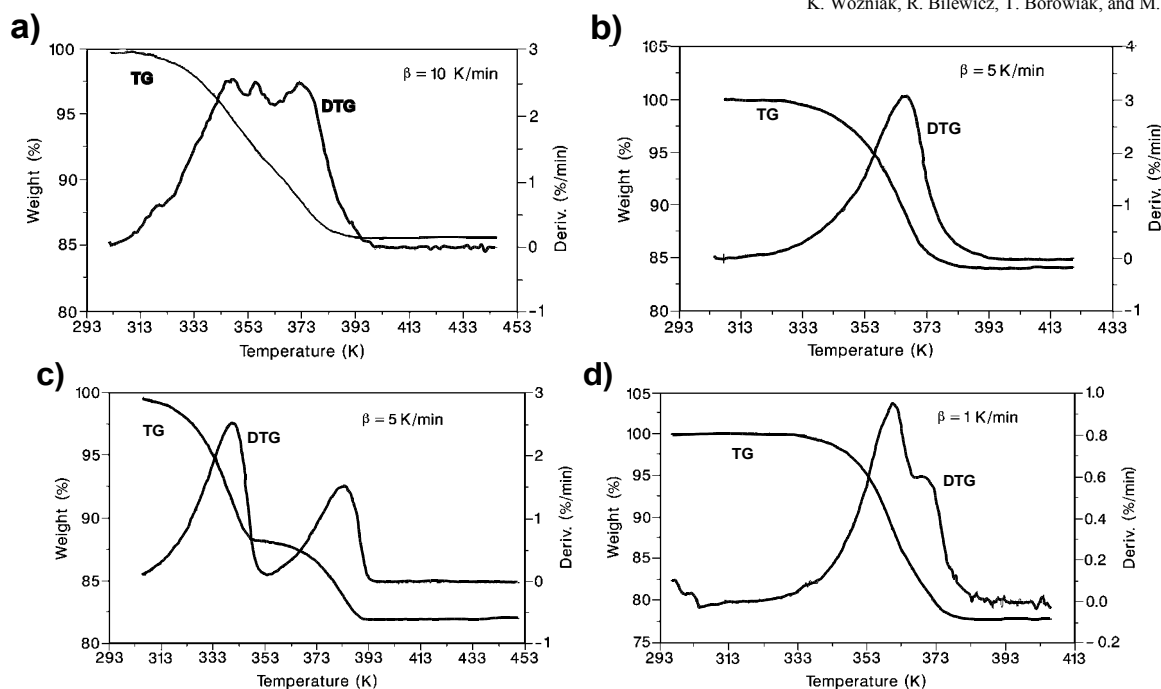


Fig. 2. TG and DTG curves of calix[4]resorcinarene (1) solvates with acetone a), methylethylketone b), dioxane c) and 1,2-dimethoxybenzene d).

The table 1 shows the thermal behaviour of selected calix[4]resorcinarene solvates. The stoichiometry of solvation was estimated on the basis of the mass loss, and ranged from 1:1 to 1:3. The character of TG and DTG curves suggested a complex pattern for desolvation. Most probably, apparent stages are strongly biased, therefore the calculated energies of activation may have a qualitative meaning.

Table 1. Thermal behaviour of calix[4]resorcinarene (1) complexes with some solvents.

Solvent	Bp. of solv., K	Mass loss, %	Midpoint, K*	1:solv., ratio	E ^a , J·mol ⁻¹
Methanol	337-338	2.6	340	1:1	106.4
Acetone	328-330	13.3	361.6	1:3	99.2
Methylethylketone	352-353	15.8	372.6	1:3	82.0
1,4-Dioxane	373-375	11.5 6.3**	356 401**	1:2 1:1	76.0 78.0
1,2-Dimethoxybenzene	478-450	21.3	386.2	1:2	130.0
Acetonitrile	352-354	4.0	360.9	1:1	156.0
Butyronitrile	388-390	7.4	343.4	1:1	-
<i>N,N</i> -Dimethylformamide	426-427	6.8 9.4**	356.5 407.7**	1:1 1:2	--
<i>N,N</i> -Dimethylacetamide	438-440	11.5 11.8**	368.7 434.5**	1:2 1:2	--
1-Methyl-2-pyrrolidinone	354/10mm	9.4	484.9	1:1	

* $\beta = 10 \text{ Kmin}^{-1}$

** Second stage of decomposition

b. X-Ray Diffraction Studies.

X-ray analysis is a convenient tool to complement the thermogravimetric studies and allow for a deeper insight into the pattern of solvation in the solid state. A range of solvates with *C*-tetra-*n*-undecylcalix[4]resorcinarene and *C*-tetra-*n*-phenylcalix[4]resorcinarene were studied by X-ray analysis [3]. The solvate grown from DMF showed three types of solvent molecules in a crystal lattice: single four DMF molecules present in the space between the polar surfaces of the calix[4]resorcinarene, and single molecules in a close proximity to the alkyl chains. Some of the DMF molecules were disordered. The nonpolar C₁₁ alkyl chains interpenetrated mutually via weak Van der Waals forces, forming dimers. The crystal lattice had the form of layers with polar receptor sites pointing toward each other. Solid-state ¹H NMR of the solvate was consistent with the X-ray examination [3].

The solvate of *C*-tetra-*n*-undecylcalix[4]resorcinarene with 1,4-dioxane was similar to that with DMF, however, the layers of receptor molecules were slightly shifted, holding two dioxane molecules between the receptor units. Two other molecules are located in the nonpolar region of the lattice [4]. The guest molecules are held by weak Van der Waals forces. Two different environments for dioxane molecules confirm the TG pattern of dioxane complex, where two distinct temperatures for release of solvent were observed [2].

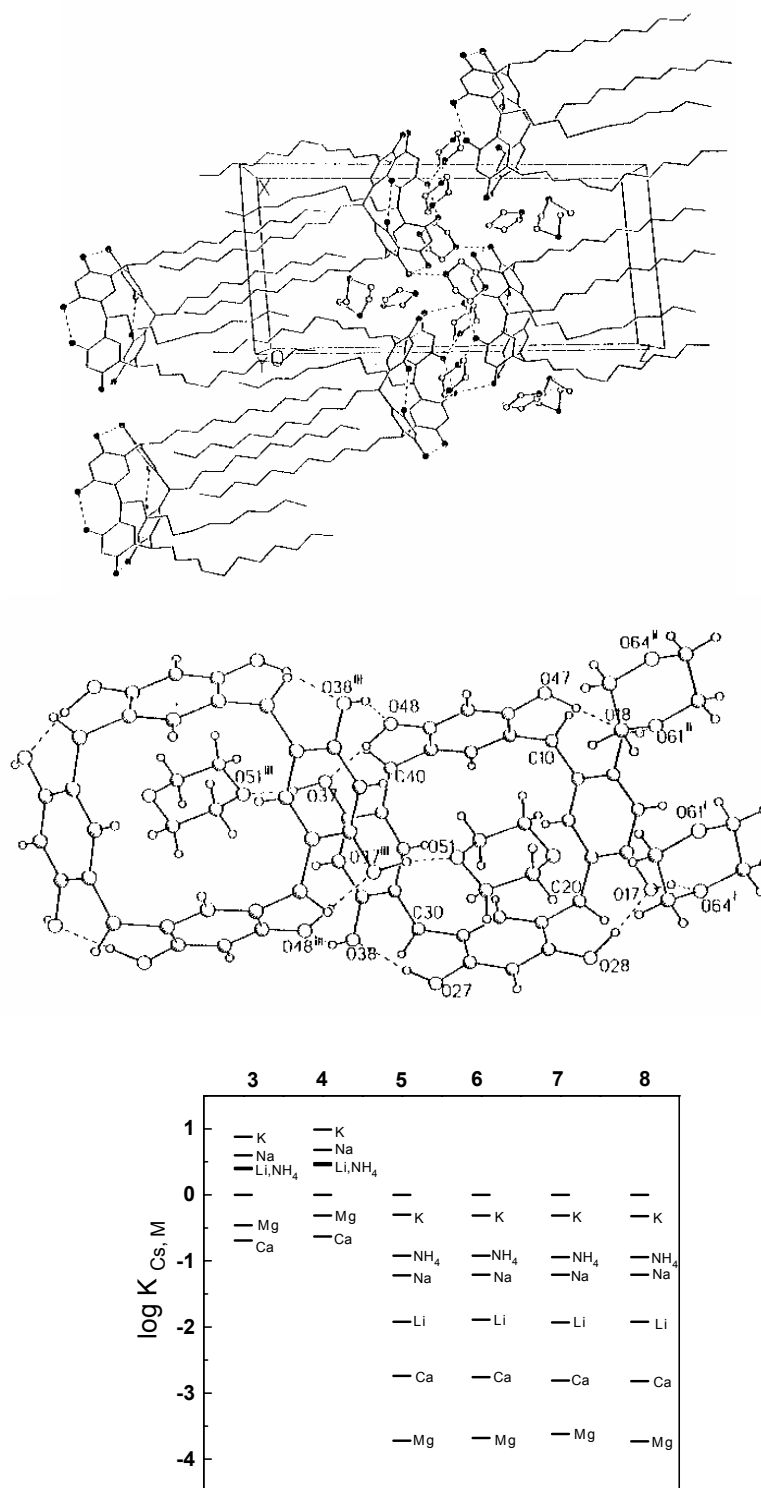


Fig. 4. Selectivity coefficients ($\log K_{Cs,m}$) of PVC membranes containing calix[4]resorcinarene derivatives. SSM method: 0.01M, pH = 4.5.

Fig. 3. Crystal structure arrangement of the C-undecylcalix[4]resorcinarene (1) solvate with dioxane molecules.

II. Electrochemistry.

Ionophoric activity of calixarenes can be followed conveniently by electrochemical methods, in particular, by modified PVC membrane potentiometric method [5]. We have prepared a number of Mannich-type ligands (Figure 2) that have been immobilised in the PVC membrane mounted further in the body of Philips IS 561 electrode.

The selectivity coefficients for inorganic cations are shown in Figure 4.

In case of oxazine-type receptors **5-8** the best selectivity was found for caesium cation, which can be interpreted as π -cation interaction with aromatic units, which is well-known phenomenon for caesium complexation by calixarenes. In the oxazine receptors the shallow cavity of the calix is extended by the aromatic walls of the substituents, thus the complexation of a large caesium ion is preferred over all smaller inorganic cations. In case of **3** and **4** no selectivity was found for caesium. The response times of PVC membranes in the presence of variable concentrations of Cs^+ and pH dependence for **5** and **6** are shown in Figure 5.

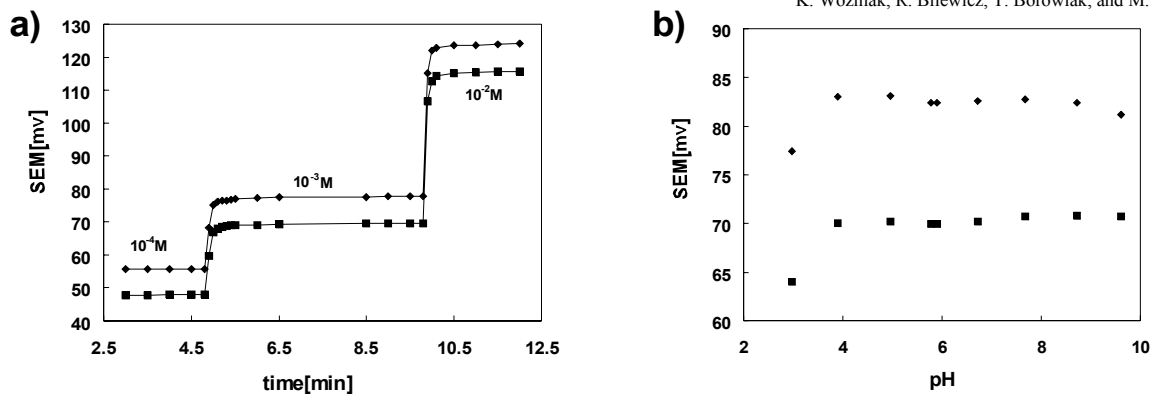


Fig. 5. a) Response times of PVC-membranes based on calix[4]resorcinarene **5** (◆) and **6** (■). Samples 10^{-4} , 10^{-3} , 10^{-2} M of CsNO_3 .
b) pH dependencies of Cs^+ - responses of PCV-membranes. Samples 0.01 M CsNO_3 .

The response time was short and SEM was stable in time in the pH range of 4-9. It seems therefore that these ligands may serve as receptors for PVC membrane Cs -selective electrodes.

III. Transport and Extraction.

a. Inorganic/Organic Ions.

Lipophilicity of the calix[4]resorcinarenes is attractive from the point of view of their applications in transport phenomena across the liquid and supported membranes involving organic and inorganic cations and neutral species. We have done a number of experiments involving unsubstituted calix[4]resorcinarenes and their Mannich-base derivatives [6]. We have used the ligands **1**, **3**, **4** for transport studies across the liquid membrane (isooctane and toluene) and extraction in the same solvents, using inorganic (Li , Na , K , Rb , Cs) and organic picrates (A: $\text{HO}(\text{CH}_2)_3\text{NH}_3^+$, B: $\text{CH}_3(\text{CH}_2)_3\text{NH}_3^+$, and C: phenylethylammonium cation).

The partition coefficients for extraction of inorganic and organic cations are shown in Figures 6a and 6b, respectively.

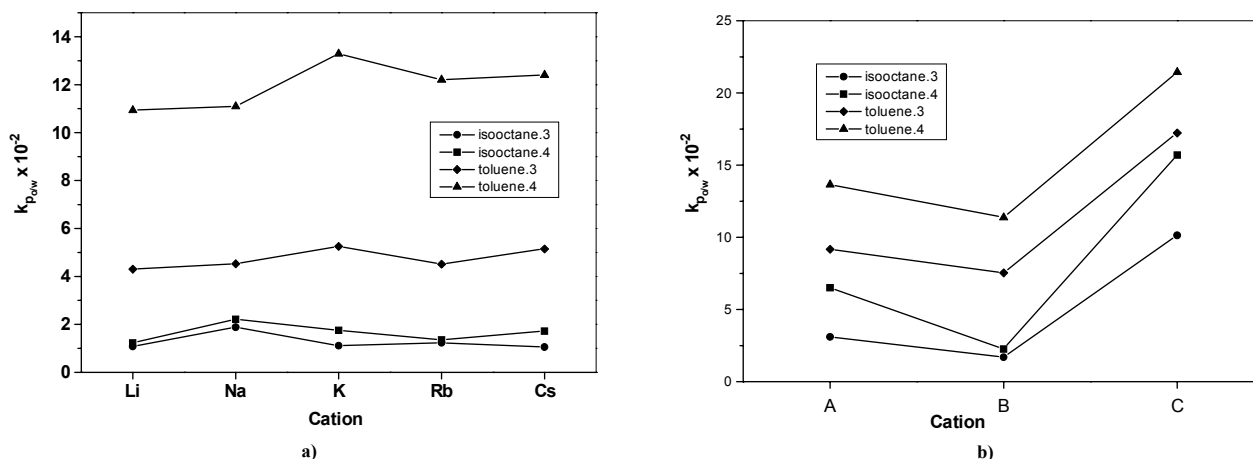


Fig. 6. Partition coefficients for inorganic a) and organic b) cations.

For inorganic and organic cations the partition coefficients between water and isooctane were lower than those in case of toluene. The extractability order in toluene for inorganic cations was the following: $4 > 3 \gg 1$. For the primary ammonium picrates the highest partition coefficient was found for phenylethyl ammonium picrate in both toluene and isooctane, for carriers **3** and **4**, due probably to the highest lipophilicity of this cation.

Several bar plots illustrate the case of transport experiments across the liquid membranes, as shown in Figures 7a-d.

In case of receptor **4** the best transport in isooctane membrane was observed for caesium cation, whereas for the same ligand in toluene an outstanding selectivity for Li^+ was found. This shows, that the transport selectivity depends not only on the carrier used, but also on the solvent used as a liquid membrane, therefore the manipulation towards desired selectivity pattern is conceivable.

In case of organic cations, the transport efficiency going from more hydrophilic (A) to more lipophilic organic cations (C) is distinct in case of carrier **4** in both isooctane and toluene.

b. Neutral Molecules.

Extraction phenomena of the neutral molecules to organic phases containing the receptors is more difficult task, since their interpretation should take into account also a competing mechanism of extraction of neutral species to organic phase, and the partitioning of the carrier between water and organic phase. Among interesting and biologically relevant molecules we have selected pyrimidine and xanthine bases [8]. For comparative studies we have used two calixarenes **1** and **2**.

We have performed the mass balance for substrates in water and organic phases. These data indicated that either for pure chloroform and chloroform with receptors the mass balance for bases in both phases was obtained in a good agreement.

Since the studied substrates are partly extracted from water to chloroform without the presence of the calixarenes, differential extractability allows to estimate which of the substrates is more strongly bound by the receptor.

Taking into account $\% \Delta E$ we can say that complexing ability of calix[4]resorcinarene decreases in the following order: cytosine $>$ uracil $>$ thymine. The same pattern we observed in our HPLC experiments while comparing the separation factors for pyrimidine bases on column with RP-18 phase coated with receptor **1** (water as eluent) [7]. In both cases we observed that cytosine is the most strongly bound by the receptor **1**. Among xanthine derivatives, dyphylline is the most strongly complexed by the same receptor. The calix[4]resorcinarene is stronger complexing agent in chloroform, for all investigating compounds, than the pyrogallol derivative Figure

8a,b. It can be rationalised in terms of self-aggregation of the calixarenes. Aoyama demonstrated that calix[4]resorcinarenes form associates in chloroform [9]. In nonprotic and nonetheral solvents self-aggregation of calix[4]resorcinarene is remarkable, due to strong hydrogen interactions between hydroxyl groups placed in the "edge" of the calix. The calixarene incorporating pyrogallol possesses twelve hydroxyl groups, thus its own self-association may be considered even stronger when compared to calix[4]resorcinarene. Therefore, its complexing abilities are inhibited by the self-association phenomena. Based on the results it is clear that the xanthine derivatives are much better complexed by two receptors **1** and **2** (particularly by **1**) than pyrimidine derivatives. It is also interesting that cytosine and dyphylline, both most strongly complexed by calix[4]resorcinarene, display a weak interaction with pyrogallol derivative. While analysing the extraction data one should keep in mind that the final effect is the result of many intermolecular interactions, such as solvation, association, hydrogen bonding and electrostatic interactions.

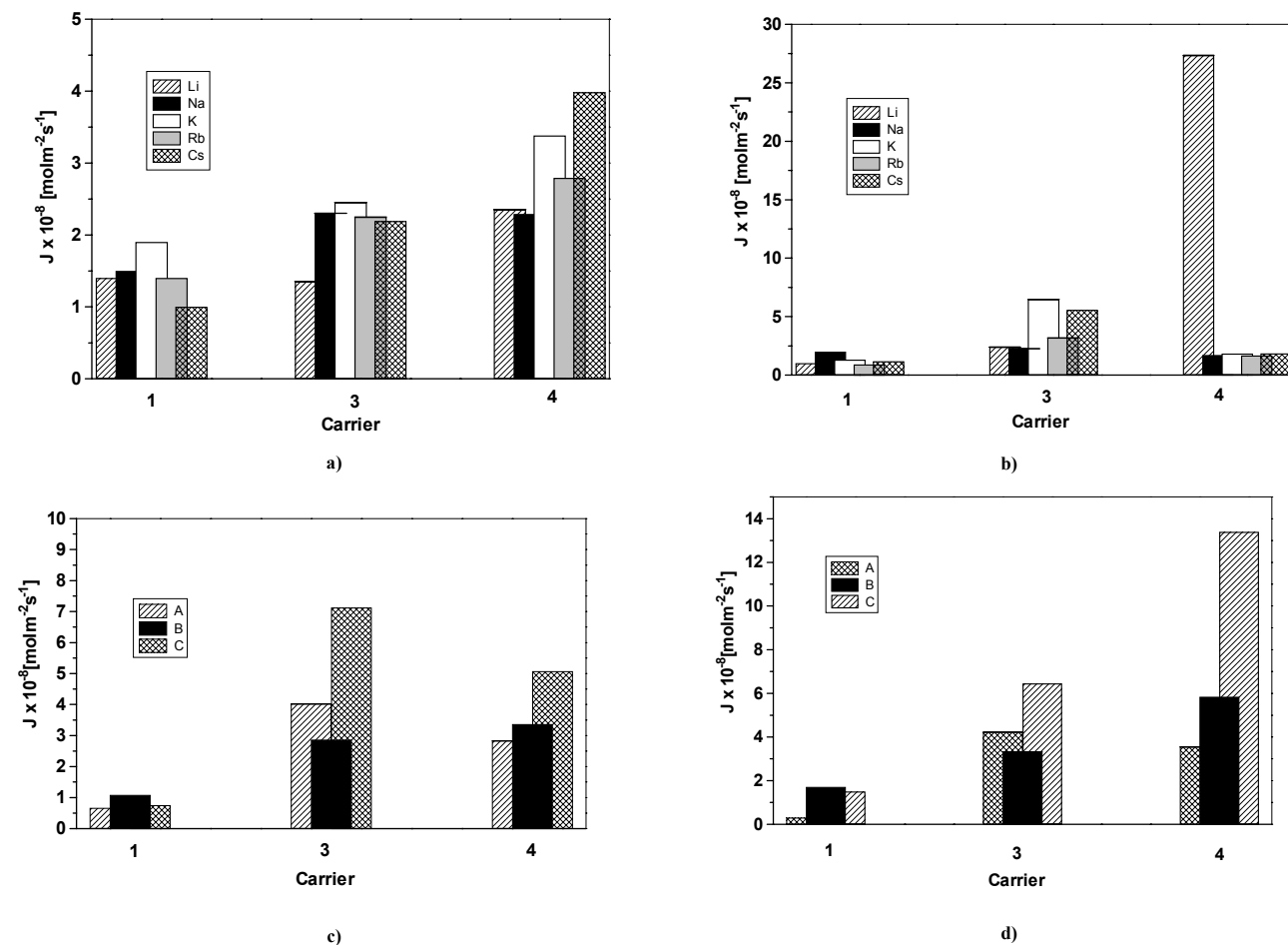


Fig. 7. Transport of alkali picrates through a) isoctane and b) toluene membrane and primary ammonium picrates through c) isoctane and d) toluene membrane.

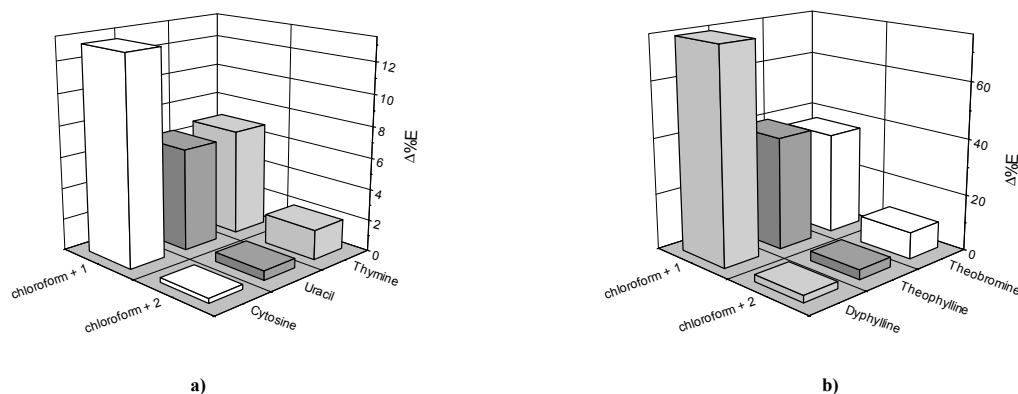


Fig. 8. Differential extractability for pyrimidine a) and xanthine b) bases in single extraction to chloroform.

Equimolar solutions of pyrimidine and xanthine bases were subjected to extraction experiments with the solvents: toluene, chloroform and diethyl sebacate. These solvents interact with calixarenes differently, thus the recognition pattern for compounds investigated was expected to be different at various conditions. Blank tests for an extraction to pure solvents indicated remarkable differences between the bases. We made a mass balance for all extractions.

Among pyrimidine bases, thymine and uracil were extracted by pure chloroform and diethyl sebacate relatively easily, which may be interpreted in this way that cytosine possessing amino function was more hydrophilic; stronger tendency to remain in water might be expected. Thymine was better extracted than uracil, due to its little higher lipophilicity than uracil. The xanthine bases were extracted

into pure solvents more easily than pyrimidine bases. Dyphylline, as most hydrophilic among them, was extracted far less effectively by pure solvents than remaining two bases.

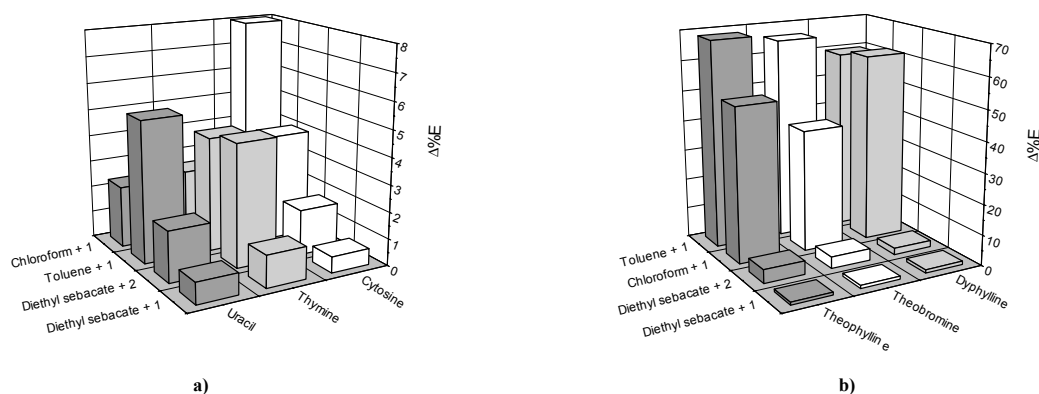


Fig. 9. Differential extractability for pyrimidine a) and xanthine b) bases in competitive extraction.

Among pyrimidine bases cytosine was most efficiently extracted to chloroform phase containing calix[4]resorcinarene. This can be rationalised in this way, that cytosine, possessing a primary amino function, may form an adduct with calix[4]resorcinarene. The formation of adducts between calixarenes and aliphatic or aromatic amines has been reported [10]. The extraction power for **1** was the lowest in diethyl sebacate, which can form competitive hydrogen bonds with hydroxyl groups of the calixarene, therefore the extraction ability of the receptor is diminished. For the uracil there is no clear extraction pattern. This base was also well extracted to diethyl sebacate. The presence of **1** enhanced the extractability slightly; a bit better is the receptor **2** possessing twelve hydroxyl groups and their cooperative interaction helps to bind the uracil more strongly than in the former case. The most efficient extraction of uracil occurred in toluene containing **1**. Thymine was almost equally well extracted into chloroform and to the diethyl sebacate. This base is more lipophilic than uracil and cytosine, therefore these extraction features were expected. Thymine was extracted most efficiently to chloroform containing **1**. The comparison of the receptors **1** and **2** indicated that for the pyrimidine bases, more efficient was **2** in diethyl sebacate. Why there is no comparison of extraction abilities of **2** in toluene and chloroform? As we have demonstrated in the case of single extraction experiments to chloroform containing **2**, the extraction power in this case was very low, and we assigned it to self-aggregation of **2** in less polar, non-oxygen solvents. Thus the extraction abilities of **2** is suggested to be studied in oxygen-containing solvents that break hydrogen bonds allowing for better penetration of the receptor site by guest molecules.

The competitive extraction experiments for the xanthine bases indicated that in case of theophylline and theobromine the best extraction results were obtained in toluene with **1**, whereas for dyphylline almost equal extraction results were observed in toluene and chloroform. Weak extraction capabilities for either **1** and **2** were observed in diethyl sebacate. For all xanthine bases the receptor **2** was more efficient than **1** in diethyl sebacate, as in former case.

An interesting point is to compare the partition coefficients in single and competitive extraction experiments. The results are shown in plots in the Figure 10.

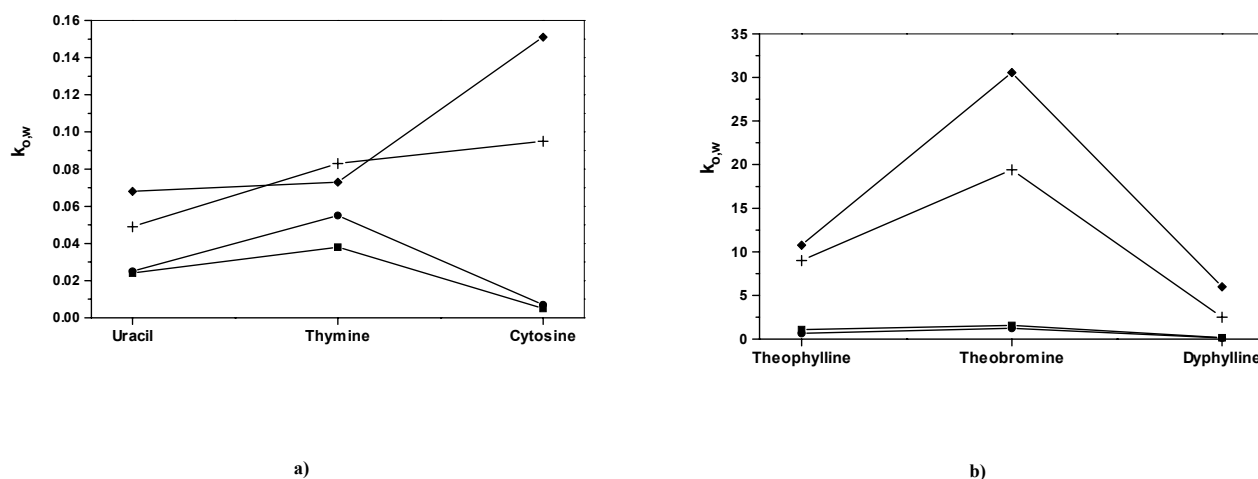


Fig. 10. a) Partition coefficients of pyrimidine bases for extractions : single (■) to chloroform, competitive (●) to chloroform, single (◆) to chloroform with **1** and competitive (+) to chloroform with **1**. b) Partition coefficients of xanthine bases for single and competitive extractions (symbols as above).

The experiments were run in chloroform. In a single extraction experiment in chloroform better extraction of thymine over cytosine and uracil was observed. While an equimolar mixture of them was subjected for extraction, the same concentrations of extracted uracil and cytosine were observed as in the case of competitive run, while thymine was significantly better extracted. The interpretation of this observation is not easy. Pyrimidine bases are known to form complementary hydrogen bond networks and self-assembly, therefore unexpected synergistic effects are conceivable, although it would require more sophisticated physicochemical method to prove the collective behaviour of pyrimidine bases in water solution. While the calix[4]resorcinarene **1** is present in chloroform phase, the single extraction experiment indicated clearly preferential extraction of cytosine, as expected, followed by thymine and almost equally uracil. In the competitive extraction experiment the pattern was not so clear; for thymine partition coefficient rose, while for uracil dropped in comparison with single extraction experiment; still the cytosine was extracted better but partition coefficient dropped much more than that for uracil. This indicated a fragile equilibrium between the processes of solvation of the pyrimidine bases in water, their self-assembly, hydrophobic/hydrophilic properties and their interactions with the receptor molecule in organic phase.

A similar comparison of the xanthine bases indicated that their single and competitive extraction to pure chloroform was not as distinct as in the case of pyrimidine bases, although extractability of pure components in single extractions indicated better partition coefficients than in competitive run. The single and competitive extractions to chloroform containing **1** indicated the same recognition pattern, but in the case of competitive experiment, the extraction coefficients were lower than in the case of single extraction experiments. This again proved a complicated equilibrium between the substrates themselves, the receptor, interactions in organic and water phase.

IV. HPLC Coatings and Molecular Recognition.

Lipophilic C₁₁ calix[4]resorcinarene possesses all-*cis* configuration of long alkyl chains and this feature allows this receptor to be embedded on the surface of RP-18 reversed HPLC stationary phase *via* hydrophobic interactions to form surface modification with new recognition properties. We have done such modification by passing the solution of C-tetraundecylcalix[4]resorcinarene in acetonitrile through the analytical HPLC column filled with RP-18 phase [11]. Initially we observed the resolution of isomeric methyl-, chloro-, and nitrophenols, whose retention times displayed different pattern from that on non-modified RP-18 bed, indicating the interactions with calix[4]resorcinarene on the surface of the bed. Then we were interested in separation of pyrimidine bases in the same manner [8, 12].

The calix[4]resorcinarenes proved to form coatings quite easily on the RP-18 solid supports. The kinetics of deposition of calix[4]resorcinarenes on RP-18 phase was verified by absorbance measurements of the eluent passed by.

A typical kinetic curve at the generation of modified RP-18 phase illustrates Figure 11:

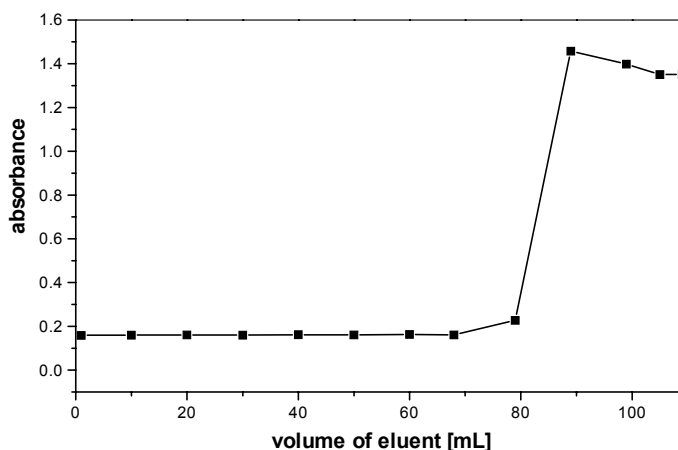


Fig. 11. Kinetics of generation of the calix[4]resorcinarene 1 modified stationary phase.

In this work we have studied the influence of the modification of the RP-18 phase on partition and selectivity coefficients of pyrimidine bases in various eluents.

The Table 2 collects the data for the chromatographic separations of three bases on nonmodified (column 1) and coated column (column 2).

Table 2. Separation and selectivity factors for pyrimidine bases.

Column	Analyte	Eluent A Eluent B				Eluent C Eluent D			
		k	α	k	α	k	α	k	α
1	cytosine	3.25		3.50		5.25		6.00	
	uracil	3.25	1.00	6.25	1.79	6.00	1.14	6.00	1.00
	thymine	4.42	1.36	16.25	2.60	16.00	2.67	14.75	2.46
2	cytosine	4.75	1.06	7.00		10.25	1.14	27.75	1.82
	uracil	3.50		8.50	1.21	9.00		8.50	
	thymine	4.50	1.29	15.00	1.76	14.75	1.44	15.25	1.79

The Figure 12 presents chromatograms of cytosine, uracil and thymine for both columns using different solvents.

The experimental data showed that no separation of the pyrimidine bases was achieved on both columns with the eluent A (20% methanol in water v/v). In acidic condition (eluent B, water pH 2), when cytosine exists in its protonated form, good separation was noted on both columns. In the case of eluents C (water, pH 4) and D (water) much better results were achieved on the modified RP-18 phase. It is clear that the water as the eluent had the strongest impact on the retention time for the cytosine, and this is not surprising, since cytosine is remarkably more basic than other two remaining pyrimidine bases, and it has been observed already that calixarenes had a tendency to form defined molecular complexes with aliphatic amines, of acid-base type [10]. So the eluent consists of proper amounts of water and methanol can effect separation of three bases on modified column in shorter time than in pure water.

We noted that the use of the eluent composed of 18% of methanol in water (eluent E) was the best among investigated eluents, because of the shortest time of analysis and satisfactory separations. The separation data are collected in the Table 3, whereas the chromatogram is shown in the Figure 13.

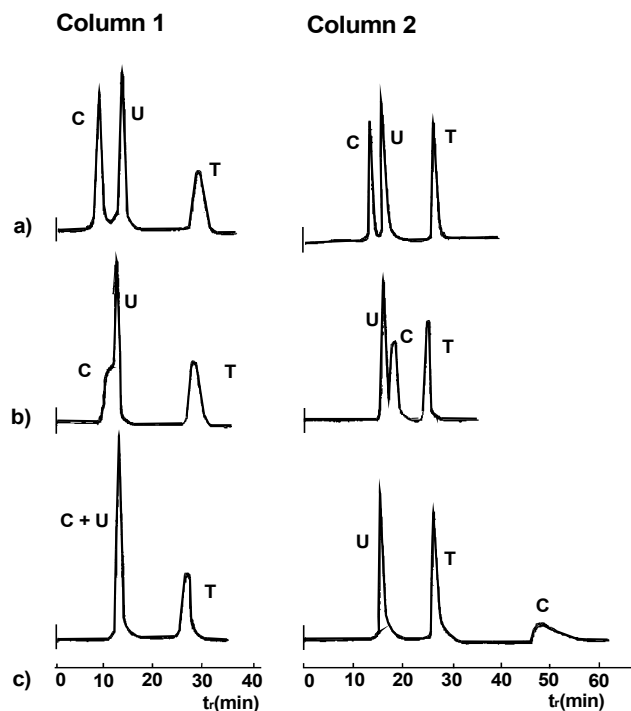


Fig. 12. Separation of cytosine (C), thymine (T) and uracil (U) on nonmodified and coated columns: a) eluent B, b) eluent C, c) eluent D.

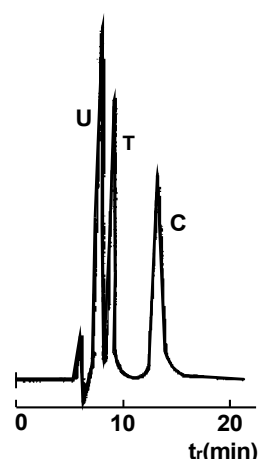


Fig. 13.

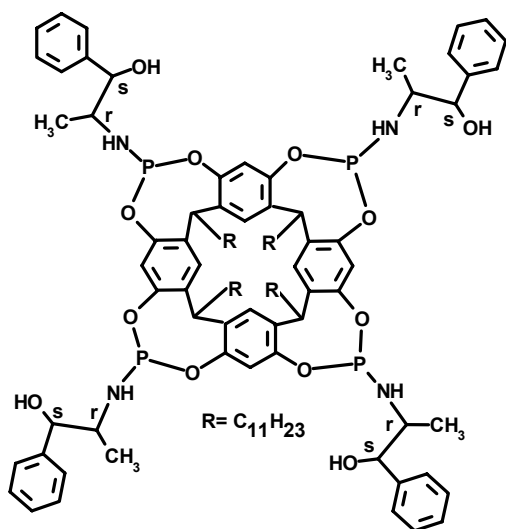


Fig. 14. Phosphorous calix[4]resorcinarene 11.

could adopt suitable conformation upon complexation and protonation during the recognition process. In order to avoid uncertainty related to conformational changes we have prepared phosphorous-containing cavitands in which oxygen atoms were linked by P atom bearing chiral substituent. The cavitant was conformationally rigid enough, although still susceptible for protonation [14]. The structure of the receptor 11 is shown in figure 14.

Pure phosphorous-containing calix[4]resorcinarene was studied in Langmuir films in the function of pH of the subphase. The receptor was protonated at different pH which was evident from increasing surface potential while passing from higher to lower pH values of the subphase. At the same time no significant changes of the surface area have been observed as a result of rigidity and preorganisation of this particular receptor.

Figures 15 and 16 illustrate the representative examples of Langmuir isotherms in the function of pH of the subphase for valine and tryptophan, respectively.

In this study the receptor system is conformationally frozen by the virtue of resorcinol oxygens linked by phosphorous atoms bearing discriminating chiral amino function. Protonation of this ligand should have an impact on the magnitude and the sign of enantiomeric recognition of amino acids. Thus we have run a number of experiments with *D*-, and *L*-tryptophan and *D*-, and *L*-valine in water subphase at various pH. It turned out that enantioselection of valine enantiomers by the host 11 was very pH-sensitive. The numerical data for A_0 , A_c , Π_c , and SP are collected in Table 4.

This is a gain when compared to our former work [13], where the pH-dependence of the surface area was evident with more flexible calix[4]resorcinarene of Mannich-type. Even at low pH the differences were remarkable. As it is evident from the Langmuir isotherms, the most significant enantioselection occurs at low pH of the subphase for both valine and tryptophan. Therefore, the changes in pH of the subphase containing guest enantiomeric molecules had a profound effect on the sign and the magnitude of enantioselection. The literature values of $pK_a = 2.83$, $pI = 5.66$ were for Valine, and $pI = 5.66$ were for tryptophan.

Table 3. Retention characteristics for pyrimidine bases in eluent E.

Column	Analyte	k	α
2	cytosine	7.00	1.56
	uracil	3.50	
	thymine	4.50	1.28

V. Molecular Recognition in Langmuir Films.

Lipophilic molecular receptors forming Langmuir films are capable of recognising the species dissolved in the subphase. We have done a number of experiments with chiral Mannich-type calix[4]resorcinarenes [13] that proved to form uniform Langmuir films and Langmuir technique turned out to be a useful tool to follow chiral molecular recognition phenomena. The interaction of the Langmuir film with the substrate in subphase manifests by profound changes of the surface pressure and area, shape of the Langmuir isotherm and surface potential. Our initial works involved the receptors 3, 9, and 10, in which the side arms and the receptor itself could have remarkable flexibility. Thus the recognition results were difficult to interpret, since the receptors

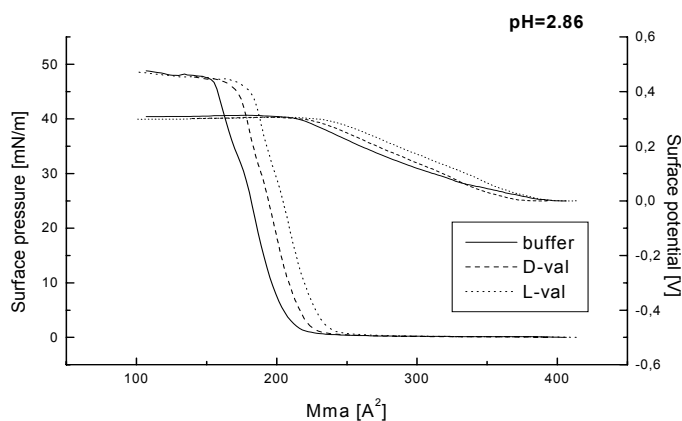


Fig. 15. Selected Langmuir isotherms and surface potentials for the receptor 11 on aqueous subphase containing *D*- or *L*-valine.

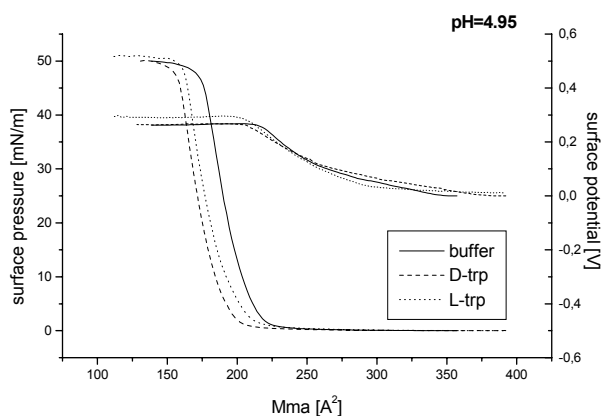


Fig. 16. Selected Langmuir isotherms and surface potentials for the receptor 11 on aqueous subphase containing *D*- or *L*-tryptophan.

The bar plots for A_0 , A_c , Π_c , and SP for the receptor 1 are shown in Figure 17. This behaviour of the receptor on subphase at different pH indicated the relative insensitivity of the A_0 , A_c , Π_c , values, due to the rigidity of the calixarene system, whereas the SP value was different, due to increasing dipole moment of the gradually protonated receptor. Table 5. collects the numerical data for tryptophan recognition. Again, in this case a remarkable influence of pH on the sign and the magnitude of enantioselection was observed.

For all cases the surface area of the receptor at different pH of the subphase remained the same within the experimental error, while the surface potential increased gradually while passing from higher to lower pH values. This observation is consistent with the fact, that protonation of the receptor has no observable influence on conformational changes of this preorganised system, while the dipole moment of the protonated forms rises in lower pH, thus the surface potential is expected to rise. Although we were able to suppress the pH-dependent conformational changes of the receptor due to its preorganisation, still the sign and the magnitude of enantiomeric discrimination depended distinctly on the protonation degree of the receptor molecule. Therefore, it will be worth of studying in the future the calix[4]resorcinarene receptors preorganised and insensitive for pH changes. This can be envisaged by an introduction of carboxamide, or sulfonamide enantioselecting groups.

VI. Charge-transfer Complexes with Organic Acceptors.

Calixarenes are the rich-electron receptors. Thus it was conceivable that might interact with electron acceptor organic molecules, such as tetracyanoethylene (TCNE), tetracyanoquinodimethane (TCNQ), chloranil, etc., to form charge-transfer complexes. we have done a series of experiments with calix[4]resorcinarenes that proved the formation of CT complexes with organic acceptors [15].

The calixarenes 1, 3, 4 promoted the hydrolysis of the TCNQ, while mixed in 1:1 ratio. The hydrolysis product was not observed, when the Ligand/Acceptor ratio was 1:4, whereas in case of calixarene *O*-octamethylated (1-OMe) a similar hydrolysis was not observed. It was interesting that for octamethyl ether of the initial calix[4]resorcinarene 1 the formation of the CT complex was possible to observe at much higher concentrations than in case of all other calixarenes. The formation of the hydrolysis product: α, α -dicyano-*p*-toluenenitrile (DCTC) was confirmed by IR after separation of this product by column chromatography on silica.

Table 4. Characteristics of isotherms for 11 at different pH and valine in subphase.

Compound	pH=2.86		pH=3.90		pH=4.77		pH=6.22		pH=6.74	
	A_0 [Å ²]	SP [V]	A_0 [Å ²]	SP [V]	A_0 [Å ²]	SP [V]	A_0 [Å ²]	SP [V]	A_0 [Å ²]	SP [V]
buffer	208 ± 5	0.307 ± 0.008	196 ± 3	0.310 ± 0.010	201 ± 6	0.270 ± 0.008	207 ± 7	0.230 ± 0.030	204 ± 3	0.250 ± 0.025
<i>d</i> -VAL	217 ± 5	0.306 ± 0.010	222 ± 6	0.300 ± 0.005	216 ± 4	0.278 ± 0.005	221 ± 4	0.253 ± 0.020	221 ± 2	0.265 ± 0.015
<i>l</i> -VAL	227 ± 3	0.333 ± 0.010	205 ± 4	0.303 ± 0.005	220 ± 5	0.282 ± 0.006	216 ± 3	0.250 ± 0.025	199 ± 3	0.276 ± 0.015

Compound	pH=2.86		pH=3.90		pH=4.77		pH=6.22		pH=6.74	
	A_c	Π_c	A_c	Π_c	A_c	Π_c	A_c	Π_c	A_c	Π_c
	[A ²]	[mN/m]	[A ²]	[mN/m]	[A ²]	[mN/m]	[A ²]	[mN/m]	[A ²]	[mN/m]
buffer	155 ± 5	47 ± 2	154 ± 3	48 ± 3	156 ± 6	47 ± 2	175 ± 7	48 ± 3	155 ± 3	47 ± 3
<i>d</i> -VAL	168 ± 5	46 ± 3	185 ± 6	46 ± 2	172 ± 4	46 ± 2	182 ± 4	46 ± 3	178 ± 2	47 ± 3
<i>l</i> -VAL	184 ± 3	45 ± 3	168 ± 4	48 ± 2	171 ± 5	47 ± 2	177 ± 3	47 ± 2	156 ± 3	47 ± 3

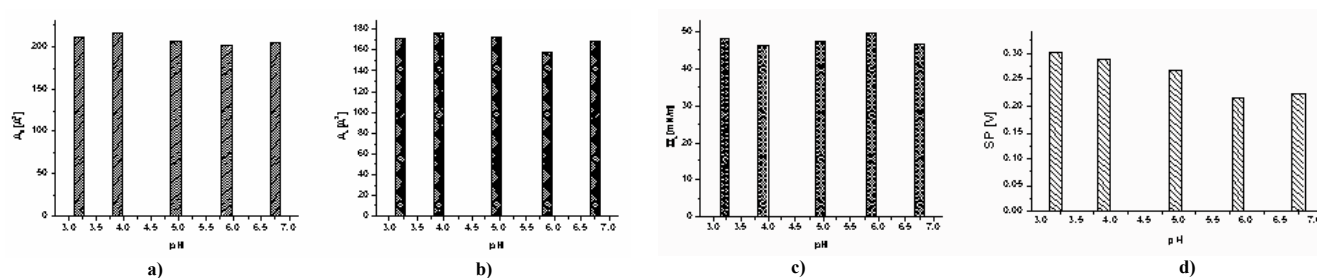


Fig. 17. Bar plots for A_0 , A_c , Π_0 , Π_c for the chiral calix[4]resorcinarene 11 on buffer subphases at different pH.

The Table 6 shows the UV-Vis/EPR confirmation of the CT complex formation. It turned out that TCNE appeared to be less efficient electron acceptor than TCNQ, since in two instances the formation of 1/TCNE, and 4/TCNE was not confirmed.

Concentration of ligands 1, 3, 4 was 5×10^{-3} M, ligand 1-OMe - 10^{-2} M, spectra were recorded after 10 min., ligand/acceptor ratio 1:1.

Table 5. Characteristics of isotherms for 11 at different pH and tryptophan in subphase.

Compound	pH=6.75		pH=5.87		pH=4.95		pH=3.80		pH=3.20	
	A_0	SP	A_0	SP	A_0	SP	A_0	SP	A_0	SP
	[A ²]	[V]	[A ²]	[V]	[A ²]	[V]	[A ²]	[V]	[A ²]	[V]
buffer	204 ± 3	0.250 ± 0.025	207 ± 7	0.230 ± 0.030	201 ± 6	0.270 ± 0.008	196 ± 3	0.301 ± 0.010	208 ± 5	0.307 ± 0.008
<i>d</i> -TRP	218 ± 3	0.240 ± 0.010	202 ± 5	0.220 ± 0.015	186 ± 3	0.266 ± 0.009	208 ± 5	0.275 ± 0.006	210 ± 5	0.335 ± 0.005
<i>l</i> -TRP	216 ± 4	0.246 ± 0.010	210 ± 5	0.230 ± 0.015	192 ± 5	0.290 ± 0.006	215 ± 3	0.300 ± 0.008	225 ± 6	0.300 ± 0.007

Compound	pH=6.75		pH=5.87		pH=4.95		pH=3.80		pH=3.20	
	A_c	Π_c	A_c	Π_c	A_c	Π_c	A_c	Π_c	A_c	Π_c
	[A ²]	[mN/m]	[A ²]	[mN/m]	[A ²]	[mN/m]	[A ²]	[mN/m]	[A ²]	[mN/m]
buffer	168 ± 3	47 ± 3	158 ± 7	49 ± 3	172 ± 6	47 ± 5	161 ± 3	49 ± 2	171 ± 5	48 ± 3
<i>d</i> -TRP	178 ± 3	66 ± 3	163 ± 5	65 ± 6	153 ± 5	48 ± 3	169 ± 5	49 ± 3	165 ± 5	48 ± 5
<i>l</i> -TRP	181 ± 4	47 ± 5	174 ± 4	47 ± 5	157 ± 5	49 ± 4	179 ± 3	48 ± 5	188 ± 5	47 ± 5

In most of cases there was a strong interaction between the receptor and donor. It seems that such systems may possess an interesting electronic properties in respect to charge migration, semiconductivity and hyperpolarizability. The UV-vis spectra of the calixarenes 1, 1-OMe, 3, 4 with TCNQ in methylene chloride at room temperature indicate the presence of the TCNQ anion-radical in the bands of 750-850 nm (figure 18). It should be noted that the complexation reaction between calixarenes and TCNQ was not immediate, as indicated by series of spectra recorded in certain time intervals.

UV-vis spectra were recorded for the combination of calixarenes 3 and 1-OMe with TCNE in methylene chloride at room temperature, as shown in Figure 19. There was a broad band with the maximum at 625 nm (3/TCNE) and 675 nm (1-OMe/TCNE) which can be assigned to CT complex.

Table 6. VIS and EPR studies of calix[4]resorcinarene complexes with TCNQ and TCNE.

Ligand	TCNQ		TCNE	
	vis	EPR	vis	EPR
1	+	+	-	-
3	+	+	+	+
4	+	+	-	-
1-OMe	+	*	+	*

Key: (+): confirmation of the CT complex formation
 (-): Absence of the CT complex
 (*): lack of data

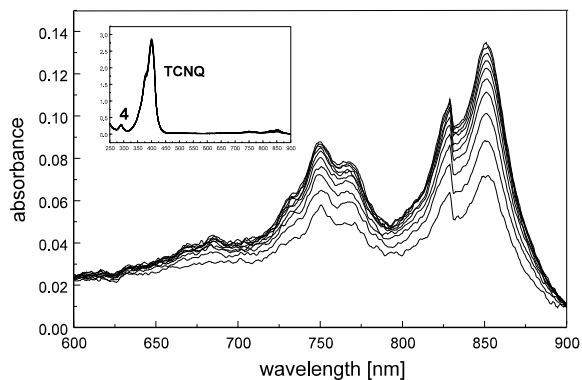


Fig. 18. UV-vis spectra of 4/TCNQ 1:4 recorded within 5h in methylene chloride.

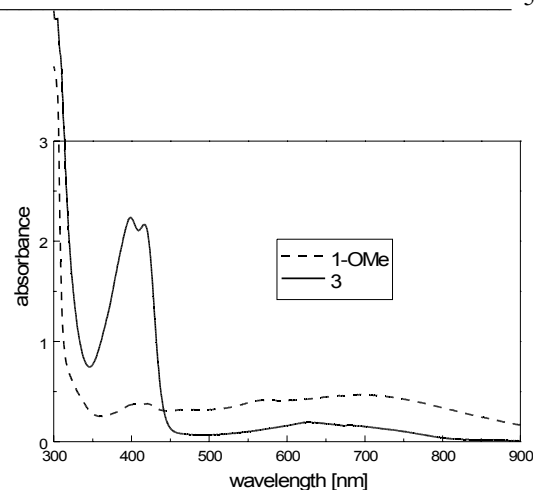


Fig. 19. 3/TCNE (10^{-3} M) and 1-OMe/TCNE (10^{-3} M) spectra recorded in methylene chloride after 10 min.

The titration experiments shows that several species were present in the solution of different stoichiometry for all calixarenes.

Conclusions

Calix[4]resorcinarenes have an enormous potential in their possible functionalisations, thus a number of receptors can be formed for specific purposes: molecular recognition, transport across the membranes, extraction, self-assembly, NLO materials, catalysis. new functional materials. Much depends on creative imagination and further works and ideas are almost unlimited.

Acknowledgement

This work was supported by National Committee for Scientific Research, grant # 3T09A 025 11.

References

- [1] A. Pochini, R. Ungaro in *Comprehensive Supramolecular Chemistry, (Vol. ed. Vugtle F.)*, Vol.2. Ch.4. P.103-142. **1996**; Aoyama Y. in *Comprehensive Supramolecular Chemistry, (Vol. ed. Vugtle F.)*, Vol.2. Ch.9. P.279-308. **1996**.
- D. Gutsche (1989) *Calixarenes, Monographs in Supramolecular Chemistry. Royal Soc.Chem., Cambridge*; J. Vicens, V. Böhmer, Calixarenes: a Versatile Class of Macrocyclic Compounds. *Kluwer Academic Publishers, Dordrecht, 1991*; J. Vicens, Z. Asfari, J. M. Harrowfield, Calixarenes 50th Anniversary: Commemorative Volume. *Kluwer Academic Publishers, Dordrecht, 1994*; C.D. Gutsche. Calixarenes Revisited, Monographs in Supramolecular Chemistry. *Royal Soc.Chem., Cambridge, 1998*.
- [2] O. Pietraszkiewicz, E. Uzig, W. Zielenkiewicz, M. Pietraszkiewicz. *J.Therm.Anal.* **1998**, 54. P.249-255.
- [3] M. Pietraszkiewicz, O. Pietraszkiewicz, W. Kołodziejki, K. Woźniak, N. Feeder, F. Benevelli, J. Klinowski. *J.Phys.Chem. B.* **2000**, 104. 1921.
- [4] T. Borowiak, M. Mącznyński, M. Pietraszkiewicz, O. Pietraszkiewicz. *J. Incl. Phenom. & Macrocycl. Chem.* **1999**, 35. 131.
- [5] Z. Brzózka, E. Liszewska, M. Pietraszkiewicz, R. Gašiorowski, Molecular Recognition & Inclusion, A.W. Coleman (Ed.). *Kluwer Academic Publishers, 1998*. P.263-266.
- [6] O. Pietraszkiewicz, M. Koźbiał, M. Pietraszkiewicz, Molecular Recognition & Inclusion, A.W. Coleman (Ed.). *Kluwer Academic Publishers, 1998*; O. Pietraszkiewicz, M. Koźbiał, M. Pietraszkiewicz. *Polish J. Chem.* **1998**, 72. P.886-892
- [7] O. Pietraszkiewicz, Z. Brzózka, M. Pietraszkiewicz. *Polish J. Chem.* **1999**, 73. P.2043-2052.
- [8] O. Pietraszkiewicz, M. Pietraszkiewicz. *J. Incl. Phenom. & Macrocycl. Chem.* **1999**, 35. P.261.
- [9] Y. Kikuchi, Y. Tanaka, S. Sutarto, K. Kobayasi, H. Toi and Y. Aoyama. *J.Am.Chem.Soc.* **1992**, 114. P.10302.
- [10] A.F. Danil de Namor, M.T. Garrido Pardo, D.A.P. Tanaka, F.J.S. Velarde, and J.D.C. Garcia: *J.Chem.Soc. Faraday Trans.* **1993**, 89. P.2727.
- [11] M. Pietraszkiewicz, O. Pietraszkiewicz, M. Koźbiał. *Polish J.Chem.* **1998**, 72. P.1963.
- [12] O. Pietraszkiewicz, M. Pietraszkiewicz. *Polish J.Chem.* **1998**, 72. P.2418.
- [13] M. Pietraszkiewicz, P. Prus, W. Fabianowski Molecular Recognition & Inclusion, A.W. Coleman (Ed.). *Kluwer Academic Publishers, 1998*. 263; M. Pietraszkiewicz, P. Prus, W. Fabianowski. *Polish J.Chem.* **1998**, 72. 1068; P. Prus, M. Pietraszkiewicz, R. Bilewicz. *Supramol. Chem.* 10. 17 (1998); M. Pietraszkiewicz, P. Prus, R. Bilewicz. *Polish J.Chem.* **1999**, 73. 1845.
- [14] M. Pietraszkiewicz, P. Prus, R. Bilewicz. *Polish J.Chem.* **1999**, 73. 2035.
- [15] O. Pietraszkiewicz, M. Koźbiał, M. Pietraszkiewicz. *Adv.Mater.Opt.Electron.* **1998**, 8. 277.