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# Investigation of complexation of thorium by humic acid using chemically immobilized humic acid on silica gel

By Gy. Szabó<sup>1,\*</sup>, J. Guzzi<sup>1</sup>, P. Reiller<sup>2</sup>, H. Geckeis<sup>3</sup> and R. A. Bulman<sup>4</sup>

<sup>1</sup> “Frédéric Joliot-Curie” National Research Institute for Radiobiology and Radiohygiene, PO Box 101, 1775 Budapest, Hungary

<sup>2</sup> Commissariat à l’Énergie Atomique, CE Saclay, Nuclear Energy Division/DPC/SERC, Laboratoire de Spéciation des Radionucléides et des Molécules, 91191 Gif-sue-Yvette Cedex, France

<sup>3</sup> Institut für Nukleare Entsorgung, Forschungszentrum Karlsruhe, Postfach 3640, 76021 Karlsruhe, Germany

<sup>4</sup> Radiation Protection Division (formerly National Radiological Protection Board), Health Protection Agency, Chilton, Didcot, OX11 0RQ, UK

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*Humic acid / Thorium /  
Conditional interaction constant ( $\beta$ )*

**Summary.** To model the influence of humic substances on the migration of tetravalent actinides (Pu, Np, U) in and around nuclear waste repositories we have immobilized humic acid on silica gel and investigated its complexation of Th(IV). It is anticipated that this material might serve as a geochemical model of the humate-coated minerals that are likely to be present in the vicinity of the repositories. The binding of Th(IV) by the immobilized humic acid was examined at pH 4, 5 and 6 in 0.1 mol L<sup>-1</sup> NaClO<sub>4</sub> by the batch method. Th(IV)-humate conditional interaction constants have been evaluated from data obtained from these experiments by using non-linear regression of binding isotherms.

## Introduction

The determination of the speciation of radionuclides in natural waters is important for the safety assessment of radioactive waste disposal in geological formation. As pointed out in the literature [1, 2], formation of complexes with humic substances might play an important role in the migration behaviour of radionuclides. This supposition has been confirmed by many *in vitro* studies as well as by environment-based investigations, which have primarily studied the potential of humic substances to influence the migration of transuranic radionuclides. As expected, both sets of literature are extensive. Reports by Choppin and his co-workers [3, 4], Moulin and Ouzounian [5] Moulin and Moulin [6] and Zhang *et al.* [7] give accounts of the relevant literature for both research topics.

The chemistry of interaction of actinides with humic substances needs to be understood so that humate-mediated migration of actinides in the environment can be predicted. The complexation behaviour of mono- [Np(V)], di- [U(VI)] or trivalent [Am(III), Cm(III)] actinides with humic acid is well documented in the literature [8–13]. However, satisfactory data on tetravalent actinides are scarce due to experimental difficulties, namely, the low solubility of their

oxide-hydroxide [14, 15] and their high affinity for vessel walls [16]. In order to study the interaction between humic acid, especially when adsorbed on to the surface of minerals, and as dissolved tetravalent actinides, it is advantageous to reduce the number of uncertain experimental parameters. This can be achieved by using chemical analogues (eg Th(IV)) of transuranic tetravalent actinides [17, 18]. As humic acid becomes a gelatinous precipitate on acidification of strongly alkaline solutions of humic acid, Bulman and Szabó and their co-workers simplified the reaction procedures for evaluating reactions between cations of the transuranic elements and humic acid by using a composite (SiO<sub>2</sub>-HA) formed by the chemical immobilization of humic acid on silica gel [19, 20]. This material was also used to study the interaction of other pollutants with humic acid [21, 22]. Subsequently, other groups [23–26] also prepared composite materials of humates and silica gel by using similar chemical reactions.

In this paper, we seek to advance the understanding of the modeling of the complexation of tetravalent actinides by humic substances by investigating the reactions of Th<sup>4+</sup>, a chemical analogue of Pu<sup>4+</sup>, with SiO<sub>2</sub>-HA.

## Experimental

### Materials and methods

Silica gel (Polygoprep Si-NO<sub>2</sub>-300, 20 µm, BET surface area 100 m<sup>2</sup> g<sup>-1</sup>) was obtained from Macherey-Nagel. Humic acid, sodium nitrite and thorium(IV) nitrate pentahydrate were purchased from Aldrich Chemical Co. Ltd. Humic acid was purified by the method of Kim *et al.* [27]. The composite material SiO<sub>2</sub>-HA was prepared by using the previously described procedure [21, 22]. The specific surface area of the prepared solid phase was determined by Brunauer-Emmett-Teller (BET) method as given in Table 1. C, H and N analyses of SiO<sub>2</sub>-HA were conducted on an automatic CHNS-O (EA1108, Fisons Instruments) analyzer. The IR spectra (Fig. 1) of SiO<sub>2</sub>-HA was recorded using a NICOLET 5PC FT-IR Spectrometer. The KBr pellet technique was applied. Th(IV) concentrations were determined by ICP-MS (HP-4500, Hewlett-Packard, USA). The

\* Author for correspondence (E-mail: szabogy@hp.osski.hu).

**Table 1.** Characteristics of SiO<sub>2</sub>-HA.

	SiO <sub>2</sub> -HA
Substrate content (mg g <sup>-1</sup> )	19.9 ± 1.2
Proton exchange capacity (μeq g <sup>-1</sup> solid matter)	67.3
BET surface area <sup>a</sup> (m <sup>2</sup> g <sup>-1</sup> )	74 ± 8

a: The surface area of the parent silica gel is 100 m<sup>2</sup> g<sup>-1</sup>.

proton exchange capacity (PEC) of the immobilized HA was determined by potentiometric titration (see Table 1) under an argon atmosphere using an automatic titration device (Mettler-Toledo, Germany). Stock solutions of Th(IV) were prepared by dissolving thorium nitrate pentahydrate in 0.1 mol L<sup>-1</sup> NaClO<sub>4</sub> at different pHs to obtain the concentrations 10<sup>-7</sup> mol L<sup>-1</sup>.

*Determination of maximal complexing capacity ( $B_{\max}$ ) and conditional interaction constants ( $\beta$ ) for Th<sub>total</sub> of the prepared solid phase*

The complexing capacity ( $B_{\max}$ ) of SiO<sub>2</sub>-HA was determined for Th(IV). Accurately weighed quantities of the gels, typically about 1 mg, were added to 10 ml of 0.1 mol L<sup>-1</sup> NaClO<sub>4</sub> solutions (pH 4–6) containing different concentrations (10<sup>-8</sup>–10<sup>-7</sup> mol L<sup>-1</sup>) of Th(IV). The resulting suspensions were shaken at room temperature for 48 h. Total concentrations of Th(IV) in aliquots, after centrifugation, were measured by ICP-MS. After sorption, the Th(IV) sorption on to vial walls was investigated. The vials were washed with distilled water and dried, then 10 ml of 2 mol L<sup>-1</sup> HClO<sub>4</sub> were added and shaken for 48 h. The Th(IV) concentration in the washing solutions was determined by ICP-MS. The amount of Th(IV) bound by SiO<sub>2</sub>-HA was calculated as a difference between the initial Th(IV) concentration (10<sup>-8</sup>–10<sup>-7</sup> mol L<sup>-1</sup>) and the sum of Th(IV) remaining in solution and Th(IV) sorbed onto vial walls.

*Calculation of maximal binding capacity ( $B_{\max}$ ) and conditional interaction constants ( $\beta$ ) of Th<sub>total</sub> from binding isotherm*

The conditional interaction constant ( $\beta$ ) is relative to the following equilibrium:



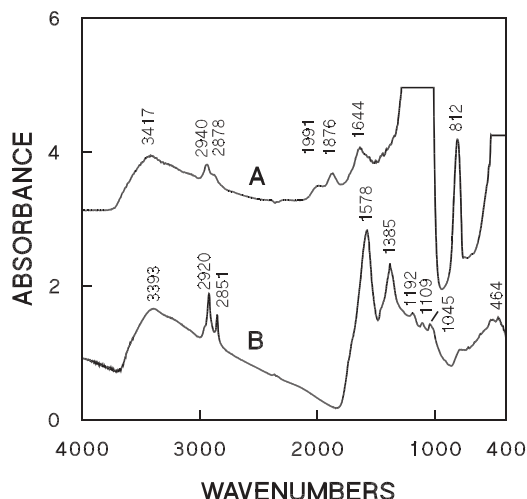
with

$$\beta = \frac{[MHA]}{[M^{z+}]_f [HA]_f} \quad (2)$$

where  $M^{z+}$ : the metal cation; HA: the total concentration of humic acid; [MHA]: the concentration of the metal humate complex;  $[M^{z+}]_f$ : the concentration of the free thorium ion;  $[HA]_f$ : the concentration of the free humic acid.

The assumption is made that the macromolecule is the central group and the complexation can be described in terms of a Langmuir-type adsorption. The free ligand concentration in Eq. (2) can be calculated by introducing  $B_{\max}$

$$[HA]_f = [B_{\max}] - [MHA] \quad (3)$$



**Fig. 1.** IR spectra of HA-SiO<sub>2</sub> (A) and the parent humic acid (B).

where  $B_{\max}$ : maximal complexing capacity of humic acid.

A combination of Eq. (2) and 3 gives the relationship that could be used for calculation of conditional interaction constants:

$$\beta = \frac{[MHA]}{[M^{z+}]_f ([B_{\max}] - [HA]_f)} \quad (4)$$

or after alteration

$$[MHA] = \frac{\beta [M^{z+}]_f B_{\max}}{1 + \beta [M^{z+}]_f} \quad (5)$$

After plotting the bound Th(IV) [MHA] versus  $(Th_{\text{total}})_{\text{free}} [M^{z+}]_f$  and using the binding isotherms, the maximal binding capacity and the conditional interaction constants ( $\beta$ ) of Th<sub>total</sub> could be determined.

*Calculation of conditional interaction constants ( $\beta$ ) of ThHA*

The reaction between Th<sup>4+</sup> and HA can be written



with

$$\beta = \frac{[ThHA]}{[Th^{4+}]_f [HA]_f} \quad (7)$$

Th<sup>4+</sup> is readily hydrolysed and it is not expected that only Th<sup>4+</sup> ion exist in solution at pH 4–6. From the Th(IV)<sub>total</sub> the  $[Th^{4+}]$  can be calculated by using the stability constants of the hydroxo complexes Th(OH)<sup>3+</sup>, Th(OH)<sub>2</sub><sup>2+</sup>, Th(OH)<sub>3</sub><sup>+</sup> and Th(OH)<sub>4</sub> [14, 18]:

$$[Th(IV)]_{\text{total}} = [Th^{4+}] + [Th(OH)^{3+}] + [Th(OH)_2^{2+}] + [Th(OH)_3^+] + [Th(OH)_4] \quad (8)$$

$$[Th(IV)]_{\text{total}} = [Th^{4+}] \alpha_{Th} \quad (9)$$

where  $\alpha$  is the species (Ringböm) coefficient [28] related to hydrolysis:

$$\alpha = 1 + \sum_i \frac{* \beta_i}{[H^+]^i}$$

If we measure the total Th(IV) concentration in the liquid phase and calculate the  $\text{Th}^{4+}$  concentration using Eq. (9), it becomes possible to calculate the conditional interaction constants ( $\log \beta$ ) of ThHA using the following equation:

$$\log \beta_{\text{total}} + \log \alpha_{\text{Th}} = \log \beta_{\text{ThHA}} \quad (10)$$

## Results and discussion

The characteristics of the prepared silica gel are shown in Table 1. From C, H, and N analyses of  $\text{SiO}_2$ -HA it has been established that the gels have average humic substances contents of  $19.9 \text{ mg g}^{-1}$  solid matter. The surface area of the silica gel was reduced from  $100 \text{ m}^2 \text{ g}^{-1}$  to  $74 \text{ m}^2 \text{ g}^{-1}$  for  $\text{SiO}_2$ -HA. The potentiometric properties of  $\text{SiO}_2$ -HA are shown in Table 1. From a total of seven determinations an average value for the PEC of  $3.38 \pm 0.14 \text{ meq g}^{-1}$  was obtained for the bound humic acid (assuming a content of  $19.9 \text{ mg HA g}^{-1}$  composite). From a comparison with the purified Aldrich HA [PEC value of  $5.43 \pm 0.16 \text{ meq g}^{-1}$  [29]], it can be concluded that a fraction of the carboxylate groups are lost during the synthesis procedure or become inaccessible for complexation.

The FT-IR spectra of the humic acid and its derivative ( $\text{SiO}_2$ -HA) are shown in Fig. 1. Both humic acid and  $\text{SiO}_2$ -HA show two peaks at  $2940\text{--}2850 \text{ cm}^{-1}$ , which are characteristic of the asymmetric and symmetric stretch vibrations of  $\text{CH}_2$  and  $\text{CH}_3$ . More specific are the peaks at  $1644 \text{ cm}^{-1}$  and  $1578 \text{ cm}^{-1}$  that can be assigned to the  $\text{C}=\text{O}$  stretch vibration of carboxyl groups. The FT-IR spectra confirm that immobilisation of humic acid was successful.

### Determination of maximal binding capacity ( $B_{\text{max}}$ ) of $\text{SiO}_2$ -HA and conditional interaction constants ( $\beta$ ) of $\text{Th}_{\text{total}}$ from binding isotherm

Typical binding isotherms (solid phase concentration vs. liquid phase concentration in equilibrium) of Th(IV) on  $\text{SiO}_2$ -HA at different pH values in  $0.1 \text{ mol L}^{-1} \text{ NaClO}_4$  are presented in Fig. 2. As seen from the Fig. 2, a high reproducibility in the isotherms is obtained. From these binding isotherms it has been possible to calculate, see Table 2, the complexing capacity  $B_{\text{max}}$  (expressed in  $\text{mol g}^{-1}$  solid

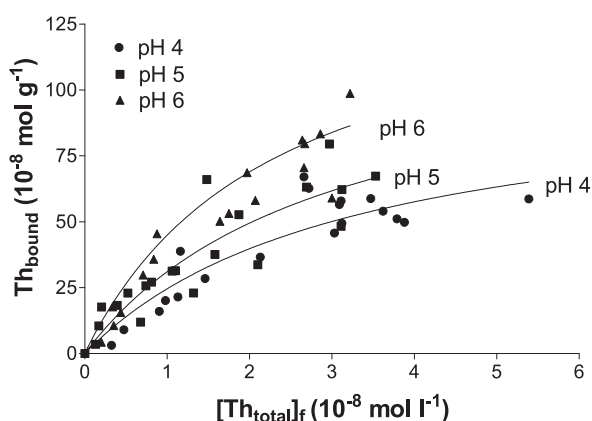


Fig. 2. Binding isotherm of  $\text{SiO}_2$ -HA for Th(IV) in  $0.1 \text{ mol L}^{-1} \text{ NaClO}_4$  at pHs 4, 5 and 6.

Table 2. Maximal binding capacity ( $B_{\text{max}}$ ) of  $\text{SiO}_2$ -HA and conditional interaction constants ( $\log \beta$ ) of  $\text{Th}_{\text{total}}$  with humic acid as a function of pH in  $0.1 \text{ mol L}^{-1} \text{ NaClO}_4$ .

	pH		
	4.09	5.07	6.19
$B_{\text{max}} (\mu\text{mol g}^{-1})$	$1.04 \pm 0.24$	$1.22 \pm 0.36$	$1.48 \pm 0.40$
$\log \beta (1 \text{ mol}^{-1})$	$7.49 \pm 0.33$	$7.53 \pm 0.31$	$7.64 \pm 0.27$

phase). As seen from Table 2, the complexing capacity of  $\text{SiO}_2$ -HA increases with increasing pH. This increase with pH is likely to have resulted from an increase in the number of ionized carboxylic binding sites. Others [30, 31] have reported a similar phenomenon. By using the nonlinear regression on the binding isotherms (Eq. (5)), the conditional interaction constants ( $\beta$ ) of  $\text{Th}_{\text{total}}$  with humic acid can be calculated (see Table 2). From Table 2, it is apparent that the conditional interaction constants appear insensitive to pH.

### Calculation of the conditional interaction constants of ThHA ( $\log \beta_{\text{ThHA}}$ )

The  $\log \beta$  values for  $\text{Th}_{\text{total}}$  with humic acid are presented in Table 2. From this table the conditional interaction constants of  $\text{Th}^{4+}$  with humic acid ( $\beta_{\text{ThHA}}$ ) can be calculated by using Eq. (10) and hydrolysis constants from Neck and Kim [14]. Fig. 3 shows the pH dependency of  $\log \beta_{\text{ThHA}}$ . The  $\log \beta_{\text{ThHA}}$  varies linearly between 8.87 at pH 4 to 13.51 at pH 6 (see Table 3). The regression line has the following equation:

$$\log \beta_{\text{ThHA}} = 2.12 \text{ pH} + 0.31 \text{ with } r^2 = 0.995.$$

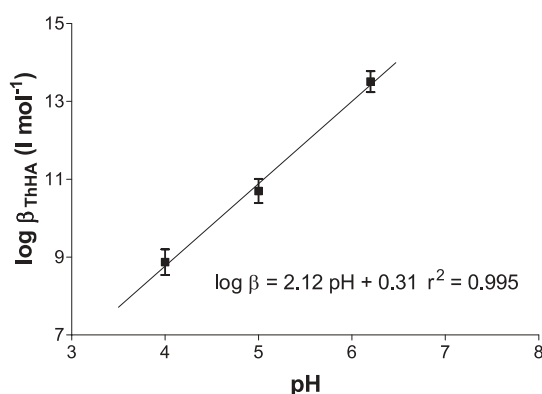
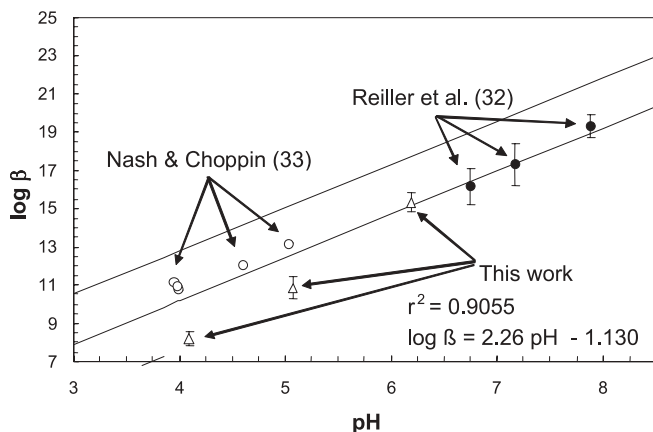


Fig. 3. Variation of the conditional interaction constants  $\log \beta_{\text{ThHA}}$  for  $\text{Th}^{4+}$  humic complexes as a function of pH.

Table 3. Conditional interaction constants ( $\log \beta$ ) of  $\text{Th}_{\text{total}}$ , side reaction coefficient ( $\log \alpha_{\text{Th}}$ ) and  $\log \beta_{\text{ThHA}}$ , as a function of pH in  $0.1 \text{ mol L}^{-1} \text{ NaClO}_4$ , according to the hydrolysis constants from Neck and Kim [14].

	pH		
	4.09	5.07	6.19
$\log \beta_{\text{total}} (\text{L mol}^{-1})$	$7.49 \pm 0.33$	$7.53 \pm 0.31$	$7.64 \pm 0.27$
$\log \alpha_{\text{Th}}$	1.38	3.17	5.87
$\log \beta_{\text{ThHA}} (\text{L mol}^{-1})$	$8.87 \pm 0.33$	$10.70 \pm 0.31$	$13.51 \pm 0.27$



**Fig. 4.** Comparison of the  $\log \beta_{\text{ThHA}}$  values obtained in this study with other constants sets Th(IV) hydrolysis data from [14]. White triangle this work.

It is interesting to compare our results with other values from the literature [32, 33], providing that the hydrolysis constants are the same. The  $\log \beta_{\text{ThHA}}$  values, calculated from the procedure of Baes and Mesmer [34], are reported in Fig. 4. It can be seen that there is a satisfactory agreement between the three independent data sets.

## Conclusions

The ready synthesis of  $\text{SiO}_2$ -HA has been established. The potential of such materials to complex cations such as  $\text{Th}^{4+}$  has been demonstrated. From an examination of the sorption isotherms of Th(IV) at different pHs it is apparent that conditional stability constants of  $\text{Th}^{4+}$  ( $\log \beta_{\text{ThHA}}$ ) can be easily calculated. This investigation indicates that humic acid materials such as  $\text{SiO}_2$ -HA are likely to be of value for modelling the role of humates in interacting with transuranic species, such as  $\text{Pu}^{4+}$ , in groundwater.

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## References

- Choppin, G. R., Allard, B.: Complexes of Actinides with Naturally Occurring Organic Compounds. In: *Handbook on the Physics and Chemistry of the Actinides*. (Freeman, A. J., Keller, C., eds.) Amsterdam (1986) Chapt. 11.
- Kim, J. I.: Chemical Behaviour of Transuranic Elements in Natural Aquatic System. In: *Handbook on the Physics and Chemistry of the Actinides* (Freeman, A. J., Keller, C., eds.) Amsterdam (1986) Chapt. 8.
- Choppin, G. R.: Humics and radionuclide migration. *Radiochim. Acta* **44/45**, 23 (1988).
- Choppin, G. R.: The role of natural organics in radionuclide migration in natural aquifer system. *Radiochim. Acta* **58/59**, 113 (1992)
- Moulin, V., Ouzounian G.: Role of colloids and humic substances in the transport of radioelements through the geosphere. *Appl. Geochem. Suppl.* **1**, 179 (1992).
- Moulin, V., Moulin, C.: Fate of actinides in the presence of humic substances under conditions relevant to nuclear waste disposal. *Appl. Geochem.* **10**, 573 (1992).
- Zhang, Y. J., Bryan, N. D., Livens, F. R., Jones, M. N.: Selectivity in the complexation of actinides by humic substances. *Environ. Pollut.* **96**, 361 (1997).
- Marquardt, C., Kim, J. I.: Complexation of Np(V) with humic acid: Intercomparison of results from different laboratories. *Radiochim. Acta* **80**, 129 (1998).
- Rao, L., Choppin, G. R.: Thermodynamic study of the complexation of neptunium(V) with humic acid. *Radiochim. Acta* **69**, 87 (1995).
- Giesy, J. P., Geiger, R. A., Kevern, N. R.:  $\text{UO}_2^{2+}$ -humate interactions in soft, acid, humate-rich waters. *J. Environ. Radioact.* **4**, 39 (1986)
- Czerwinski, K. R., Buckau, G., Scherbaum, F., Kim, J. I.: Complexation of the uranyl ion with aquatic humic acid. *Radiochim. Acta* **65**, 111 (1994).
- Maes, A., De Brabandere, J., Cremers, A.: Complexation of  $\text{Eu}^{3+}$  and  $\text{Am}^{3+}$  with humic substances. *Radiochim. Acta* **52/53**, 41 (1991).
- Kim, J. I., Rhee, D. S., Wimmer, H., Buckau, G., Klenze, R.: Complexation of trivalent actinide ions ( $\text{Am}^{3+}$ ,  $\text{Cm}^{3+}$ ) with humic acid: a comparison of different experimental methods. *Radiochim. Acta* **62**, 35 (1993)
- Neck, V., Kim, J. I.: Solubility and hydrolysis of tetravalent actinides. *Radiochim. Acta* **89**, 1 (2001).
- Fanghanel, Th., Neck, V.: Aquatic chemistry and solubility phenomena of actinide oxides/hydroxides. *Pure Appl. Chem.* **74**, 1895 (2002).
- Östholts, E.: Thorium sorption on amorphous silica. *Geochim. Cosmochim. Acta* **59**, 1249 (1995).
- Choppin, G. R.: Utility of oxidation state analogs in the study of plutonium behaviour. *Radiochim. Acta* **85**, 89 (1999).
- Reiller, P.: Prognosticating the humic complexation for redox sensitive actinides through analogy, using the charge neutralisation model. *Radiochim. Acta* **93**, 43 (2005).
- Bulman, R. A., Szabó, Gy.: Investigations of the interactions of transuranic radionuclides with humic and fulvic acids immobilized on silica gel. *Lect. Notes Earth Sci.* **33**, 329 (1991).
- Bulman, R. A., Szabó, Gy., Clayton, R. F., Clayton, C. R.: Investigation of the uptake of transuranic radionuclides by humic and fulvic acids chemically immobilized on silica gel and their competitive release by complexing agents. *Waste Management* **17**, 191 (1997).
- Szabó, Gy., Prosser S. L., Bulman, R. A.: Determination of the adsorption coefficient ( $K_{\text{OC}}$ ) of some aromatics for soil by RP-HPLC on two immobilized humic acid phases. *Chemosphere* **21**, 777 (1990).
- Szabó, Gy., Farkas, Gy., Bulman, R. A.: Evaluation of silica-humate and alumina-humate HPLC stationary phases for estimation of the adsorption coefficient,  $K_{\text{OC}}$ , of soil for some aromatics. *Chemosphere* **24**, 403 (1992).
- Koopal, L. K., Yang, Y., Minnaard, A. J., Theunissen, P. L. M., Van Riemsdijk, W. H.: Chemical immobilisation of humic acid on silica. *Colloid Surf. A: Physicochem. Eng. Aspects* **141**, 385 (1998).
- Yang, Y., Koopal, L. K.: Immobilisation of humic acids and binding of nitrophenol to immobilised humics. *Colloid Surf. A: Physicochem. Eng. Aspects* **151**, 201 (1999).
- Czerwinski, K. R., Cerefice, G. S., Buckau, G., Kim, J. I., Milcent, M. C., Barbot, C., Pieri, J.: Interaction of europium with humic acid covalently bound to silica beads. *Radiochim. Acta* **88**, 417 (2000).
- Barbot, C., Czerwinski, K. R., Buckau, G., Kim, J. I., Moulin, V., Vial, M., Pieri, J., Durand, J. P., Goudard, F.: Characterization of humic gel synthesized from an activated epoxy silica gel. *Radiochim. Acta* **90**, 211 (2002).
- Kim, J. I., Rhee, D., Buckau, G.: Complexation of Am(III) with humic acids of different origin. *Radiochim. Acta* **52/53**, 49 (1991).
- Ringböm, A.: *Complexation in Analytical Chemistry*. Interscience, New York (1963).
- Buckau, G.: Komplexierung von Americium(III) mit Huminstoffen in natürlichen Grundwässern. Thesis, FU Berlin (1991).
- Moulin, V., Tits, J., Moulin, C., Decambox, P., Mauchien, P., de Ruty, O.: Complexation behaviour of humic substances towards actinides and lanthanides studied by time-resolved laser-induced spectrofluorometry. *Radiochimica Acta* **58/59**, 121 (1992).
- Hummel, W.: Binding Model for Humic Substances. In: *Modelling in Aquatic Chemistry*. (Grenthe, I., Puigdomenech, I., eds.) NEA-OECD (1997).

32. Reiller, P., Moulin, V., Casanova, F., Dautel, C.: On the study of Th(IV)-humic acid interactions by competition sorption studies with silica and determination of global interaction constants. *Radiochim. Acta* **91**, 513 (2003).
33. Nash, K. L., Choppin, G. R.: Interaction of humic and fulvic acids with Th(IV). *J. Inorg. Nucl. Chem.* **42**, 1045 (1980).
34. Baes, C. F., Mesmer, R. E.: *The Hydrolysis of Cations*. Wiley Interscience Publication, New York (1976).