

Complex formation and lactonization reactions in aqueous solutions containing Ca²⁺ or Nd³⁺ ions and sugar-type ligands

Bence Kutus

Ph.D. Theses



Supervisors:

Prof. Pál Sipos

Prof. István Pálinkó

Doctoral School of Chemistry

Department of Inorganic and Analytical Chemistry

Faculty of Science and Informatics

University of Szeged

Szeged

2018

1. Introduction

Polyhydroxy carboxylic acids can be synthesized by the oxidation of carbohydrates. D-gluconic acid, being a member of this family, is used in general as an additive for food industry, while its sodium salt (NaGluc) is applied in chelation therapy, metallurgy as well as in paper industry.

NaGluc, applied as an additive for the formulation of cementitious materials, is likely to be present in the pore water of low- and intermediate-level radioactive waste repositories established in underground salt mines. Based on literature results, highly stable binary and ternary complexes are formed between Gluc^- , trivalent actinide ions (An^{3+}) as well as Ca^{2+} ions arising from Portland cement. The ligand therefore can facilitate the mobilization of radionuclides, originally deposited in the form of hydroxides of low solubilities. Hence, the complexation equilibria taking place between these species are pivotal to be quantitatively described from the point of view of environmental protection.

In our previous works, multinuclear complexes were found to be formed between Ca^{2+} and Gluc^- ions in strongly alkaline medium. For Nd^{3+} , being frequently used as a model for An^{3+} ions, the formation of mononuclear complexes was only detected to date. Moreover, the impact of the configuration of the ligand on various association processes is still not fully understood. The stereochemistry can affect both the stability and the structure of coordination compounds being important in fundamental research.

2. Aims of the work

During this research, we aimed at determining the composition, stability constant and the metal ion-binding sites of complexes forming between Nd^{3+} and Gluc^- ions in the pH range of 2–8. Furthermore, our goal was to assess how the incident multinuclear complexes would affect the equilibria occurring in radioactive waste repositories.

In order to reveal the role of configuration, the diastereomer of D-gluconate, L-gulonate (Gul^-) that is, was chosen as a model compound. For a comprehensive description, we studied the lactonization processes taking

place in acidic medium as well as the Ca(II) complexation reactions occurring in neutral and alkaline solutions. We compared our results with those reported in the literature for D-gluconate and D-heptagluconate (Hp_gl⁻). The effect of different functional groups for the stability was investigated *via* the complexes forming between Ca²⁺ ions and the derivatives of D-glucose.

3. Experimental

The protonation constant of Gul⁻ was determined by potentiometric titrations, polarimetric, ¹H and ¹³C spectroscopic measurements, while the γ - and δ -lactonization constants for gulonic acid were estimated with the aid of ¹³C NMR spectra. In order to validate the results, the lactonization experiments were carried out with gluconate as well, and the results were compared with literature data. The relative stability of gulonolactones was assessed *via* quantum chemical computations as well. The time dependence of lactonization was followed by ¹³C NMR spectroscopy and polarimetry.

Concerning Ca²⁺ ions and D-glucose or its derivatives (D-sorbitol, D-mannitol, D-gluconate, D-heptagluconate, D-glucuronate and D-glucarate), the complex formation equilibria taking place in neutral medium were studied by potentiometric titrations applying Ca²⁺ ionselective electrode (Ca-ISE).

In the presence of Ca²⁺ and Gul⁻ ions, the association and deprotonation processes occurring in neutral and alkaline media were followed potentiometrically employing Ca-ISE and hydrogen electrode. The conformational changes of the ligand upon complexation was studied by polarimetry, while the structure of the CaGul⁺ species was modelled by quantum chemical calculations. The possible coordination sites of Gul⁻, Gluc⁻ and Hp_gl⁻ were deduced on the basis of ¹H and ¹³C NMR spectra.

The complex formation processes between Nd³⁺ and Gluc⁻ ions were studied by means of potentiometry and spectrophotometry. The binding sites were assigned on the basis of ¹H NMR spectra, whilst the structure of the NdGlucH₂⁰ species was optimized by quantum chemical methods.

4. New scientific results

T1. Of the five- and six-membered cyclic esters of L-gulonic and D-gluconic acids, the L-gulonic acid γ -lactone (γ -HGul) was proven to be by far the most stable species.

The lactonization constant was estimated on the basis of the ^{13}C NMR peak areas belonging to the lactone or the acid form. Our calculations were validated by comparing the determined and the literature values for the gluconolactones. As a result, the lactonization constant of γ -HGul is higher nearly by one order of magnitude than that of the other three isomers (δ -HGul, γ -HGluc, δ -HGluc). According to the time dependence of the lactonization reactions, the formation of the δ -lactone is much faster; however, the hydrolysis of the γ -lactone is much slower yielding larger equilibrium constant.

T2. It has been demonstrated that gulonic acid is able to catalyze its own lactonization as well as the reverse reaction, the hydrolysis of the lactone.

Assuming solely the well-known proton-catalyzed esterification, hydrolysis does not result in satisfactory fitting between the measured and calculated optical rotations. The deviations can be markedly decreased by considering that the formation and hydrolysis of the predominant γ -lactone can also be catalyzed by L-gulonic acid as a source of protons. The respective rate coefficients are smaller by an order of magnitude than those of the traditional acid catalysis. This finding can be explained considering that H^+ more readily dissociates from H_3O^+ than from HGul.

T3. In addition to the known 1:1 calcium(II) complexes, species with 1:2 stoichiometry were found to be formed with aliphatic polyhydroxy carboxylates in neutral medium.

By means of the potentiometric method, the formation of 1:2 complexes can be detected for L-gulonate, D-gluconate as well as D-heptagluconate on applying high ligand to metal ratios. Additionally, our findings are confirmed by the literature data corresponding to Gluc^- . Furthermore, the fact that such

species cannot be observed for the cyclic D-glucuronate points to the key role of ligand flexibility.

T4. It has been established that the stability of the 1:1 calcium(II) complexes ranges in the order of D-glucose < D-mannitol < D-sorbitol < D-glucuronate < L-gulonate < D-heptagluconate \approx D-gluconate < D-gucarate.

This order reflects the role of (i) ligand flexibility (glucose < sorbitol and glucuronate < gluconate), (ii) spatial arrangement of the OH groups (mannitol < sorbitol), (iii) participation of the COO⁻ functional group (sorbitol < gluconate) and (iv) the number of COO⁻ moieties.

T5. Our results confirmed that the highly stable Ca₃Gul₂H₋₄⁰ species was readily formed in alkaline medium in agreement with previous findings found for Gluc⁻ and Hp_gl⁻. It was shown that the conformation of the complexed Gul⁻ markedly differed from that of the free anion inferring the deprotonation of the OH group(s).

In agreement with our previous results, the interpretation of the potentiometric titration curves requires the assumption of the trinuclear, neutral complex. It can be stated that the complexation reactions of polyhydroxy carboxylates are very similar in a given pH-range, while the processes taking place in neutral or alkaline solutions are very different. When the Ca²⁺/Gul⁻ system is concerned, the metal-promoted deprotonation of the ligand leads to significant change in the conformation, hence, the specific rotation of Gul⁻.

T6. It was found that for the complexes forming in alkaline medium, the different configurations result in different coordination sites.

For Gluc⁻, the C2-OH and C3-OH, while for Gul⁻ and Hp_gl⁻, the C2-OH and C4-OH functions (beyond COO⁻) are the most probable metal ion binding sites. Consequently, if the configuration of the C2-OH and C3-OH groups is *threo* (Gluc⁻), the C3-OH, if it is *erythro* (Gul⁻, Hp_gl⁻), the C4-OH group participates in the complexation. (The arrangement of the C3-OH and C4-OH functions is *treo* in each ligand.)

T7. Beside the already known mononuclear species, unexpected binuclear Nd(III) gluconate complexes were found to be formed on applying higher metal ion concentrations. By our calculations, however, these species do not affect the equilibria under the conditions prevailing in radioactive waste repositories.

Simultaneous fitting of the potentiometric and spectrophotometric data resulted in that the (previously unknown) $\text{Nd}_2\text{Gluc}_3\text{H}_{-2}^+$ and $\text{Nd}_2\text{Gluc}_4\text{H}_{-2}^0$ complexes were formed to a significant extent. Conversely, the solubility of $\text{Nd}(\text{OH})_3$ and the estimated concentration of gluconate being present in waste deposits ($< 0.01 \text{ M}$) indicates that these binuclear species do not have considerable impact on the equilibria occurring in pore waters. On the other hand, the mononuclear NdGlucH_{-2}^0 species becomes predominant upon increasing pH.

5. Practical applications

Although, our work was mostly of fundamental nature, we believe that the results presented here help to better understand and model the complicated equilibrium systems affecting the long-term stability of waste repositories. Moreover, our findings concerning the stability and structure of $\text{Ca}(\text{II})$ complexes forming in neutral and alkaline media may be useful for the characterization of certain industrial processes, when polyols, polyhydroxy carboxylates and/or other metal ions are applied.

6. Publications and conference participations

6.1. Full papers directly related to the Theses published in peer-reviewed journals

1. **B. Kutus**, Cs. Dudás, G. Peintler, I. Pálinkó, P. Sipos: Configuration-dependent complex formation between $\text{Ca}(\text{II})$ and sugar carboxylate ligands in alkaline medium: comparison of L-gulonate with D-gluconate and D-heptagluconate

Carbohydrate Research, 2018, 460, pp. 34–40.

impact factor (2016): 2.096

2. **B. Kutus**, N. Varga, G. Peintler, A. Lupan, Amr A. A. Attia, I. Pálinkó, P. Sipos: Formation of mono- and binuclear neodymium(III)-gluconate complexes in aqueous solutions in the pH range of 2–8

Dalton Transactions, 2017, 46, pp. 6049–6058.

impact factor (2016): 4.029

3. **B. Kutus**, D. Ozsvár, N. Varga, I. Pálinkó, P. Sipos: ML and ML₂ complex formation between Ca(II) and D-glucose derivatives in aqueous solutions

Dalton Transactions, 2017, 46, pp. 1065–1074.

impact factor (2016): 4.029

4. **B. Kutus**, Á. Buckó, G. Peintler, I. Pálinkó, P. Sipos: Calcium-complexation and acid-base properties of L-gulonate, a diastereomer of D-gluconate

Dalton Transactions, 2016, 45, pp. 18281–18291.

impact factor (2016): 4.029

6.2. Full papers directly related to the Theses published in conference proceedings

1. Á. Buckó, **B. Kutus**, G. Peintler, I. Pálinkó, P. Sipos: Az L-gulonátion protonálódásának és laktonizációjának vizsgálata (Studying the protonation and lactonization of the L-gulonate ion)

XXXVIII. Kémiai Előadói Napok, Program és előadás összefoglalók, ISBN 978–963–9970–64–9, 2015, pp. 179–184.

6.3. Full papers not directly related to the Theses published in peer-reviewed journals

1. Cs. Dudás, **B. Kutus**, É. Böszörményi, G. Peintler, Z. Kele, I. Pálinkó, P. Sipos: Comparison of the Ca²⁺ complexing properties of isosaccharinate and gluconate – is gluconate a reliable structural and functional model of isosaccharinate?

Dalton Transactions, 2017, 46, pp. 13888–13896.

impact factor (2016): 4.029

2. A. Gácsi, **B. Kutus**, Z. Csendes, T. Faragó, G. Peintler, I. Pálínkó, P. Sipos: Calcium L-tartrate complex formation in neutral and in hyperalkaline aqueous solutions

Dalton Transactions, 2016, 45, pp. 17296–17303.

impact factor (2016): 4.029

3. A. Gácsi, **B. Kutus**, Z. Kónya, Á. Kukovecz, I. Pálínkó, P. Sipos: Estimation of the solubility product hydrocalumite-hydroxide, a layered double hydroxide with the formula of $[\text{Ca}_2\text{Al}(\text{OH})_6]\text{OH}\cdot n\text{H}_2\text{O}$

Journal of Physics and Chemistry of Solids, 2016, 98, pp. 110–116.

impact factor (2016): 2.059

4. **B. Kutus**, A. Gácsi, A. Pallagi, I. Pálínkó, G. Peintler, P. Sipos: A comprehensive study on the dominant formation of the dissolved $\text{Ca}(\text{OH})_{2(\text{aq})}$ in strongly alkaline solutions saturated by Ca(II)

RSC Advances, 2016, 6, pp. 45231–45240.

impact factor (2016): 3.108

5. Gácsi A., **B. Kutus**, Á. Buckó, Z. Csendes, G. Peintler, I. Pálínkó, P. Sipos: Some aspects of the aqueous chemistry of the $\text{Na}^+/\text{Ca}^{2+}/\text{OH}^-/\text{Cit}^{3-}$ system: The structure of a new calcium citrate complex forming under hyperalkaline conditions

Journal of Molecular Structure, 2016, 1118, pp. 110–116.

impact factor (2016): 1.753

6. A. Pallagi, É. G. Bajnóczi, S. E. Canton, T. Bolin, G. Peintler, **B. Kutus**, Z. Kele, I. Pálínkó, P. Sipos: Multinuclear complex formation between Ca(II) and gluconate ions in hyperalkaline solutions

Environmental Science & Technology, 2014, 48, pp. 6604–6611.

impact factor (2014): 5.330

7. A. Pallagi, Z. Csendes, **B. Kutus**, E. Czeglédi, G. Peintler, P. Forgo, I. Pálínkó, P. Sipos: Multinuclear complex formation in aqueous solutions of Ca(II) and heptagluconate ions

Dalton Transactions, 2013, 42, pp. 8460–8467.

impact factor (2013): 4.097

8. Z. Csendes, J. T. Kiss, **B. Kutus**, P. Sipos, I. Pálínkó: Ni-S(upper)oxide-D(ismutase) inspired Ni(II)-amino acid complexes covalently grafted onto Merrifield's resin – synthesis, structure and catalytic activity

Materials Science Forum, 2013, 730–732, pp. 1012–1017.

impact factor (2013): 0

6.4. Other full papers not directly related to the Theses published in conference proceedings

1. Á. Buckó, **B. Kutus**, G. Peintler, I. Pálínkó, P. Sipos: Temperature dependence of proton dissociation and complexation processes in the Ca^{2+} /gluconate system under hyperalkaline conditions

XXVI International Conference on Coordination and Bioinorganic Chemistry, Vol. 13, Modern Trends in Coordination, Bioinorganic and Applied Inorganic Chemistry, ISBN 978–80–89597–65–9, 2017, pp. 27–36.

2. C. Dudás, **B. Kutus**, R. Béltéki, A. Gácsi, I. Pálínkó, P. Sipos: Acid-base properties and calcium complexation of α -ketoglutarate in strongly alkaline aqueous solutions

XXVI International Conference on Coordination and Bioinorganic Chemistry, Vol. 13, Modern Trends in Coordination, Bioinorganic and Applied Inorganic Chemistry, 2017, ISBN 978–80–89597–65–9. pp. 37–44.

3. É. Böszörményi, Cs. Dudás, **B. Kutus**, I. Pálínkó, P. Sipos: Az izoszacharinát- és a glükonát-ion sav-bázis és kalcium-kompleképző tulajdonságainak összehasonlítása (Comparison of the acid-base properties and the calcium complexing ability of the isosaccharinate and the the L-gulonate ions)

XXXIX. Kémiai Előadói Napok, Program és előadás összefoglalók, 2016, ISBN 978–963–9970–73–1, pp. 60–64.

4. Dudás Cs., **B. Kutus**, É. Böszörményi, P. Medvegy, O. Orbán, I. Pálínkó, P. Sipos: Kalcium- és nátrium-izoszacharinát előállítása és jellemzése (The synthesis and characterisation of calcium and sodium isosaccharinate)

XXXVIII. Kémiai Előadói Napok, Program és előadás összefoglalók, 2015, ISBN 978–963–9970–64–9, pp. 42–47.

5. **B. Kutus**, G. Peintler, A. Pallagi, I. Pálinkó, P. Sipos: Kalcium-cukorkarboxilát komplexek vizsgálata egyszerű fizikai-kémiai módszerekkel (Studying calcium(II) sugar carboxylate complexes by simple physico-chemical methods)

III. Eötvözet Konferencia, Az Eötvös József Collegium és az Eötvös Loránd Kollégium III. közös konferenciáján elhangzott előadások, ISBN 978-963-306-373-6, 2015, pp. 172-182.

6. **B. Kutus**, Gácsi A., A. Pallagi, I. Pálinkó, P. Sipos, G. Peintler: Comprehensive study on the dissolved $\text{Ca}(\text{OH})_2$ in strongly alkaline solutions

10th International Alumina Quality Workshop, Conference Proceedings, 2015, ISBN 978-0-9943162-0-2, pp. 285-289.

7. **B. Kutus**, A. Pallagi, G. Peintler, I. Pálinkó, P. Sipos: Kalcium-glükonát komplexek egyensúlyi jellemzése magas pH-jú oldatokban (Equilibrium characterisation Ca-gluconate complexes in high pH solutions)

XXXVI. Kémiai Előadói Napok, Program és előadás összefoglalók, ISBN 978-963-315-145-7, 2013, pp. 235-239.

8. **B. Kutus**, A. Pallagi, G. Peintler, I. Pálinkó, P. Sipos: Kalcium-heptaglukonát komplexek összetétele és egyensúlyai erősen lúgos oldatokban ((The composition and equilibria of calcium heptagluconate complexes in hyperalkaline solutions)

XXXV. Kémiai Előadói Napok, Program és előadás összefoglalók, 2012, ISBN 978-963-315-099-3, pp. 275-279.

6.5. Other conference participations

Co-author of 15 lectures presented in international conferences

Co-author of 16 lectures presented in Hungarian conferences

Co-author of 12 posters presented in international conferences

Full papers published in peer-reviewed journals:

Related to the Theses: 4

Total: 12

Cumulative impact factor:

Related to the Theses: 14.183

Total: 38.588