

Complex formation between calcium and hydroxy/oxocarboxylates in neutral and highly alkaline aqueous solutions

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PhD Theses



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1. Introduction

Under the highly alkaline conditions prevailing in low and intermediate level radioactive waste (L/ILW) repositories, the presence of small molecular metal chelators are considered to have significant impact on the mobilization of radionuclides. Being the main alkaline degradation product of cellulose, the ligand present in the largest quantity in these repositories is α -D-isosaccharinate (Isa^-), however, D-gluconate (Gluc^-) is frequently used as its structural and functional model (Fig. 1). Moreover, several minor species, *e.g.*, lactate (Lac^- , see Fig 1) may also be present in L/ILW repositories. In these systems, calcium is present in significantly higher quantities than actinides or lanthanides, hence it can influence the complexing ability of the ligands towards the radioactive metal ions either by forming complexes with them or by causing their precipitation in the form of sparingly soluble salts. Therefore, investigating the complexation of these ligands with calcium in highly alkaline medium is important with regard to environmental protection.

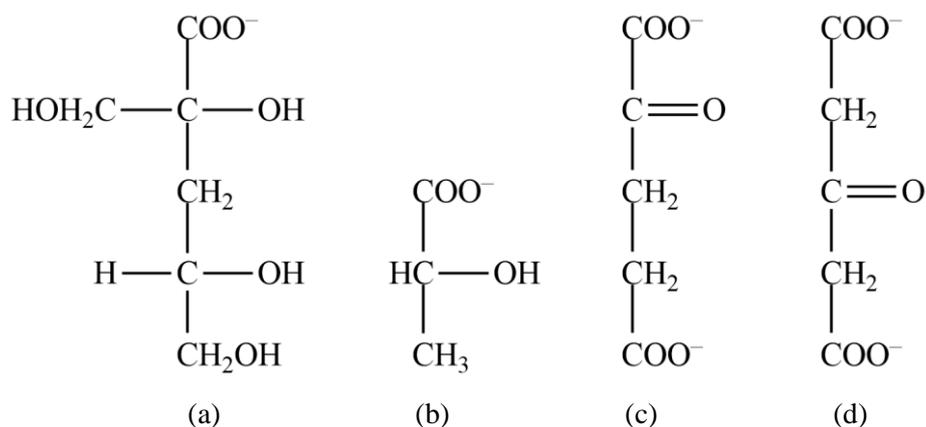


Figure 1. Structures of α -D-isosaccharinate (Isa^- , a), lactate (Lac^- , b), α -ketoglutarate ($\alpha\text{-Ket}^{2-}$, c) and β -ketoglutarate ($\beta\text{-Ket}^{2-}$, d).

In our previous works, we showed that calcium was able to induce the deprotonation of polyhydroxy carboxylates in alkaline medium forming high stability, sometimes multinuclear complexes involving the coordination of one (or more) alcoholate group(s). However, little is known about the effect of Ca^{2+} on the deprotonation of oxocarboxylates, where deprotonation occurs on a methylene group instead of a hydroxy moiety.

2. Aims of the work

In the present work, we aimed to investigate the composition, formation constant and structure of the species formed between Ca^{2+} and Isa^- both in neutral and highly alkaline media. We aimed at comparing the behaviour of Isa^- and Gluc^- in these systems to examine whether Gluc^- is a reliable model for Isa^- under the conditions of L/ILW repositories. Furthermore, we embarked on the determination of the single crystal structure of both calcium isosaccharinate and calcium gluconate. Additionally, our goal was to investigate the behaviour of Lac^- (which contains similar structural elements than Isa^- , moreover, may be present in L/ILW wastes) in the presence of Ca^{2+} in neutral and strongly alkaline solutions.

We also aimed to determine whether (under suitable conditions) Ca^{2+} was able to induce the deprotonation of oxocarboxylates. For this, our goal was to study the interactions between Ca^{2+} and α/β -ketoglutarate (α/β -Ket²⁻, see Fig 1) in order to identify the complexes forming in neutral and alkaline media.

3. Experimental

The complex formation between Ca^{2+} and Isa^- , Lac^- , α -Ket²⁻ or β -Ket²⁻ was studied in neutral medium by potentiometry using a calcium ion selective electrode (Ca-ISE). For Lac^- , ¹³C NMR and ESI-MS measurements were also performed. The structure of the CaIsa^+ and CaGluc^+ complexes were optimized by quantum chemical calculations.

The crystal structures of CaIsa_2 and $\text{CaGluc}_2 \cdot \text{H}_2\text{O}$ were determined by single crystal X-ray diffraction analyses.

In order to determine the alkaline deprotonation constants of Isa^- and Lac^- , ¹³C NMR experiments were conducted. The deprotonation constants of α -Ket²⁻ and β -Ket²⁻ were deduced on the basis of UV spectrophotometric measurements.

The complexation reaction taking place in highly alkaline medium between Ca^{2+} and Isa^- was studied by means of pH potentiometry (using a hydrogen electrode), ¹³C and ¹H NMR spectroscopies as well as ESI-MS measurements and quantum chemical optimizations. For Lac^- , solubility measurement were performed in strongly alkaline medium, the calcium content of the solutions was determined *via* ICP-OES. The calcium complexation of α -Ket²⁻ and β -Ket²⁻ was investigated in alkaline solutions by ¹H NMR spectroscopy and UV spectrophotometry.

4. New scientific results

T1. It was demonstrated that in alkaline medium both Isa^- , Lac^- , $\alpha\text{-Ket}^{2-}$ and $\beta\text{-Ket}^{2-}$ underwent deprotonation. The deprotonation constants of the ligands were determined by ^{13}C NMR spectroscopy or UV spectrophotometry.

For Isa^- and Lac^- , the deprotonation occurred on a hydroxy group, while for $\alpha\text{-Ket}^{2-}$ and $\beta\text{-Ket}^{2-}$, it occurred in a methylene group resulting in the formation of an enolate anion. All these ligands were found to be very weak acids, the $\text{p}K_a$ values ranging between 14.4 and 15.8.

T2. It was found that in highly alkaline medium, in the presence of Isa^- and Ca^{2+} , the CaIsaH_{-1}^0 complex was formed. Its structure was determined *via* molecular modelling calculations.

From H_2/Pt potentiometric measurements, the formation of the CaIsaH_{-1}^0 complex was observed. From quantum chemical calculations, four coordination isomers were found, in which Isa^- acted either as a bidentate or a tridentate ligand.

T3. Our results confirmed that the behaviour of Isa^- in alkaline medium in the presence of Ca^{2+} was significantly different from that of Gluc^- , therefore Gluc^- is not a reliable for modelling Isa^- in, *e.g.*, L/ILW repository type systems.

In the Gluc^- -containing solutions the formation of the $\text{Ca}_2\text{GlucH}_{-3}^0$ and $\text{Ca}_3\text{GlucH}_{-4}^0$ complexes were previously shown, moreover, these species were found to be the predominant ones. However, in the presence of Isa^- , such polynuclear species were not observed. It is suggested that the prerequisite for the formation of such polynuclear species is the possibility of the simultaneous participation of the two hydroxy groups closest to the carboxylate moiety in the metal ion binding. While this condition holds for Gluc^- , it does not hold for Isa^- . Therefore, the two ligands are not expected to behave identically in strongly alkaline medium in the presence of both calcium and actinides/lanthanides, *i.e.* under the conditions of the L/ILW repositories.

T4. The positions of the hydroxy hydrogen sites and the hydrogen bonding network of calcium isosaccharinate were determined by X-ray diffractometric measurements using a synchrotron source.

Although the single crystal structure of CaIsa_2 was determined previously in 1968, weak diffraction from the small specimen did not allow the location of the hydroxy hydrogen sites. The use of a synchrotron source in this work provided data of sufficient quality to determine the location of the electron density associated with the hydroxy hydrogen sites. An extensive hydrogen bonding network was found to be present in the structure of CaIsa_2 .

T5. Single crystal structure of $\text{CaGluc}_2 \cdot \text{H}_2\text{O}$ has been solved for the first time, after preparing single crystals by the hanging drop method.

Although gluconic acid is produced in a quantity of $\sim 100,000$ tonnes per year, moreover, calcium gluconate is commonly used, *e.g.*, as dietary calcium source, the single crystal structure of calcium gluconate has not been determined yet. In our work, from single crystal X-ray diffraction measurements we found that the structure of $\text{CaGluc}_2 \cdot \text{H}_2\text{O}$ was orthorhombic with non-centrosymmetric $\text{P}2_12_12_1$ symmetry. It was shown that adjacent metal centres were linked by μ -oxo bridges with the calcium ion being coordinated eightfold. This structure is significantly different from that of CaIsa_2 , in which adjacent metal centres are spanned by two Isa^- ligands.

T6. Based on solubility measurements, two novel species, CaLacH_{-1}^0 and CaLacH_{-2}^- were identified in strongly alkaline solutions in the presence of Lac^- and Ca^{2+} . It is assumed that in these species the deprotonation occurs on one (or two) of the water molecules coordinated to the Ca^{2+} ion.

Since in these strongly alkaline solutions (*i.e.*, up to 2.6 M NaOH) calcium is almost exclusively present as CaOH^+ and $\text{Ca}(\text{OH})_2^0$, furthermore the formation constants of the CaLacH_{-1}^0 and CaLacH_{-2}^- complexes were found to be significantly lower than that of a complex containing a deprotonated hydroxy group (*i.e.*, an O^- moiety), these complexes most probably contain a Lac^- ligand coordinated to a CaOH^+ or a $\text{Ca}(\text{OH})_2^0$ unit.

T7. It was demonstrated that in alkaline medium calcium was able to induce the deprotonation of the two oxocarboxylates studied (*i.e.*, $\alpha\text{-Ket}^{2-}$ and $\beta\text{-Ket}^{2-}$). From ^1H NMR spectroscopic and UV spectrophotometric measurements, two novel species were identified between Ca^{2+} and both $\alpha\text{-Ket}^{2-}$ and $\beta\text{-Ket}^{2-}$.

The behaviour of the two ligands was found to be similar. For α -Ket²⁻, the formation of the Ca(α -Ket)H₋₁⁻ and Ca₂(α -Ket)H₋₃⁻ complexes was observed. β -Ket²⁻ was shown to form Ca(β -Ket)H₋₁⁻ and Ca₂(β -Ket)H₋₁⁺ species was detected. These species involve the coordination of an enolate functionality. The formation of the Ca₂(α -Ket)H₋₃⁻ species is somewhat unexpected. Since it is unlikely that (α -Ket)H₋₁³⁻ undergoes a second (and a third) deprotonation step, this complex is suggested to be a mixed calcium hydroxido enolate species.

5. Practical applications

Although this work is mostly of fundamental nature, some of the observations here may have potential industrial applications. Our findings regarding the complex formation between calcium and these ligands under highly alkaline solutions may help to better understand the processes occurring under the conditions of the low and intermediate level radioactive waste repositories and may provide fundamental results for more complicated systems involving several other metal ions.

6. Publications and conference participations

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

1. **C. 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, 46 (2017) 13888-13896.
impact factor: 4.099
2. V. Bugris, **Cs. Dudás**, B. Kutus, V. Harmat, K. Csankó, S. Brockhauser, I. Pálinkó, P. Turner, P. Sipos: Crystal and solution structures of calcium complexes relevant to problematic waste disposal: calcium gluconate and calcium isosaccharinate
Acta Crystallographica Section B, 2018, DOI: 10.1107/S2052520618013720
impact factor (2017): 6.467
3. **Cs. Dudás**, B. Kutus, G. Peintler, I. Pálinkó, P. Sipos: The formation of Ca(II) enolato complexes with α - and β -ketoglutarate in strongly alkaline solutions
Polyhedron, 156 (2018) 89-97.
impact factor (2017): 2.067

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

1. **Cs. Dudás**, B. Kutus, Á. Buckó, É. Böszörményi, T. Faragó, G. Peintler, I. Pálinkó, P. Sipos: Small M_w hydroxy- and oxocarboxylate type organics relevant to the Bayer process – acid-base properties and calcium-complexation in moderately to highly alkaline medium

Alumina2018: The 11th AQW International Conference – Conference Proceedings, ISBN 978-0-646-99164-1, 2018, pp. 381-386.

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

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

3. É. Böszörményi, **Cs. Dudás**, B. Kutus, I. Pálinkó, P. Sipos: Az izoszacharinát és laktát ionok semleges és lúgos kémhatású oldatokban képződő kalciumkomplexeinek összehasonlítása (Comparison of the calcium complexes of isosaccharinate and lactate forming in neutral and alkaline medium)

XL. Kémiai Előadói Napok, Program és előadás összefoglalók, ISBN 978-963-9970-83-0, 2017, pp. 166-171.

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

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

5. **Cs. Dudás**, B. Kutus, É. Böszörményi, P. Medvegy, O. Orbán, I. Pálinkó, 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, ISBN 978-963-9970-64-9, 2015, pp. 42-47.

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

1. B. Kutus, **Cs. Dudás**, G. Peintler, I. Pálkó, P. Sipos: Configuration-dependent complex formation between Ca(II) and sugar carboxylate ligands in alkaline medium: Comparison of L-gulonate with D-gluconate and D-heptagluconate
Carbohydrate Research, 460 (2018) 34-40.
impact factor: (2017) 2.074
2. Sz. Muráth, **Cs. Dudás**, Á. Kukovecz, Z. Kónya, P. Sipos, I. Pálkó: From nicotinate-containing layered double hydroxides (LDHs) to NAD coenzyme-LDH nanocomposites – Syntheses and structural characterization by various spectroscopic methods
Journal of Molecular Structure, 1140 (2017) 39-45.
impact factor: 2.011
3. N.H. Truong, A. Ádám, G. Varga, **Cs. Dudás**, Z. Kele, P. Sipos, I. Pálkó: Thionation of a cyanoxime derivative to form the sulphur-containing derivative, a novel ligand for complexation with transitional metal ions
Structural Chemistry, 28 (2017) 475-478.
impact factor: 2.019
4. Z. Csendes, **Cs. Dudás**, G. Varga, É.G. Bajnóczy, S.E. Canton, P. Sipos, I. Pálkó: Superoxide dismutase inspired Fe(III)-amino acid complexes covalently grafted onto chloropropylated silica gel – Syntheses, structural characterisation and catalytic activity
Journal of Molecular Structure, 1044 (2013) 39-45.
impact factor: 1.599
5. A. Pallagi, **Cs. Dudás**, Z. Csendes, P. Forgó, I. Pálkó, P. Sipos: Structure and equilibria of Ca²⁺-complexes of glucose and sorbitol from multinuclear (¹H, ¹³C and ⁴³Ca) NMR measurements supplemented with molecular modelling calculations
Journal of Molecular Structure, 993 (2011) 336-340.
impact factor: 1.634

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

1. **Cs. Hancsákné Dudás**, M. Sipiczki, P. Sipos, I. Pálinkó: Enzimutánzó katalizátorok készítése – az első lépések (Synthesis of enzyme-mimicking catalysts – the first steps)
XXXVI. Kémiai Előadói Napok, Program és előadás összefoglalók, ISBN 978-963-315-145-7, 2013, pp. 122-126.
2. **Cs. Hancsákné Dudás**, Z. Csendes, É.G. Bajnóczi, S.E. Canton, P. Sipos, I. Pálinkó: Módosított szilikagél felületén kovalens kötéssel rögzített vas–aminosavkeverék komplexek készítése, szerkezeti jellemzése és katalitikus aktivitásának vizsgálata (Synthesis, structural characterisation and catalytic activities of iron-mixed amino acid complexes covalently anchored on modified silica gel)
XXXV. Kémiai Előadói Napok, Program és előadás összefoglalók, ISBN 978-963-315-099-3, 2012, pp. 138-142.

6.5. Other conference participations

Author or co-author of 8 lectures presented in international conferences

Author or co-author of 8 lectures presented in Hungarian conferences

Author or co-author of 6 posters presented in international conferences

Full papers published in peer-reviewed journals:

Related to the Theses: 3

Total: 8

Cumulative impact factor:

Related to the Theses: 12.633

Total: 21.970