Metal Binding by Amino Acids: Preparation and Crystal Structures of Lithium, Sodium, and Potassium Hydrogen Bis-L-pyroglutamate

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Lithium, sodium and potassium hydrogen bis-L-pyroglutamate [Li(L-pGlu)(L-pGluH)], [Na(L-pGlu)(L-pGluH)] and [K(L-pGlu)(L-pGluH)], respectively, have been prepared by reaction of aqueous solutions of the metal hydroxides with L-pyroglutamic acid in the molar ratio 1:2, or in methanol. Crystalline samples of the salts could be obtained by slow evaporation of solutions of the salts in methanol. In the solid state, Li(L-pGlu)(L-pGluH) adopts a chain structure with the lithium atoms arranged in double strands. Adjacent metal centers are bridged by the carboxylate groups of the L-pGlu$^-$ ligands. The L-pGluH ligands are attached to the metal centers through the amide oxygen atoms. Na(L-pGlu)(L-pGluH) forms a three-dimensional coordination polymer with two half-occupied sodium positions, one L-pGlu$^-$ and one L-pGluH ligand in the asymmetric unit. The carboxyl and carboxylate groups of the L-pGluH and the L-pGlu$^-$ ligands are bridging the sodium centers, giving rise to eight-membered rings, which consist of two sodium atoms, a carboxyl and a carboxylate group. The hydrogen atoms of the carboxyl group of the L-pGluH ligands are involved in strong hydrogen bonds between a carboxyl and an adjacent carboxylate oxygen atom. K(L-pGlu)(L-pGluH) adopts a layer structure with strands of potassium atoms. The metal centers are connected through bridging carboxyl and carboxylate groups of the L-pGluH and L-pGlu$^-$ ligands, respectively. The structure features eight-membered ring units comparable to those observed for Na(L-pGlu)(L-pGluH), again with the hydrogen atom of the carboxyl group engaged in a strong transannular hydrogen bond. The amide oxygen atoms of the L-pGlu$^-$ and the L-pGluH ligands are coordinated to the metal centers of adjacent coordination chains. The results of ^{1}H- and ^{13}C-NMR investigations of aqueous solutions of the compounds indicate extensive electrolytic dissociation in dilute solutions.

Metal L-pyroglutamates ("pidolates") are important industrial products and used e.g. as drugs and components of cosmetics. Free L-pyroglutamic acid has been detected as an intermediate in many biosyntheses and in the transport of amino acids through cell membranes[1]. Sodium L-pyroglutamate has been identified in the natural moisterizing factor (NMF) of human skin[2] and is – in the racemic form – an important ingredient for a variety of cosmetics[3]. The magnesium salt is an effective magnesium drug, and the calcium salt has been used in the therapy of calcium deficiency[3,4].

The applications of metal L-pyroglutamates are mainly oriented towards supplementation of alkali and alkaline earth metals, whose essential role in biological systems is well established[5,6]. Knowledge of the details of the interaction of L-pyroglutamatic acid with these metals, however, is still very limited. As part of ongoing pertinent studies we have become interested in the structures of alkali and alkaline earth metal L-pyroglutamates. Recently, a new synthetic route to these compounds has been described: Thermal dehydration of *molten* L-glutamate salts is a particularly attractive procedure, which gives high yields and is accompanied by very little racemization[3]. Four products, sodium L-pyroglutamate trihydrate[7], zinc bis-L-pyroglutamate dihydrate[8], lithium L-pyroglutamate[9] and calcium bis-L-pyroglutamate[9] have been obtained as crystalline samples. The X-ray structure investigation of these products revealed that the crystal structures are governed largely by a delicate balance between metal-oxygen contacts and hydrogen bonds: In Li(L-pGlu) and Ca(L-pGlu)$_2$, which both crystallize without hydrate water, all three oxygen donors of the ligand are coordinated to the metal center, and only the amide hydrogen atom is available for hydrogen bonding[9]. On the other hand, in Na(L-pGlu) · 3 H_2O only the amide oxygen atoms are coordinated to the sodium atom, while the carboxylate group is exclusively involved in hydrogen bonding[7]. Zn(L-pGlu)$_2$ · 2 H_2O adopts an intermediate position between these two extremes[8].

We now report the preparation, crystallization and X-ray structure determination of the acid salts of the alkali metals lithium, sodium and potassium with L-pyroglutamic acid.

Results

[Li(L-pGlu)(L-pGluH)], [Na(L-pGlu)(L-pGluH)] and [K(L-pGlu)(L-pGluH)] have been prepared by reaction of the metal hydroxides with L-pyroglutamic acid in the molar ratio 1:2 in aqueous solutions or in methanol. Crystalline samples of the salts were generated by slow evaporation of solutions of the salts in methanol. From aqueous solutions no crystals suitable for X-ray structure investigation could be obtained.

Li(L-pGlu)(L-pGluH) crystallizes in the acentric space group $P2_12_12_1$ with four formula units in the unit cell. The lattice features a chain structure with the lithium atoms arranged in double strands. Adjacent metal centers are

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bridged by the carboxylate groups of the L-pGlu⁻ ligands. The L-pGluH ligands are attached to the metal centers through the amide oxygen atoms. The double strands are interconnected by a network of hydrogen bonds (Figure 1, Table 1). The strong O1–H13···O6 hydrogen bonds are particularly noteworthy. Through these bonds the amide oxygen donors of the L-pGlu⁻ ligands of a double strand are connected with the carboxyl groups of the L-pGluH ligands of an adjacent double strand. The lithium atom lies at the center of a slightly distorted tetrahedron (Figure 2) and is connected with three carboxylate oxygen atoms of three different L-pGlu⁻ ligands and one amide oxygen atom of a L-p-GluH ligand (Figure 1, Figure 2). The Li–O distances range from 1.953(3) to 2.023(3) Å with no clear distinction between the $\mathrm{Li-O_{carboxylate}}$ and the $\mathrm{Li-O_{amide}}$ distances.

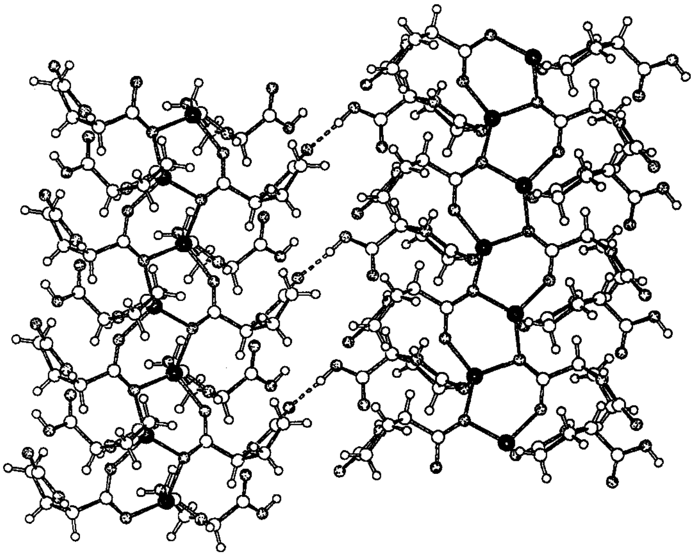

Figure 1. Crystal structure of Li(L-pGlu)(L-pGluH) (Li: black; O: dark shading; N: light shading; C: large, white; H: small, white)

Table 1. Prominent hydrogen bonds in the structure of Li(L-pGlu)(L-pGluH)

X–H···Y	X–H	H···Y	X···Y	X–H···Y
N2–H7···O2[a]	0.910	1.992	2.872	162.4
O1–H13···O6[b]	0.866	1.740	2.586	165.3

Symmetry positions of atom Y: [a] $x + 0.5, -0.5 - y, -z$. — [b] x, y, z.

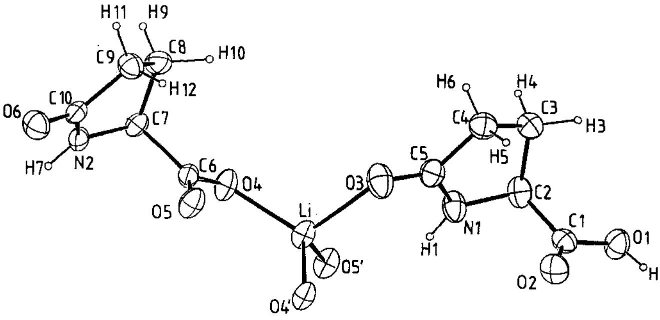

Figure 2. Inner coordination sphere of the lithium ion of Li(L-pGlu)(L-pGluH) with atomic numbering (ORTEP, displacement parameters at the 50% probability level; H atoms with arbitrary radii).
Important interatomic distances [Å] and angles [°]: C1–O1 1.316(2), C1–O2 1.205(2), C5–O3 1.226(2), C6–O4 1.260(2), C6–O5 1.249(2), C10–O6 1.241(2), Li–O3 1.997(3), Li–O4 1.953(3), Li–O4′ 2.023(3), Li–O5′ 1.957(3); O3–Li–O4 114.7(1), O3–Li–O5′ 102.2(1), O4′–Li–O5′ 118.6(1), O4′–Li–O3 99.2(1), O4′–Li–O4 115.5(1), O4–Li–O5′ 106.1(1)

The crystals of Na(L-pGlu)(L-pGluH) are monoclinic, space group C2, with four formula units in the unit cell. The asymmetric unit features two half-occupied sodium positions (at crystallographic two-fold axes), one L-pGlu⁻ ligand and one L-pGluH ligand. The carboxyl and carboxylate groups of the L-pGluH and the L-pGlu⁻ ligands are bridging the sodium centers, giving rise to eight-membered rings, which consist of two sodium atoms, a carboxyl and a carboxylate group (Figure 3). The carboxyl hydrogen atoms L-pGlu*H* are involved in strong hydrogen bonds with an adjacent carboxylate oxygen atom (Figure 3, Table 2, hydrogen bond: O4–H13···O1, O1···O4: 2.475 Å). In both crystallographically independent positions the sodium atoms feature a distorted octahedral coordination sphere, which includes two amide oxygen atoms and four carboxylate or carboxyl oxygen atoms (Figure 3). The Na–O distances range from 2.311(1) to 2.474(1) Å with the $\mathrm{Na-O_{amide}}$ contacts significantly shorter than the $\mathrm{Na-O_{carboxylate}}$ distances. The sodium atoms of Na(L-pGlu)(L-pGluH), which are arranged in strands (Figure 4), are interconnected through the bridging carboxyl and the carboxylate groups of the L-pGlu⁻ and L-pGluH ligands. The amide oxygen atoms of the L-pGlu⁻ and L-pGluH ligands are coordinated to the metal centers of adjacent chains, giving rise to a three-dimensional coordination polymer.

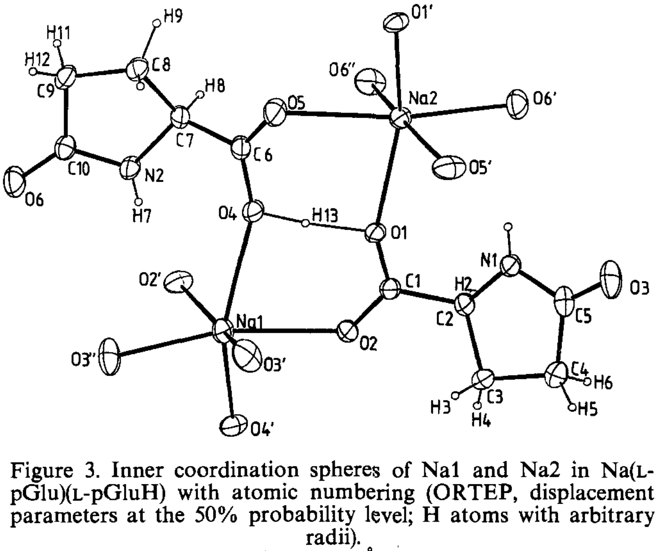

Figure 3. Inner coordination spheres of Na1 and Na2 in Na(L-pGlu)(L-pGluH) with atomic numbering (ORTEP, displacement parameters at the 50% probability level; H atoms with arbitrary radii).
Important interatomic distances [Å] and angles [°]: C1–O1 1.280(2), C1–O2 1.241(2), C5–O3 1.227(2), C6–O4 1.298(2), C6–O5 1.211(2), C10–O6 1.235(2), Na1–O2 2.463(1), Na1–O4 2.455(1), Na1–O3 2.311(1), Na2–O1 2.364(1), Na2–O5 2.474(1), Na2–O6 2.338(1); O4–Na1–O4′ 144.6(1), O1–Na2–O1′ 152.5(1)

Table 2. Prominent hydrogen bonds in the structure of Na(L-pGlu)(L-pGluH)

X–H···Y	X–H	H···Y	X···Y	X–H···Y
N1–H1···O6[a]	0.799	2.414	3.195	166.0
N2–H7···O2[b]	0.809	2.148	2.946	169.8
O4–H13···O1[c]	1.079	1.402	2.475	172.2

Symmetry positions of atom Y: [a] $x - 0.5$, $y - 0.5$, $z + 1$. – [b] $2 - x$, y, $2 - z$. – [c] x, y, z.

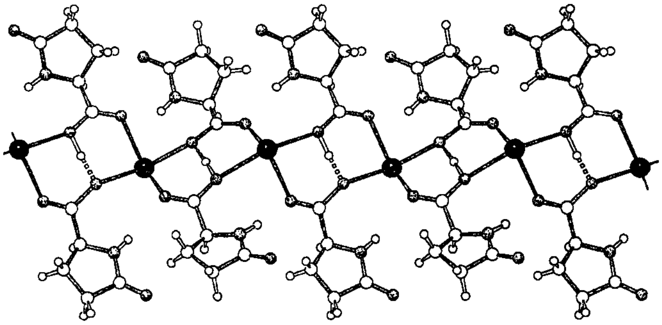

Figure 4. Strand of sodium atoms in Na(L-pGlu)(L-pGluH) (the coordination spheres of the sodium atoms are completed by two amide oxygen atoms from L-pyroglutamate ligands of neighbouring sodium strands. These amide oxygen atoms are omitted for the sake of clarity.) (Na: black; O: dark shading; N: light shading; C: large, white; H: small, white)

K(L-pGlu)(L-pGluH) crystallizes in the orthorhombic space group $P2_12_12_1$ and adopts a layer structure with strands of potassium atoms (Figure 5). The metal centers are connected through bridging carboxyl and carboxylate groups of the L-pGluH and L-pGlu⁻ ligands. The structure features thus eight-membered ring units, which contain two metal atoms, one carboxylate and one carboxyl group. These main building units are comparable to those observed for Na(L-pGlu)(L-pGluH), again with the hydrogen atom of the carboxyl group engaged in a strong transannular hydrogen bond (O1–H7···O4; O1···O4: 2.446 Å). The amide oxygen atoms of the L-pGlu⁻ and the L-pGluH ligands are coordinated to the metal centers of adjacent coordination chains (Figure 5). Several hydrogen bonds are observed in the crystal lattice (Table 3). The potassium atoms are coordinated by four carboxyl/carboxylate oxygen atoms and two amide oxygen atoms (Figure 6). As in Na(L-pGlu)(L-pGluH), the metal amide oxygen contacts are shorter than the metal carboxylate oxygen contacts.

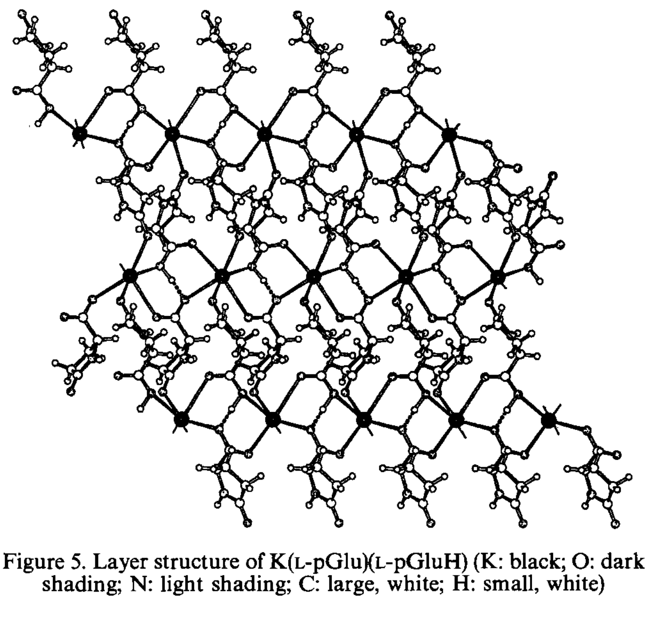

Figure 5. Layer structure of K(L-pGlu)(L-pGluH) (K: black; O: dark shading; N: light shading; C: large, white; H: small, white)

Table 3. Prominent hydrogen bonds in the structure of K(L-pGlu)(L-pGluH)

X–H···Y	X–H	H···Y	X···Y	X–H···Y
N1–H1···O5[a]	0.857	2.109	2.915	156.5
O1–H7···O4[b]	0.882	1.565	2.446	177.7
N2–H8···O2[c]	0.953	2.001	2.910	158.9

Symmetry positions of atom Y: [a] $-x - 0.5$, $2 - y$, $z - 0.5$. – [b] $x + 1$, y, z. – [c] $0.5 - x$, $2 - y$, $z + 0.5$.

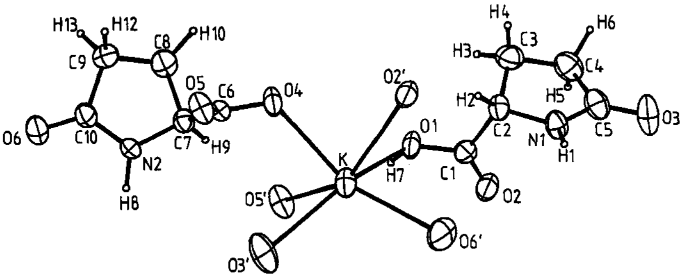

Figure 6. Inner coordination sphere of the potassium ion of K(L-pGlu)(L-pGluH) with atomic numbering (ORTEP, displacement parameters at the 50% probability level; H atoms with arbitrary radii).
Important interatomic distances [Å] and angles [°]: C1–O1 1.297(1), C1–O2 1.215(3), C5–O3 1.230(3), C6–O4 1.296(3), C6–O5 1.218(3), C10–O6 1.233(3), K–O1 2.778(2), K–O2' 2.926(2), K–O3' 2.695(3), K–O4 2.699(2), K–O5' 2.813(2), K–O6' 2.623(2); O4–K–O6' 147.3(1), O2'–K–O5' 140.5(1), O4–K–O2' 71.2(1)

The NMR spectra (^{1}H, ^{13}C) of solutions of Li(L-pGlu)(L-pGluH), Na(L-pGlu)(L-pGluH) and K(L-pGlu)(L-pGluH) show neither in water nor in methanol any significant differences in the chemical shift values and coupling constants for the L-pyroglutamate ligands. There are, however, differences between the NMR spectra of the acid salts M(L-pGlu)(L-pGluH) and the "normal" salts of the stoichiometry M(L-pGlu) (M = Li, Na, K)[10]. The ^{1}H-NMR resonances of the acid salts are shifted to lower field as compared with the resonances of the "normal" salts[10], while the ^{13}C-NMR resonances of the acid salts are shifted to higher field[10].

Discussion

The present investigation has established the existence of acid salts of the stoichiometry M(L-pGlu)(L-pGluH) (M = Li, Na, K). Acid salts of carboxylic acids of the stoichiometry $M(RCO_2)(RCO_2H)$ (M = monovalent metal ion) are a well-established class of compounds[11–15]. Individual compounds of this series normally adopt structures in which the carboxyl hydrogen atom is engaged in hydrogen bonding to a carboxylate oxygen atom. While Na(L-pGlu)(L-pGluH) and K(L-pGlu)(L-pGluH) also show this structural pattern, Li(L-pGlu)(L-pGluH) adopts a lattice in which the carboxyl hyrogen atom is in a bridging position between a carboxyl oxygen atom and an amide oxygen donor.

The present structure investigations have provided further evidence for the participation of all three oxygen donors of the L-pyroglutamate ligand in metal coordination. It is noteworthy that in Na(L-pGlu)(L-pGluH) and K(L-pGlu)(L-pGluH) the $M-O_{carboxylate}$ contacts are significantly longer than the $M-O_{amide}$ bonds. This seems to indicate that the Na^+ and K^+ cations, having a rather small charge density, prefer the amide oxygen donors for coordination. Further evidence for this assumption is provided by the structure of Na(L-pGlu) · 3 H_2O[7], which contains hexacoordinate sodium atoms bridged by the carboxamide oxygen atoms and two water molecules with no metal contacts at the carboxylate groups. In this respect it is quite interesting that carrier molecules for potassium in biological systems such as e.g. valinomycin or enniatin feature carbonyl oxygen donors, but no carboxylate groups for metal complexation[10,16].

The NMR investigations of solutions of the acid L-pyroglutamate salts proved to be of little value for obtaining information on the coordination chemistry in solution. Neither in ^{13}C- nor in ^1H-NMR spectra significant differences between the ligand resonances of Li(L-pGlu)(L-pGluH), Na(L-pGlu)(L-pGluH) and K(L-pGlu)(L-pGluH) are observed. This result seems to exclude any specific metal complexation, which should cause major differences. The observed chemical shift differences in ^1H- and ^{13}C-NMR spectra of acid and "normal" salts of L-pyroglutamic acid can be explained by the influence of the pH (acid salts: pH $\approx$ 3.4; "normal" salts: pH $\approx$ 8) on the degree of ionisation of the L-pyroglutamate ligand[10]. The data agree with the results of previous investigations of the colligative properties (electrical conductivity, apparent molecular mass, etc.) of pyroglutamates, which indicate quite extensive dissociation

Table 4. Crystallographic data for Li(L-pGlu)(L-pGluH), Na(L-pGlu)(L-pGluH) and K(L-pGlu)(L-pGluH)

	Li(L-pGlu)(L-pGluH)	Na(L-pGlu)(L-pGluH)	K(L-pGlu)(L-pGluH)
Chemical formula	$C_{10}H_{13}N_2O_6Li$	$C_{10}H_{13}N_2O_6Na$	$C_{10}H_{13}N_2O_6K$
M_r	264.16	280.22	296.33
Crystal system	orthorhombic	monoclinic	orthorhombic
Space group	$P2_12_12_1$ (no. 19)	C2(no. 5)	$P2_12_12_1$ (no. 19)
a [Å]	5.172(1)	15.013(2)	5.276(1)
b [Å]	8.691(1)	8.966(1)	14.667(2)
c [Å]	25.511(3)	13.103(1)	16.764(2)
α [°]	90	90	90
β [°]	90	137.86(1)	90
γ [°]	90	90	90
V [$Å^3$]	1146.72	1183.38	1297.25
$d_{calcd.}$ [gcm^{-3}]	1.530	1.573	1.517
Z	4	4	4
F(000) [e]	552	584	616
$\mu(MoK_\alpha)$ [cm^{-1}]	1.2	1.5	4.3
T [°C]	23	23	23
Scan	$\vartheta-\vartheta$	$\vartheta-2\vartheta$	$\vartheta-2\vartheta$
Scan width [°]	$0.9 + 0.35 \tan\vartheta$	$1.0 + 0.35 \tan\vartheta$	$0.8 + 0.35 \tan\vartheta$
hkl range	±6, 11, 33	±19, ±11, 16	±6, 17, 19
$(\sin\vartheta/\lambda)_{max}$ [$Å^{-1}$]	0.660	0.638	0.593
Measured refl.	3152	2472	2752
Unique refl.	2753	2466	2272
R_{int}	0.017	0.0002	0.013
Observed refl.	2631 $[F_0 \geq 1\sigma(F_0)]$	2386 $[F_0 \geq 4\sigma(F_0)]$	1949 $[F_0 \geq 1\sigma(F_0)]$
Refined parameters	224	224	224
$R^{a)}$	0.036	0.026	0.036
$R_w{}^{b)}$	0.032	0.029	0.022
$(\mathrm{Shift/error})_{max}$	0.002	0.002	0.002
$\Delta\rho_{fin}$(max/min) [e/$Å^3$]	+0.42/−0.30	+0.33/−0.33	+0.30/−0.32

a) $R = \Sigma(||F_0| - |F_c||)/\Sigma|F_0|$.– b) $R_w = [\Sigma w(|F_0| - |F_c|)^2/\Sigma wF_0{}^2]^{1/2}$, $w = 1/\sigma^2(F_0)$.

and concomitant solvation of the cation and the anion by water molecules in aqueous solution[7,9].

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Experimental

General: All experiments were carried out in pure, bidistilled water. Reagents were commercial and of p.a. grade. – pH values: Knick apparatus, reference electrodes (AgCl/KCl) Ingold. – NMR spectra: Bruker WP100SY (^{1}H, ^{13}C) spectrometer. Standards: ^{1}H NMR: internal standard: *tert*-butyl alcohol (δ = 1.20). ^{13}C NMR: internal standard: dioxane (δ = 66.7). – Elemental analysis: Microanalytical laboratory of the Technical University, Garching. Standard procedures were used.

Lithium Hydrogen Bis-L-pyroglutamate: L-pyroglutamic acid (4.07 g, 31.52 mmol), dissolved in 20 ml of methanol, is treated with LiOH (0.38 g, 15.87 mmol). 5 ml of water is added to the resulting white suspension. The reaction mixture is heated for 2 h under reflux, cooled to ambient temperature and filtered. Upon slow evaporation of the resulting clear solution in an exsiccator white crystals of Li(L-pGlu)(L-pGluH) are formed (3.38 g, 12.80 mmol; 81% yield; m.p. >200°C). – ^{1}H NMR: (D_2O, 20°C): δ = 4.20 (m, O_2C-CH), 1.9–2.5 (m, CH_2, $COCH_2$). – ^{1}H NMR: (CD_3OD, 20°C): δ = 4.22 (m, O_2C-CH), 2.0–2.6 (m, CH_2, $COCH_2$). – $^{13}C\{^1H\}$ NMR (D_2O, 20°C): δ = 181.4 (CO_2), 178.1 (CO), 56.8 (HCCOO), 29.4 (CH_2CO), 24.8 (CH_2CHCOO). – $^{13}C\{^1H\}$ NMR (CD_3OD, 20°C): δ = 181.5 (CO_2), 177.9 (CO), 58.5 (HCCOO), 31.0 (CH_2CO), 26.7 (CH_2CHCOO).

$C_{10}H_{13}LiN_2O_6$ (264.2) Calcd. C 45.47 H 4.96 N 10.61
Found C 45.33 H 5.00 N 10.60

Sodium Hydrogen Bis-L-pyroglutamate: 0.58 g of sodium hydroxide (14.50 mmol) and 3.74 g of L-pyroglutamic acid (28.96 mmol) in 30 ml of water are stirred for three hours at ambient temperature. The solvent is removed and the resulting white solid is dissolved in 10 ml of methanol. Slow evaporation of the methanol yields after one month colourless crystals of Na(L-pGlu)(L-pGluH) (2.43 g, 8.67 mmol; 60% yield; m.p. 166°C). ^{1}H NMR: (D_2O, 20°C): δ = 4.21 (m, O_2C-CH), 1.9–2.5 (m, CH_2, $COCH_2$). – ^{1}H NMR: (CD_3OD, 20°C): δ = 4.25 (m, O_2C-CH), 2.0–2.6 (m, CH_2, $COCH_2$). – $^{13}C\{^1H\}$ NMR (D_2O, 20°C): δ = 181.7 (CO_2), 178.6 (CO), 57.0 (HCCOO), 29.4 (CH_2CO), 24.9 (CH_2CHCOO). – $^{13}C\{^1H\}$ NMR (CD_3OD, 20°C): δ = 181.5 (CO_2), 178.6 (CO), 58.6 (HCCOO), 31.1 (CH_2CO), 26.7 (CH_2CHCOO).

$C_{10}H_{13}N_2NaO_6$ (280.2) Calcd. C 42.86 H 4.68 N 10.00
Found C 42.79 H 4.76 N 10.10

Potassium Hydrogen Bis-L-pyroglutamate: 0.61 g of potassium hydroxide (10.87 mmol) and 2.81 g L-pyroglutamic acid (21.76 mmol) are heated in 60 ml of methanol under reflux for 3 h. The solvent is then removed, and the resulting white solid is dried in vacuo to give the product (3.14 g, 10.60 mmol; 97% yield; m.p. 177–179°C). Slow evaporation of a solution of the product in methanol yields crystals suitable for X-ray analysis. – ^{1}H NMR: (D_2O, 20°C): δ = 4.18 (m, O_2C-CH), 1.9–2.5 (m, CH_2, $COCH_2$). – ^{1}H NMR: (CD_3OD, 20°C): δ = 4.23 (m, O_2C-CH), 2.0–2.6 (m, CH_2, $COCH_2$). – $^{13}C\{^1H\}$ NMR (D_2O, 20°C): δ = 181.6 (CO_2), 178.2 (CO), 56.9 (HCCOO), 29.4 (CH_2CO), 24.8 (CH_2CHCOO). – $^{13}C\{^1H\}$ NMR (CD_3OD, 20°C): δ = 181.4 (CO_2), 178.0 (CO), 58.5 (HCCOO), 31.0 (CH_2CO), 26.8 (CH_2CHCOO).

$C_{10}H_{13}KN_2O_6$ (296.3) Calcd. C 40.50 H 4.39 N 9.45
Found C 41.01 H 4.35 N 9.58

Table 5. Fractional atomic coordinates and thermal displacement parameters for Li(L-pGlu)(L-pGluH)

ATOM	X/A	Y/B	Z/C	U(eq.)
O1	0.5887(3)	0.3795(1)	0.21329(5)	0.301
O2	0.2958(2)	0.2318(1)	0.17349(5)	0.406
O3	0.4633(3)	0.0526(1)	0.02695(4)	0.353
N1	0.6690(3)	0.1402(2)	0.10013(5)	0.308
C1	0.5071(3)	0.2899(2)	0.17513(6)	0.264
C2	0.7010(3)	0.2793(2)	0.13093(6)	0.299
C3	0.6436(4)	0.4062(2)	0.08964(7)	0.326
C4	0.4666(4)	0.3265(2)	0.05028(7)	0.304
C5	0.5284(3)	0.1569(2)	0.05647(6)	0.272
C6	0.5693(3)	-0.2867(2)	-0.07886(5)	0.182
C7	0.7011(3)	-0.3015(2)	-0.13270(5)	0.196
C8	0.6348(3)	-0.1595(2)	-0.16657(6)	0.255
C9	0.3945(4)	-0.2075(2)	-0.19703(6)	0.280
C10	0.4047(3)	-0.3811(2)	-0.19645(5)	0.179
O4	0.7084(2)	-0.2377(1)	-0.04190(4)	0.228
O5	0.3336(2)	-0.3167(1)	-0.07651(4)	0.255
O6	0.2609(3)	-0.4696(1)	-0.22107(4)	0.317
N2	0.5919(3)	-0.4257(1)	-0.16387(5)	0.211
LI	0.5569(5)	-0.1702(3)	0.02436(9)	0.238

Table 6. Fractional atomic coordinates and thermal displacement parameters for Na(L-pGlu)(L-pGluH)

ATOM	X/A	Y/B	Z/C	U(eq.)
O1	0.7193(1)	0.6990(2)	0.6385(1)	0.020
O2	0.9380(1)	0.7128(2)	0.8045(1)	0.018
O3	0.5896(1)	0.5594(2)	0.1801(1)	0.043
N1	0.6856(1)	0.5712(2)	0.4196(1)	0.022
C1	0.8267(1)	0.6711(2)	0.6812(2)	0.016
C2	0.8165(1)	0.5759(2)	0.5773(2)	0.018
C3	0.9046(2)	0.6318(2)	0.5643(2)	0.019
C4	0.8302(2)	0.5827(2)	0.4061(2)	0.025
C5	0.6871(2)	0.5699(2)	0.3186(2)	0.026
O4	0.7767(1)	0.7940(2)	0.8591(1)	0.023
O5	0.5587(1)	0.7930(2)	0.6986(1)	0.034
O6	0.9277(1)	0.9594(2)	1.3200(1)	0.031
N2	0.8287(1)	0.8332(2)	1.1049(1)	0.024
C6	0.6713(2)	0.7920(2)	0.8266(2)	0.019
C7	0.6985(1)	0.7790(2)	0.9635(2)	0.018
C8	0.6033(2)	0.8719(2)	0.9491(2)	0.026
C9	0.6873(2)	0.9114(2)	1.1130(2)	0.026
C10	0.8287(2)	0.9064(2)	1.1937(2)	0.022
NA1	1.00000	0.87730	1.00000	0.021
NA2	0.50000	0.6363(1)	0.50000	0.020

Table 7. Fractional atomic coordinates and thermal displacement parameters for K(L-pGlu)(L-pGluH)

ATOM	X/A	Y/B	Z/C	U(eq.)
O1	0.3621(4)	0.8875(1)	0.3108(1)	0.033
O2	0.7011(4)	0.9294(1)	0.2400(1)	0.037
O3	0.6549(5)	0.8809(1)	-0.0114(1)	0.053
O4	-0.3798(4)	0.8966(1)	0.43172(9)	0.035
O5	-0.7109(4)	0.9437(1)	0.5035(1)	0.036
O6	0.1580(5)	1.1044(1)	0.2555(1)	0.054
N1	0.4138(5)	0.9070(2)	0.0988(1)	0.034
N2	-0.4232(4)	0.9255(2)	0.6444(1)	0.030
C1	0.4871(7)	0.8994(2)	0.2450(2)	0.030
C2	0.3378(6)	0.8640(2)	0.1733(2)	0.032
C3	0.4061(8)	0.7632(2)	0.1585(2)	0.041
C4	0.6059(8)	0.7657(2)	0.0936(2)	0.045
C5	0.5642(6)	0.8563(2)	0.0526(2)	0.040
C6	-0.4973(6)	0.9129(2)	0.4980(1)	0.027
C7	-0.3452(6)	0.8826(2)	0.5702(2)	0.029
C8	-0.4036(7)	0.7807(2)	0.5859(2)	0.038
C9	-0.6075(8)	0.7828(2)	0.6499(2)	0.040
C10	-0.5694(6)	0.8727(2)	0.6904(2)	0.035
K	-0.0052(2)	1.00272(4)	0.37345(3)	0.037

Crystal Structure Determinations[17]: Crystal data and data-collection parameters for Li(L-pGlu)(L-pGluH) (a), Na(L-pGlu)(L-pGluH) (b) and K(L-pGlu)(L-pGluH) (c) are listed in Table 4. During the data collection (Enraf-Nonius CAD4 diffractometer, Mo-K_α radiation, λ = 0.71069 Å, graphite monochromator) three standard reflections were periodically measured as a general check of crystal and instrument stability. No significant changes were observed during data collection. Reduced cell calculations did not indicate any higher symmetry (DELOS, LEPAGE). Lp correction was applied, but not absorption correction. All structures were solved by direct methods (SHELXS-86) and completed by difference Fourier syntheses (SHELX-76). All hydrogen atoms in the asymmetric unit could be located in difference Fourier syntheses for (a), (b) and (c). The non-H atoms were refined with anisotropic, the H atoms with isotropic displacement parameters. Refinement of the enantiomorphic coordinate set yielded no differences in *R* values and geometrical parameters due to small anomalous dispersion for all three compounds. Final atomic coordinates for all structures are listed in Tables 5 – 7.

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[17] Further details of the crystal structure determinations are available on request from the Fachinformationszentrum Karlsruhe, Gesellschaft für wissenschaftlich-technische Information mbH, D-7514 Eggenstein-Leopoldshafen 2, on quoting the depository number CSD-56288, the names of the authors, and the journal citation.

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