Electronic Supplementary Material (ESI) for RSC Advances.

Structural Characterization of α-Amino Acid Complexes of Molybdates: a Spectroscopic and DFT Study

Lorenzo Biancalana, Marco Bortoluzzi, Claudia Forte, Fabio Marchetti, Guido Pampaloni

SUPPORTING INFORMATION

Synthesis of $Mo_2O_4(OH)_4(aaH)$ complexes: the influence of experimental parameters. Compounds **1-6** were obtained under different experimental conditions as follows. The formation of identical products was checked by comparison of spectroscopic (IR, ^{13}C CP-MAS NMR) and elemental analysis data (C, H, N, Mo).

A) Formation of $Mo_2O_4(OH)_4(GlyH)$, 1.

at pH = 0. Compound $Na_2MoO_4 \cdot 2H_2O$ (974 mg, 4.02 mmol) and glycine (153 mg, 2.03 mmol) were dissolved in 1 M HNO_3 (35 mL). 65% HNO_3 was added up to pH ≈ 0. The resulting pale yellow mixture ($c_{Mo} = 0.11$ M) was stirred at room temperature for 19 hours. Thus **1** was isolated (589 mg, 75%).

at pH = 1. Compound $(NH_4)_2MoO_4$ (100 mg, 0.51 mmol) was dissolved in water (10 mL) and glycine (21 mg, 0.28 mmol) was dissolved in 1 M HCl (3 mL). The two solutions were mixed together and 6 M HCl was added dropwise until pH = 1. The resulting colourless solution ($c_{Mo} = 36$ mM) was stirred at reflux temperature. After ca. 20 minutes **1** precipitated as a colourless solid (102 mg, 91%).

B) Formation of $Mo_2O_4(OH)_4(aaH)$ at different Mo/aaH molar ratios. The following reactions were carried out by a procedure analogous to that described for the Mo/aaH 2:1 synthesis (Experimental Section), unless otherwise specified. Amino acid nitrates, $[aaH_2]NO_3$, were obtained from the filtered solution after complete solvent removal in vacuo.

aaH = GlyH, Mo/aaH = 1:2, pH = 1.8. From $Na_2MoO_4 \cdot 2H_2O$ (271 mg, 1.12 mmol), glycine (169 mg, 2.25 mmol), water (30 mL), 1 M HNO_3 (2.8 mL). $Mo_2O_4(OH)_4(GlyH)$. **1** (174 mg, 78%). $[GlyH_2]NO_3$ (218 mg).

aaH = GlyH, Mo/aaH = 1:13.7, pH = 1.8. From $Na_2MoO_4 \cdot 2H_2O$ (279 mg, 1.15 mmol), glycine (1.19 g, 15.8 mmol), water (92 mL), 1 M HNO_3 (11.2 mL). $Mo_2O_4(OH)_4(GlyH)$. **1** (161 mg, 70%). $[GlyH_2]NO_3$ (161 mg).

aaH = PheH, Mo/aaH = 1:2, pH = 2.0. From $Na_2MoO_4 \cdot 2H_2O$ (415 mg, 1.71 mmol), L-phenylalanine (566 mg, 3.42 mmol), water (20 mL) and 1 M HNO_3 (5.2 mL). $Mo_2O_4(OH)_4(PheH)$, **2** (349 mg, 84%). $[PheH_2]NO_3$ (162 mg). **2** was also obtained by using $(NH_4)_2MoO_4$ (ca. 1.5 mmol) in the place of $Na_2MoO_4 \cdot 2H_2O$, both at room temperature (97%, reaction time 2 hours) and at 70°C (99%, reaction time 1.5 hours).

aaH = LeuH, Mo/aaH = 1:1, pH = 1.8. From $Na_2MoO_4 \cdot 2H_2O$ (358 mg, 1.48 mmol), L-leucine (195 mg, 1.48 mmol), water (20 mL) and 1 M HNO_3 (3.5 mL). The mixture was stirred at 50°C for 3.5 hours and then at room temperature for 3 days: no solid formed under these conditions. Then the mixture was concentrated to 14 mL in vacuo, thus allowing the precipitation of **3** (249 mg, 74%).

aaH = LeuH, Mo/aaH = 1:2, pH = 1.8. From $Na_2MoO_4 \cdot 2H_2O$ (358 mg, 1.48 mmol), L-leucine (388 mg, 2.96 mmol), water (20 mL) and 1 M HNO_3 (5 mL). The mixture was heated at 50°C and complex **3** formed after 3.5 hours (312 mg, 93%). $[LeuH_2]NO_3$ (312 mg).

aaH = MetH, Mo/aaH = 1:2, pH = 2.0. From $(NH_4)_2MoO_4$ (301 mg, 1.53 mmol), L-methionine (458 mg, 3.07 mmol), water (40 mL) and 3 M HNO_3 (few drops). $Mo_2O_4(OH)_4(MetH)$, **4**: yield 269 mg, 74%. Some unreacted excess methionine was isolated from the liquors.

aaH = ProH, Mo/aaH = 1:2. From $(NH_4)_2MoO_4$ (307 mg, 1.57 mmol), L-proline (361 mg, 3.13 mmol), water (80 mL) and 3 M HNO_3 (few drops). $Mo_2O_4(OH)_4(MetH)$, **5 (**233 mg, 68%).

C) Influence of pH variations on the formation of 1 and 4. A suspension of **1** (434 mg, 1.09 mmol) in water (20 mL, pH ≈ 3) was treated with 0.194 M NaOH (8.10 mL, 1.57 mmol) up to complete dissolution of the solid (pH = 4.83). Further NaOH (11.1 mL, 2.15 mmol) was added up to pH = 5.31. Afterwards 1.08 M HNO_3 (2.05 mL, 2.22 mmol) was added dropwise, thus compound **1** was recovered (yield 411 mg, 95% with respect to the initial amount). A similar behaviour was observed with compound **4**.

Table S1. Formation of **1** in variable experimental conditions with pH monitoring.

Entry [a]	Mo/GlyH molar ratio	c_{Mo} / 10^{-2} M [b]	Induction period [c]	pH change interval [d]	Lowest pH	Final pH	Yield
#1	1.0	5.0	15 min	57 min	2.05	2.17	84%
#2	1.6	1.0	22 min	96 min	2.08	2.48	88%
#3	2.0	6.7	39 min	93 min	2.08	2.36	87%

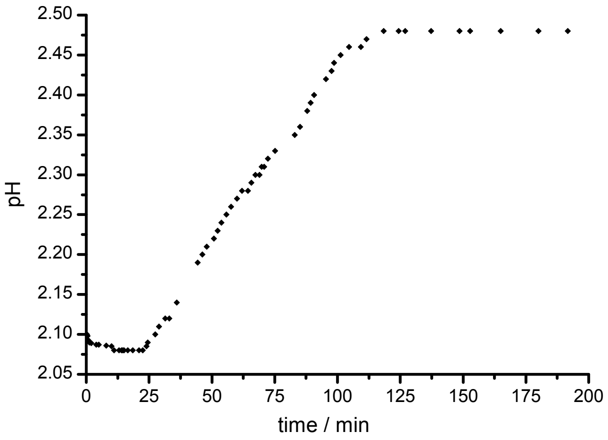
a 1.08 M HNO_3 was prepared from 67% HNO_3. Reactions #1-#3 were carried out by mixing appropriate amounts of GlyH (100-150 mg), $Na_2MoO_4 \cdot 2H_2O$ (600-800 mg) and water (*ca.* 30 mL), then 1.08 HNO_3 was added until pH = 2 (4-5 mL).

b Initial molar concentration of molybdenum in the reaction mixture.

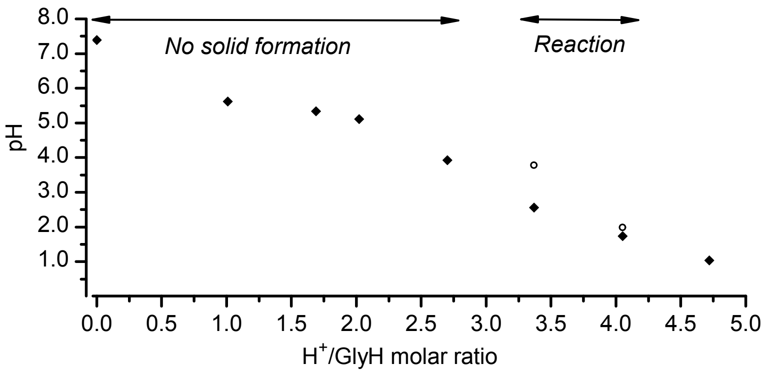
c period of time during which the pH remained almost constant. For the definition of induction period, see A. D. McNaught and A. Wilkinson in *Compendium of Chemical Terminology - the "Gold Book"*. 2nd ed., IUPAC, Oxford, 1997.

d period of time during which the pH increased

Graph S1. Profile of pH vs. time for the reaction reported as entry #2 in Table S1.



Graph S2. Titration of an aqueous mixture of Na_2MoO_4 and GlyH (2:1 molar ratio) with 1.08 M HNO_3. Filled squares refer to pH values measured soon after each HNO_3 addition. Empty circles refer to final pH values measured after the formation of **1**.



pH values did not vary after addition, up to H^+/GlyH = 2.70 (in this case, pH = 3.93 did not vary after 15 hours). With H^+/GlyH = 3.37, pH quickly reached 2.55 and it began to increase after ca. 30 minutes with the formation of a colourless solid. The final value of pH = 3.93 was reached. When H^+/GlyH was raised to 4.05, a small increase in pH was still detected, thus indicating residual formation of **1**.

Calculation of $\mathbf{v_{H+}}$: The amount of HNO_3 added and the pH of the solution after the second and final reaction are known (the "end of reaction" corresponds to the empty circle for H^+/GlyH = 4.05 in Graph S2, when pH stopped increasing). Therefore, the moles of H^+ reacted (Δn_{H+}) can be calculated by Equation S1. By knowing the amount of product isolated (m) and its molar mass (M), the molar ratio between Δn_{H+} and $Mo_2O_4(OH)_4(GlyH)$ is given by Equation S2.

$$\Delta n_{H+} = V_{HNO3} \times c_{HNO3} - V \times 10^{-pH} \qquad \text{(Equation S1)}$$

Δn_{H+} = reacted moles of H^+

V_{HNO3}, c_{HNO3} = volume and molar concentration of the HNO_3 solution

V = final volume of the solution, assuming that volumes are additive ($V = V_0 + V_{HNO3}$)

$$v_{H+} = \Delta n_{H+} \times M / m \qquad \text{(Equation S2)}$$

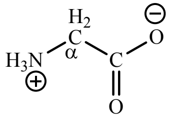
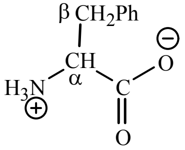
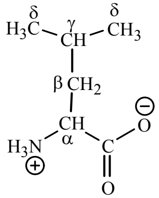
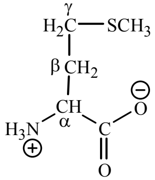
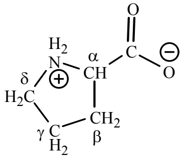
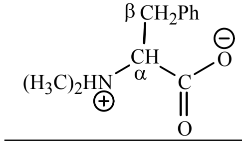
v_{H+} = molar ratio between Δn_{H+} and $Mo_2O_4(OH)_4(GlyH)$

m = amount of solid $Mo_2O_4(OH)_4(GlyH)$ isolated

M = molar mass of $Mo_2O_4(OH)_4(GlyH)$

The value obtained for the v_{H+} coefficient is 4.43, which is very close to the stoichiometric coefficient of H^+ required for the formation reaction proposed (see Equation 1). The value of Δn_{H+} obtained with equation S2 is inevitably overestimated since it does not consider any possible equilibrium, established after the formation of **1**, which may involve H^+, reducing its concentration. Examples are the protonation of unreacted glycine or molybdate. Nevertheless, since the formation of **1** was almost quantitative (88% yield) and the reaction was carried out under stoichiometric conditions, the value of Δn_{H+} may be not too biased.

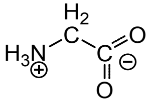
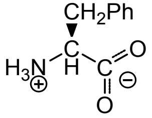
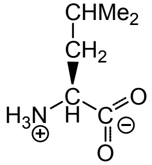
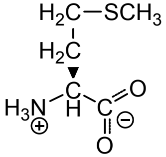
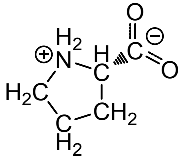
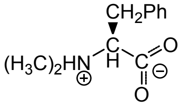
Table S2. Compared ^{13}C CP-MAS chemical shifts (ppm) of aaH, $[aaH_2]NO_3$ and $Mo_2O_4(OH)_4(aaH)$.[a]

α-Amino Acid	Compound	CO	C_α	C_β	C_γ	C_δ or Ph	Ref.
	GlyH	176.2	43.5				b
	$[GlyH_2]NO_3$	171.7	41.1				This work
	$Mo_2O_4(OH)_4(GlyH)$, **1**	172.0	41.3				This work
	PheH	175.3	58.3, 56.4	40.4, 37.6		135.4, 130.1, 128.4	This work
	$[PheH_2]NO_3$	173.9, 173.2	56.3, 55.5	37.0, 36.3		135.2, 132.8, 132.3, 129.8, 129.3, 127.6, 127.3	
	$Mo_2O_4(OH)_4(PheH)$, **2**	172.6	57.3	35.6		134.5, 133.6, 132.5, 129.6	
	LeuH	176.7, 175.8	53.8, 52.7	42.4, 40.6	24.6	24.6	This work
	$[LeuH_2]NO_3$	173.9, 173.1	52.9	39.2	24.7	23.3, 22.3, 21.7, 20.0	
	$Mo_2O_4(OH)_4(LeuH)$, **3**	173.2	53.2	39.2	25.1	21.3, 20.1	
	MetH	176.7	55.2, 52.1	32.9, 32.0	31.0	17.3, 15.3	This work
	$[MetH_2]NO_3$	173.7, 172.2	54.6, 54.4	32.9	30.2	16.0, 15.5	
	$Mo_2O_4(OH)_4(MetH)$, **4**	174.4, 171.8	54.7	31.5, 30.4	28.7	15.3, 14.3, 12.4	
	ProH	176.7	60.6	29.6	25.1	47.8	This work
	$Mo_2O_4(OH)_4(ProH)$, **5**	176.8, 175.2, 173.5	65.0, 61.0	30.2, 29.4	26.2, 25.8, 23.7	49.7, 47.3, 46.9	
	dmPheH	172.6	66.5	35.4	39.0 (NCH_3)	139.0, 130.6, 129.1, 127.7, 125.1	This work
	$Mo_2O_4(OH)_4(dmPheH)$, **6**	171.6	69.9	30.4	42.0, 36.6 (NCH_3)	140.9, 130.8, 128.8, 127.8	

a Splitted signals for PheH, $[PheH_2]NO_3$, LeuH, $[LeuH_2]NO_3$, MetH, $[MetH_2]NO_3$ are due to the presence of two crystallographically independent molecules in the asymmetric unit.

b C. Gervais, R. Dupree, K. J. Pike, C. Bonhomme, M. Profeta, C. J. Pickard and F. Mauri, *J. Phys. Chem. A*, 2005, **109**, 6960-6969

Table S3. Main solid state IR absorptions (cm^{-1}) and vibrational assignments for compounds **1-6** and the related α-amino acids.

α-Amino Acid	Compound	Carboxylate group			Ammonium group		Mo-O backbone					Ref.
		$\nu_{asym}(CO_2^-)$	$\nu_{sym}(CO_2^-)$	$\Delta\nu_{a-s}$ ($\Delta\nu^{rel}_{a-s}$)	$\delta_{asym}(NH_3^+)$	$\delta_{sym}(NH_3^+)$	$\nu_{sym}(MoO_2)$	$\nu_{asym}(MoO_2)$	$\nu_{asym}(Mo_2O)$	ν(Mo-O$_{ligand}$) or/and $\nu(Mo_2O_2)$	$\nu_{sym}(Mo_2O)$	
	GlyH	1610	1407	203	1580	1500						a
	$Mo_2O_4(OH)_4$(GlyH), **1**	1623	1412	211 (+*8*)	1590	1512	946	918, 903	761	531	473	This work
	PheH	1556	1408	148	1622	1494						b
	$Mo_2O_4(OH)_4$(PheH), **2**	1607	1426	181 (+*33*)	1607	1525	942	913, 904	756	534		This work
	LeuH	1578	1406	172	1608	1512						c
	$Mo_2O_4(OH)_4$(LeuH), **3**	1599	1428	171 (*–1*)	1620	1513	939	909, 896	768	537	479	This work
	MetH	1582, 1560	1406	165 (av.)	1608	1508						d
	$Mo_2O_4(OH)_4$(MetH), **4**	1575	1427	148 (*–17*)	1603	1504	942	913, 894	762	540	486	This work
	ProH	1613	1404	209	$\delta(NH_2^+)$: 1553							e
	$Mo_2O_4(OH)_4$(ProH), **5**	1603	1432	171 (*–38*)	$\delta(NH_2^+)$: 1558		944	914, 901	767	543	463	This work
	dmPheH	1610	1416	194	$\nu(N–CH_3)$: 1485							This work
	$Mo_2O_4(OH)_4$(dmPheH), **6**	1626	1412	214 (+*20*)	$\nu(N–CH_3)$: 1495		946	916, 901	769	547	484	

IR spectra of α-amino acids were recorded by FT-IR; the following references assisted with band assignments: (a) M. Tsuboi, T. Onishi, T. S. Nakagawa and S. I. Mizushima, *Spectrochim. Acta* 1958, **12**, 253-261; (b) S. Olsztynska, M. Komorowska, L. Vrielynck and N. Dupuy, *Appl. Spectrosc.*, 2001, **55**, 901-907; (c) J. F. Jackovitz and J. L. Walter, *Spectrochim. Acta,* 1966, **22**, 1393-1406; (d) A. Grunenberg and D. Bougeard, *J. Mol. Struct.*, 1987, **160**, 27-36; (e) C. C. Wagner, M. H. Torre and E. J. Baran, *Lat. Am. J. Pharm.,* 2008, **27**, 197-202.

Figure S1. Solid state IR spectrum of $Mo_2O_4(OH)_4(GlyH)$, **1**.

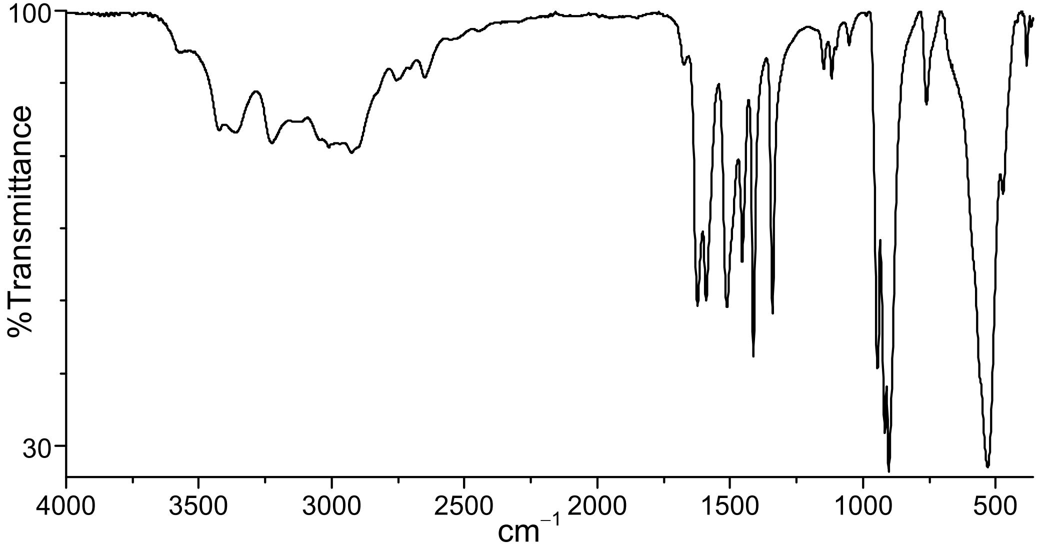


Figure S2. Solid state IR spectrum of $Mo_2O_4(OH)_4(PheH)$, **2**.

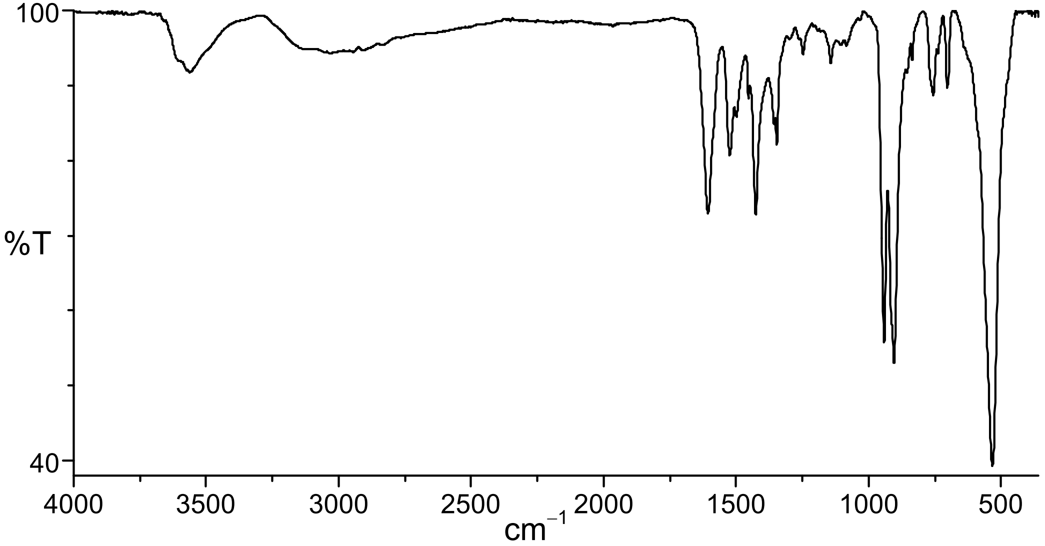


Figure S3. Solid state IR spectrum of $Mo_2O_4(OH)_4$(LeuH), **3**.

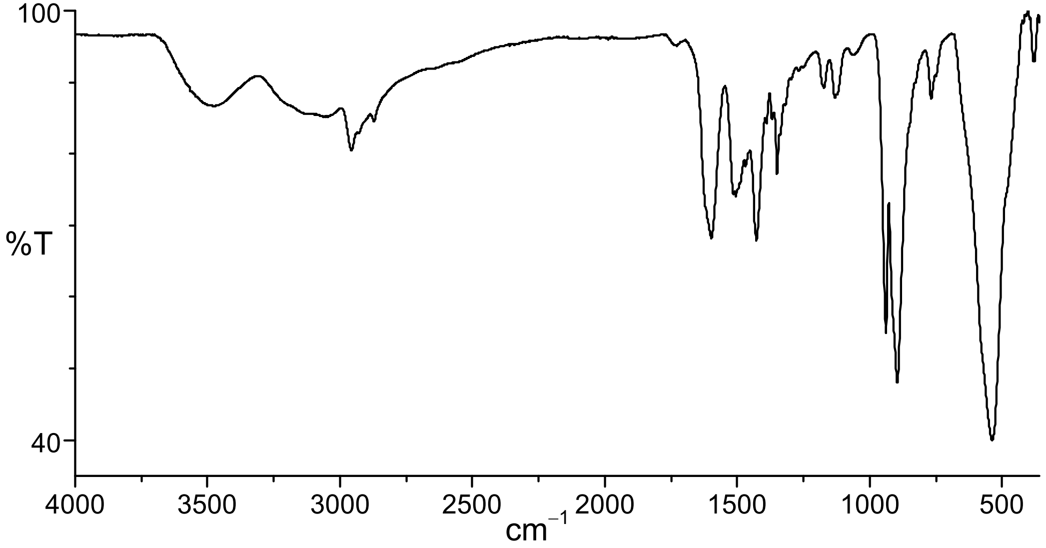


Figure S4. Solid state IR spectrum of $Mo_2O_4(OH)_4$(MetH), **4**.

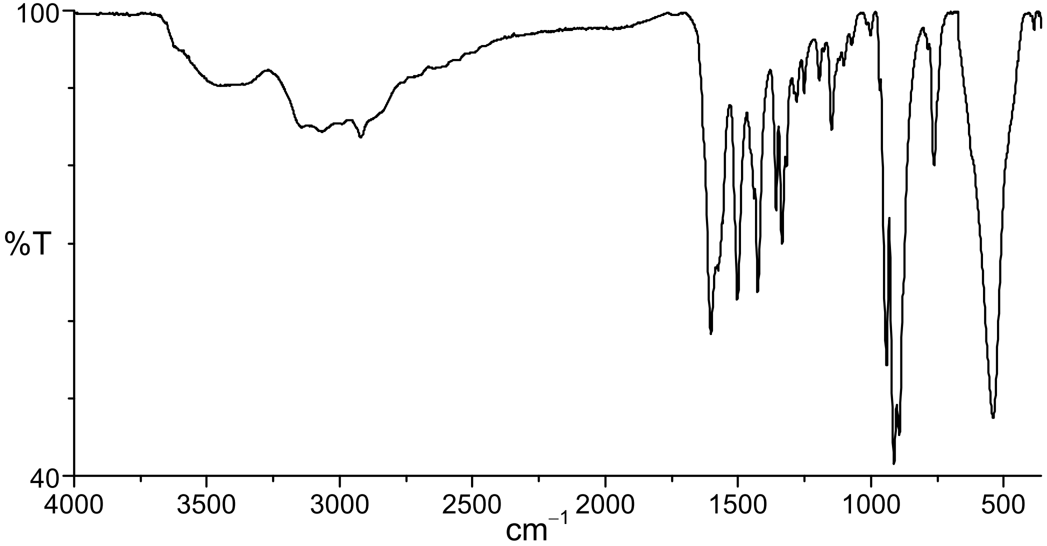


Figure S5. Solid state IR spectrum of $Mo_2O_4(OH)_4$(ProH), **5**.

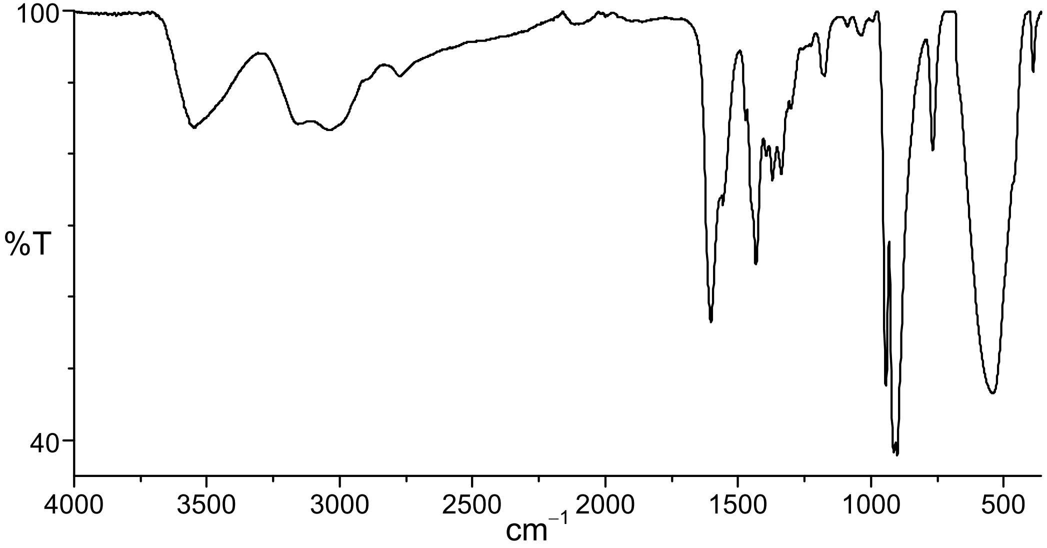


Figure S6. Solid state IR spectrum of $Mo_2O_4(OH)_4$(dmPheH), **6**.

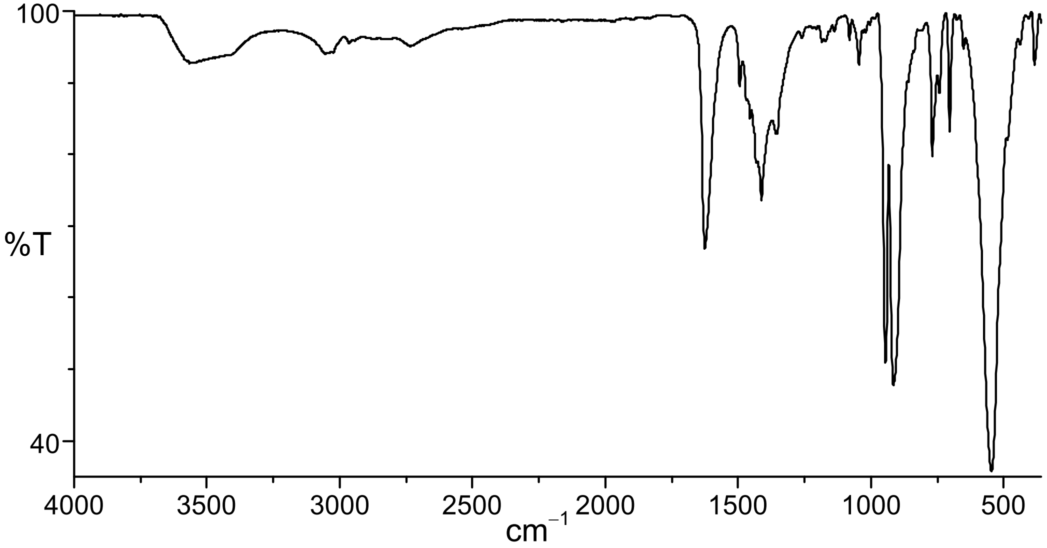
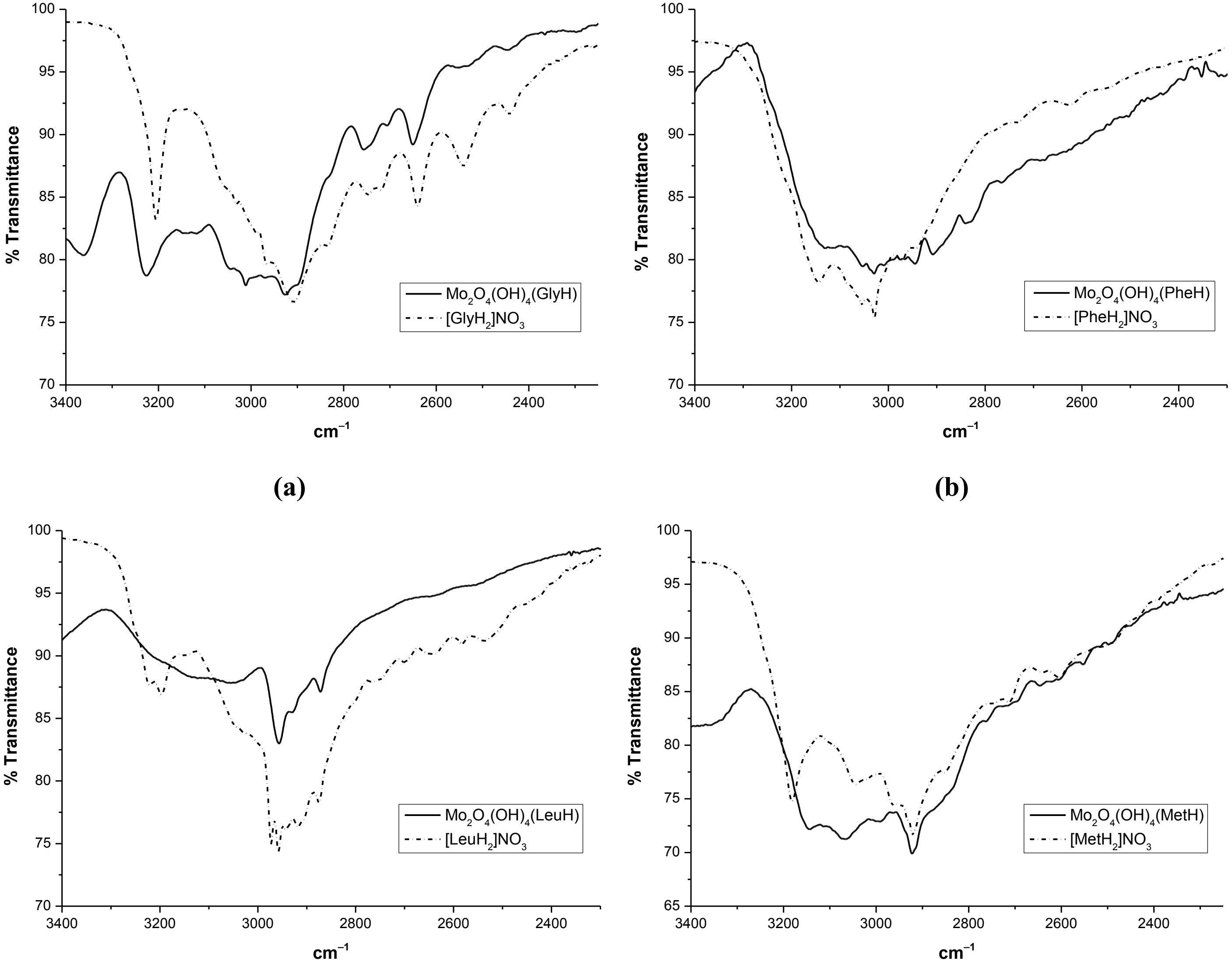


Figure. S7. Comparison of $Mo_2O_4(OH)_4(aaH)$ (straight line) and $[aaH_2]NO_3$ (dashed line) IR spectra in the 2300-3400 cm^{-1} interval for glycine (a), L-phenylalanine (b), L-leucine (c) and L-methionine (d).



(a) **(b)**

(c) **(d)**