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Central European Journal of Chemistry
DOI: 10.2478/s11532-006-0034-0
Research article
CEJC 4(4) 2006 695–707

Solid-state linear-dichroic infrared (IR-LD) spectroscopic and theoretical characterization of 2-[(2-ethoxy-3,4-dioxocyclobut-1-en-yl)amino]propanamide

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Received 3 April 2006; accepted 10 July 2006

Abstract: 2-[(2-Ethoxy-3,4-dioxocyclobut-1-en-yl)amino]propanamide (N-alaninamidoamide of squaric acid ethyl ester) has been characterized structurally and spectroscopically by *ab initio* calculations and IR-LD spectroscopy of oriented crystals suspended in a nematic liquid crystal. The results are compared with single crystal X-ray structures illustrating the possibilities of this experimental approach to obtaining structural information as well as assigning IR bands.

Keywords: 2-[(2-Ethoxy-3,4-dioxocyclobut-1-en-yl)amino]propanamide, N-alaninamidoamide of squaric acid ethyl ester, solid-state IR-LD spectroscopy, ab initio *calculations*

1 Introduction

Building on previous spectroscopic and structural studies of some optically active derivatives of amino acids with potential nonlinear optical and electro-optical properties [1, 2], the crystal structures of a series of amino acid amides of squaric acid [3–8] and hydrogen-squarates [9–12] have been reported. Structural studies of some C-gα-amidated amino acids (Ile, Val, Thr, Ser, Met, Trp, Gln and Arg) have been performed and compared with their C-α-unamidated counterparts [13].

These complex molecules represent a new class of compounds with great biological importance. It is known that most mammalian peptide hormones possess a C-α-terminal

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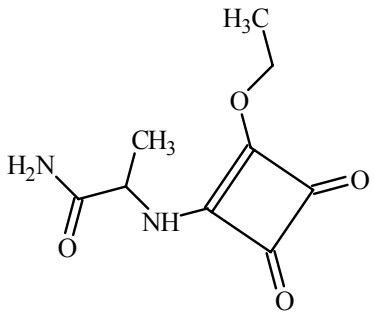
amide (e. g. calcitonin, gastrin, neurokinins, neuropeptides and their related peptides [14]). Amidation arises from oxidative cleavage of C-α-terminal glycine-extended prohormones [15]; its function is not fully understood. In many cases C-α-amides are much more biologically active than the corresponding C-α-terminal free acids, as measured by the potency ratio of a peptide amide to that of the corresponding peptide free acid. Neurocinin A, for example, possesses a potency ratio > 10 000 [16, 17]. In recent years the bioactivity of squaric acid and some derivatives as inhibitors and VLA-4 integrin antagonists, potassium channel openers and matrix metalloprotease-1 inhibitors have been also reported [18–21].

Since the protonated forms of amino acid amides are present in the living cell, structural information may be useful in understanding the different biological functions of C-α-amide and C-α-acid peptides. In addition, squaric acid and its optically active amino acid amides crystallize noncentrosymmetrically and are of great interest for nonlinear optical and electro-optical applications.



Scheme 1 2-[(2-Ethoxy-3,4-dioxocyclobut-1-en-yl)amino]propanamide.

This work investigates the structure and IR spectrum of 2-[(2-ethoxy-3,4-dioxocyclobut-1-en-yl)amino]propanamide (N-alaninamidoamide of squaric acid ethylester) (Scheme 1) using polarized infrared linear-dichroic (IR-LD) spectroscopy, based on the orientation of guest crystals suspended in a nematic liquid crystal. These data are compared with single crystal X-ray results [8, 22–30] and theoretical *ab initio* calculations. The possibilities of this new approach have been demonstrated in a series of peptide systems [8, 22–30].

2 Experimental

2.1 Synthesis

2-[(2-Ethoxy-3,4-dioxocyclobut-1-en-yl)amino]propanamide was synthesized according the procedure described in [4].

2.2 Methods

IR spectra were measured on a Bomem-Michelson 100 FTIR spectrometer (4000 – 400 cm^{-1}, 2 cm^{-1} resolution, 150 scans) equipped with a Perkin Elmer wire-grid polarizer. Non-polarized solid-state IR-spectra were recorded using the KBr disk technique. Oriented samples were obtained as a suspension in a nematic 4'-cyano-4'-alkylbicyclohexyl mixture (ZLI 1695, Merck), because its poorly resolved IR spectrum allows recording the guest compound bands over the whole 4000 - 400 cm^{-1} range. The presence of an isolated nitrile stretch at about 2230 cm^{-1} additionally serves as an orientation indicator. Orientation of solid samples was achieved as follows: 5 mg of compound was mixed with the liquid crystal until a slightly viscous suspension was obtained. This mixture was pressed between KBr-plates which had been ground in one direction by fine sandpaper. Rubbing the prepared mull in the grinding direction further promotes orientation [8, 22–30].

The IR-LD spectroscopy theory and the difference-reduction procedure used for polarized IR spectral interpretation are described in [8, 22–29]. The method consists in subtraction of IR_s (a perpendicular spectrum, resulting from a 90° angle between the polarized light beam electric vector and the sample orientation) from IR_p (a parallel spectrume, obtained with co-linear mutual orientation). The recorded difference (IR_p-IR_s) spectrum divides the parallel (A_p) and perpendicular (A_s) integrated absorbances of each band into positives, originating from transition moments which form average angles with the orientation direction between 0° and 54.7° and negatives, corresponding to angles between 54.7° and 90°. If the perpendicular spectrum multiplied by the parameter $\boldsymbol{c}$ is subtracted from the parallel one (where $\boldsymbol{c}$ is varied until a band or set of bands are eliminated) then the simultaneous disappearance of bands in the (IR_p - $\boldsymbol{c}IR_s$) reduced IR-LD spectrum means that the corresponding transition moments are co-linear, yielding information regarding the mutual disposition of the molecular fragments.

The position (ν_i) and integrated absorbances (A_i) for each peak were determined by deconvolution and curve-fitting procedures assuming a 1:1 ratio of Lorentzian to Gaussian peak shapes, χ^2 factors within 10^{-3} – 10^{-7}, and 2000 iterations [30, 31]. The means of two treatments were compared by the Student t-test. The experimental IR spectra were acquired and processed by GRAMS /AI 7.01 IR spectroscopy (Thermo Galactic, USA) and STATISTICA for Windows 5.0 (StatSoft, Inc., Tulsa, OK, USA) program packages.

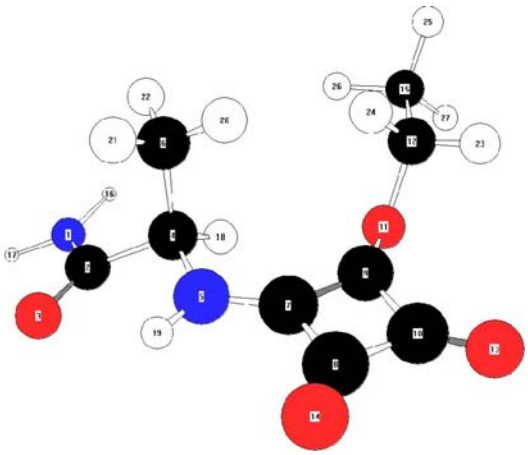
Structure optimization was carried out by *ab initio* Hartree-Fock calculations using the 6-31++G** basis set performed by the Dalton program [32].

3 Results and discussion

3.1 Theoretical analysis

Gas phase conformational analysis was performed by energy minimization with respect to dihedral angles. Seven conformers were obtained with energy difference (ΔE) minima of 11.2 – 0.0 kJ/mol. The predicted parameters listed in Table 1 correspond to the most

stable (atom numbering is listed in Scheme 2). The optimized bond lengths and angles (Table 1) agree reasonably well with those obtained by X-ray diffraction (Scheme 3) [4]. Comparing the experimental and theoretical values, the atomic distances and angles do not differ by more than 0.067 Å and 2.4(1)° (see Table 1 and Scheme 3).

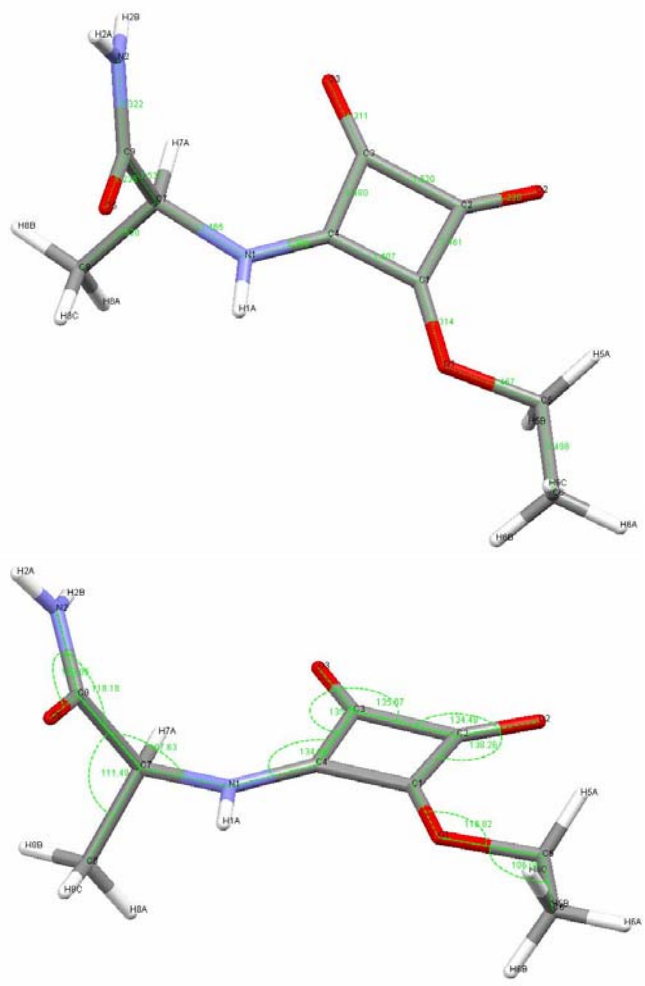


Scheme 2 Predicted geometry of 2-[(2-ethoxy-3,4-dioxocyclobut-1-en-yl)amino]propanamide.

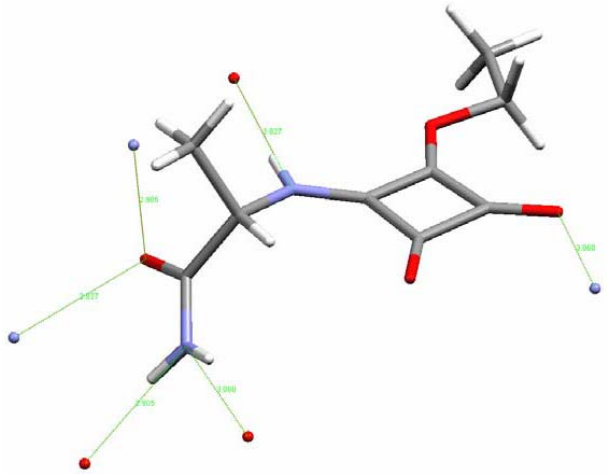
However, there is significant deviation between the dihedral angles in the gaseous and solid states. The calculated value of H-N5-C7-C8 of 1.7° differs from the solid's value of 174.7°. This deviation may be explained by strong intermolecular interactions in the solid. Similar results have been obtained for di-, and tripeptide systems as well as ester amides of squaric acid [8, 23–28]. In the latter case a series of intermolecular interactions have been crystallographically determined (Scheme 4) with participation of both amide and NH fragments N-H...O(=C) (2.827 Å), HNH...O(=C) (2.905 Å) and HNH ...O(=C) (3.060 Å), respectively.

3.2 IR-LD spectral data

Due to strong overlap in the NH- and C=O stretching regions (Fig. 1) a preliminary deconvolution and curve-fitting are required. The maxima at 3399 cm^{-1}, 3296 cm^{-1} and 3078 cm^{-1} correspond to ν^{as}_{NH2}, and ν^{s}_{NH2}split byFermi resonance due to the participation of NH_2 in asymmetric intermolecular interactions. This has been described in detail in [33]; asymmetric hydrogen bonds of the -NH_2 cause the overtone of its scissoring mode to interact with the ν^{s}_{NH2}, leading to splitting of the latter peak. The peak at 3352 cm^{-1} belongs to ν_{NH}. The other two maxima in Fig. 1 at 3220 cm^{-1} and 3175 cm^{-1} can be described as overtone and combination modes of (1610 × 2) and (1509 + 1666). In the 850 – 1500 cm^{-1} region the peaks at 1811 cm^{-1}, 1700 cm^{-1} and 1610 cm^{-1} correspond to squarate ν^{as}_{CO}, ν^{s}_{CO} and $\nu_{C=C}$frequencies, values typical for other ester amides of squaric acid and hydrogensquarates [3–12]. The peaks at 1688 cm^{-1} and 1666 cm^{-1} correspond to amide I ($\nu_{C=O}$) and amide II (δ_{NH2}) modes and the 1509 cm^{-1} to δ_{NH}, respectively.



Scheme 3 Geometric parameters of 2-[(2-ethoxy-3,4-dioxocyclobut-1-en-yl)amino]propanamide [4].



Scheme 4 Hydrogen bonds in 2-[(2-ethoxy-3,4-dioxocyclobut-1-en-yl)amino]propanamide.

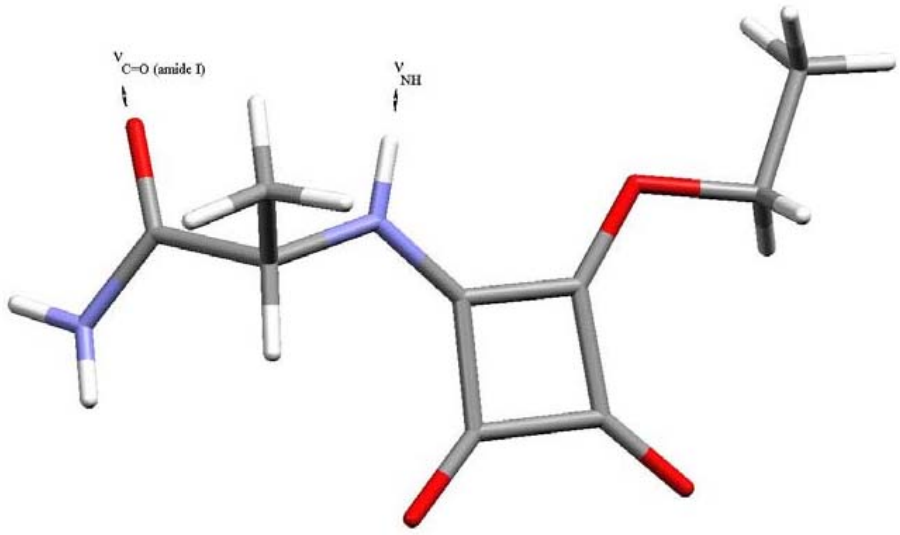
Table 1 Calculated geometry parameters as bond lengths (Å) and angles (°) of 2-[(2-ethoxy-3,4-dioxocyclobut-1-en-yl)amino]propanamide (numbering in Scheme 2).

Name	Definition	Value	Name	Definition	Value
R1	R(1,2)	1.347	R15	R(7,9)	1.371
R2	R(1,16)	0.990	R16	R(8,10)	1.524
R3	R(1,17)	0.992	R17	R(8,14)	1.203
R4	R(2,3)	1.227	R18	R(9,10)	1.463
R5	R(2,4)	1.519	R19	R(9,11)	1.342
R6	R(4,5)	1.452	R20	R(10,13)	1.210
R7	R(4,6)	1.538	R21	R(11,12)	1.461
R8	R(4,18)	1.083	R22	R(12,15)	1.509
R9	R(5,7)	1.328	R23	R(12,23)	1.080
R10	R(5,19)	0.997	R24	R(12,24)	1.080
R11	R(6,20)	1.080	R25	R(15,25)	1.083
R12	R(6,21)	1.082	R26	R(15,26)	1.082
R13	R(6,22)	1.083	R27	R(15,27)	1.082
R14	R(7,8)	1.488			
A1	A(2,1,16)	122.9(6)	A24	A(8,7,9)	91.5(9)
A2	A(2,1,17)	118.6(0)	A25	A(7,8,10)	87.3(3)
A3	A(16,1,17)	118.4(1)	A26	A(7,8,14)	134.6(5)
A4	A(1,2,3)	122.5(8)	A27	A(10,8,14)	138.0(0)
A5	A(1,2,4)	116.3(1)	A28	A(7,9,10)	94.3(7)
A6	A(3,2,4)	121.0(8)	A29	A(7,9,11)	130.9(0)
A7	A(2,4,5)	107.0(8)	A30	A(10,9,11)	134.7(1)
A8	A(2,4,6)	110.3(6)	A31	A(8,10,9)	86.6(9)
A9	A(2,4,18)	109.2(6)	A32	A(8,10,13)	136.6(0)
A10	A(5,4,6)	111.9(9)	A33	A(9,10,13)	136.7(0)
A11	A(5,4,18)	108.8(8)	A34	A(9,11,12)	119.5(1)
A12	A(6,4,18)	109.1(9)	A35	A(11,12,15)	106.6(3)
A13	A(4,5,7)	124.0(0)	A36	A(11,12,23)	108.4(1)
A14	A(4,5,19)	116.2(3)	A37	A(11,12,24)	108.4(2)
A15	A(7,5,19)	119.7(6)	A38	A(15,12,23)	112.2(4)
A16	A(4,6,20)	109.5(3)	A39	A(15,12,24)	112.2(3)
A17	A(4,6,21)	110.1(0)	A40	A(23,12,24)	108.7(3)
A18	A(4,6,22)	111.2(8)	A41	A(12,15,25)	110.0(3)
A19	A(20,6,21)	109.0(1)	A42	A(12,15,26)	110.6(2)
A20	A(20,6,22)	108.1(1)	A43	A(12,15,27)	110.5(9)
A21	A(21,6,22)	108.7(2)	A44	A(25,15,26)	108.4(9)
A22	A(5,7,8)	131.3(7)	A45	A(25,15,27)	108.4(8)
A23	A(5,7,9)	137.0(1)	A46	A(26,15,27)	108.5(3)

Table 1 (continued) Calculated geometry parameters as bond lengths (Å) and angles (°) of 2-[(2-ethoxy-3,4-dioxocyclobut-1-en-yl)amino]propanamide (numbering in Scheme 2).

Name	Definition	Value	Name	Definition	Value
D1	D(16,1,2,3)	-177.5	D30	D(5,7,8,10)	179.4204
D2	D(16,1,2,4)	4.0	D31	D(5,7,8,14)	-0.7635
D3	D(17,1,2,3)	1.0	D32	D(9,7,8,10)	0.2696
D4	D(17,1,2,4)	-177.4	D33	D(9,7,8,14)	-179.9
D5	D(1,2,4,5)	-161.9	D34	D(5,7,9,10)	-179.3
D6	D(1,2,4,6)	75.9	D35	D(5,7,9,11)	1.2
D7	D(1,2,4,18)	-44.1	D36	D(8,7,9,10)	-0.2
D8	D(3,2,4,5)	19.5	D37	D(8,7,9,11)	-179.7
D9	D(3,2,4,6)	-102.5	D38	D(7,8,10,9)	-0.2
D10	D(3,2,4,18)	137.3	D39	D(7,8,10,13)	179.7
D11	D(2,4,5,7)	161.0	D40	D(14,8,10,9)	179.9
D12	D(2,4,5,19)	-18.3	D41	D(14,8,10,13)	-0.0
D13	D(6,4,5,7)	-77.8	D42	D(7,9,10,8)	0.2
D14	D(6,4,5,19)	102.7	D43	D(7,9,10,13)	-179.7
D15	D(18,4,5,7)	43.0	D44	D(11,9,10,8)	179.6
D16	D(18,4,5,19)	-136.4	D45	D(11,9,10,13)	-0.3
D17	D(2,4,6,20)	179.6	D46	D(7,9,11,12)	179.0
D18	D(2,4,6,21)	59.8	D47	D(10,9,11,12)	-0.1
D19	D(2,4,6,22)	-60.8	D48	D(9,11,12,15)	179.8
D20	D(5,4,6,20)	60.4	D49	D(9,11,12,23)	58.7
D21	D(5,4,6,21)	-59.3	D50	D(9,11,12,24)	-59.1
D22	D(5,4,6,22)	179.9	D51	D(11,12,15,25)	179.9
D23	D(18,4,6,20)	-60.1	D52	D(11,12,15,26)	60.1
D24	D(18,4,6,21)	179.9	D53	D(11,12,15,27)	-60.1
D25	D(18,4,6,22)	59.3	D54	D(23,12,15,25)	-61.4
D26	D(4,5,7,8)	179.7	D55	D(23,12,15,26)	178.6
D27	D(4,5,7,9)	-1.4	D56	D(23,12,15,27)	58.3
D28	D(19,5,7,8)	-0.8	D57	D(24,12,15,25)	61.3
D29	D(19,5,7,9)	177.9	D58	D(24,12,15,26)	-58.4
			D59	D(24,12,15,27)	-178.7

Application of the reducing-difference procedure leads to the following results: (i) The elimination of the peak at 1688 cm^{-1} (Fig. 2.2) causes disappearance of those at 3352 cm^{-1} and 1810 cm^{-1}, due to the nearly co-linear orientation of amide I, $\nu^{s}_{C=O}$ and ν_{NH} transition moments within a single 2-[(2-ethoxy-3,4-dioxocyclobut-1-en-yl)amino]propanamide molecule (Scheme 5). (ii) The reduction of 1590 cm^{-1} along with 1666 cm^{-1}, 3296 cm^{-1} and 3078 cm^{-1} (Fig. 2.3) confirms the assumptions stated above about the origin of these maxima. The procedure leads to parallel disappearance at 798 cm^{-1} and



Scheme 5 Structure and transition moments of 2-[(2-ethoxy-3,4-dioxocyclobut-1-en-yl)amino]propanamide [4].

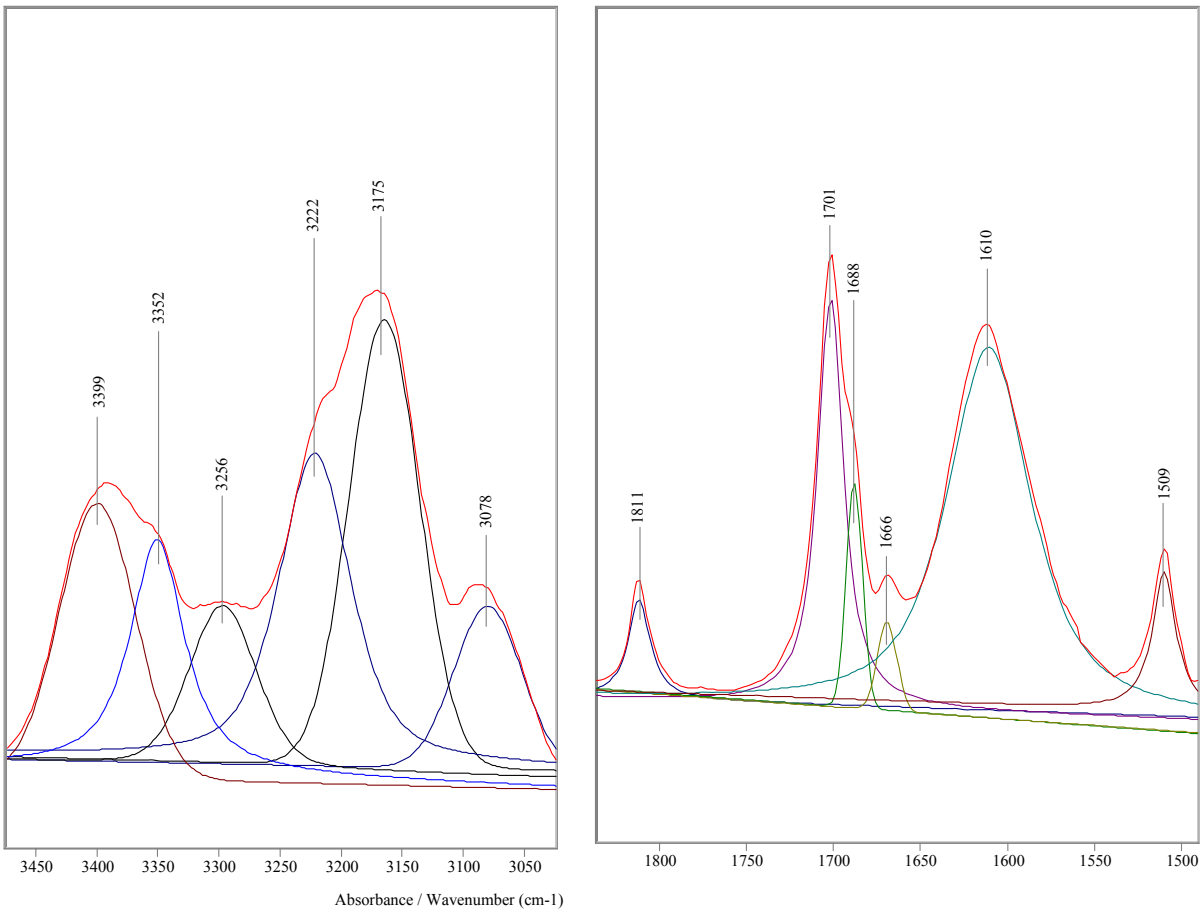


Fig. 1 Curve-fit of IR-spectrum of 2-[(2-ethoxy-3,4-dioxocyclobut-1-en-yl)amino]propanamide.

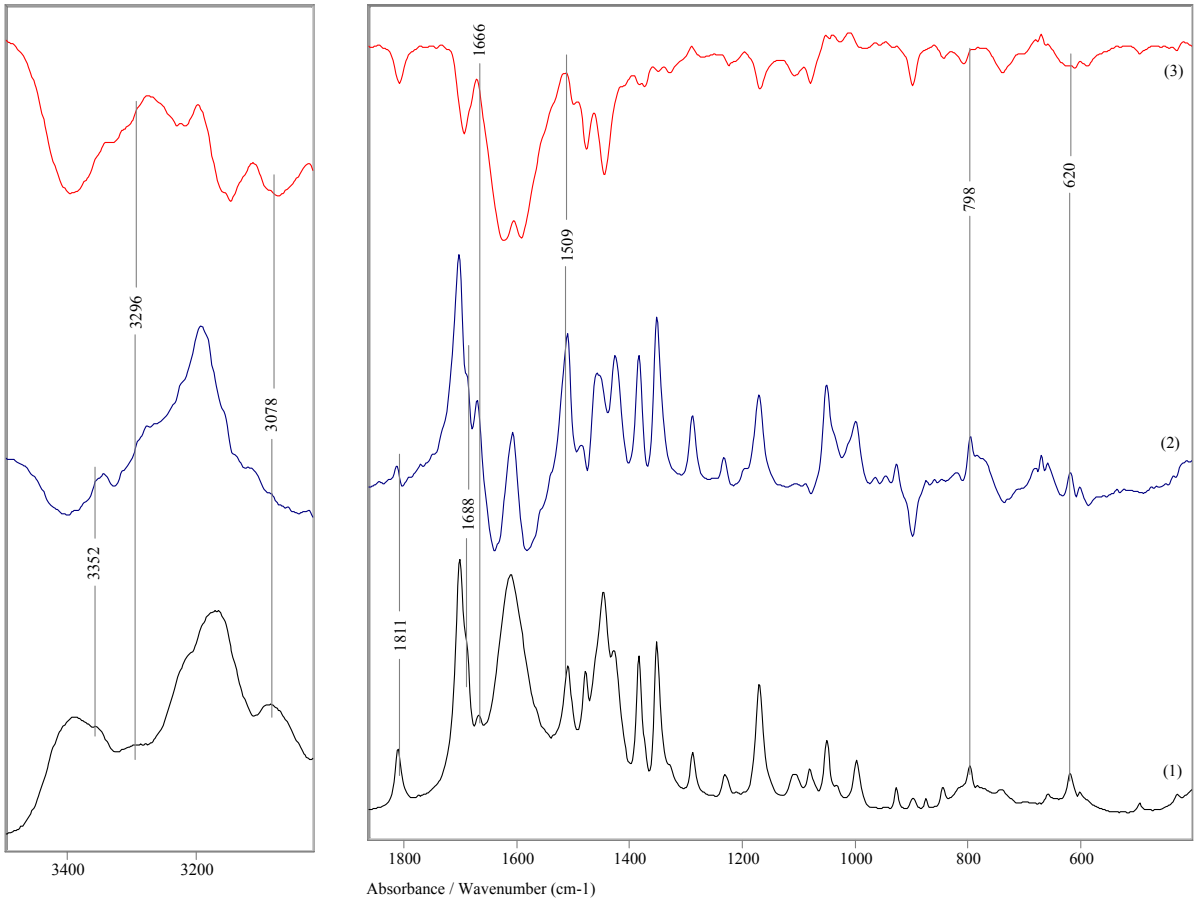
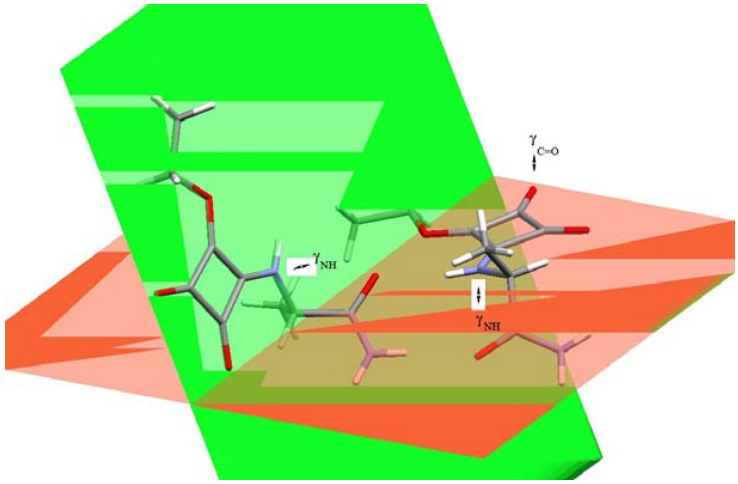


Fig. 2 Non-polarized IR-(1) and reduced IR-LD spectra of 2-[(2-ethoxy-3,4-dioxocyclobut-1-en-yl)amino]propanamide after elimination of the peaks at 1688 cm^{-1} (2) and 1509 cm^{-1} (3).



Scheme 6 Pairs of molecules in the unit cell of 2-[(2-ethoxy-3,4-dioxocyclobut-1-en-yl)amino]propanamide [4].

620 cm^{-1}, which can be assigned to $\gamma_{C=O}$ of the squarate fragment and γ_{NH}. In the the unit cell [4] the molecules are oriented at an angle of 87.3° causing a co-linearity of these transition moments (Scheme 6). These results correlate well with other amides and secondary amines [34].

This experimental confirmation of IR assignments (Table 2) as well as the additional structural information from IR-LD spectral analysis in the solid-state supports the crystallographic data in [4].

Table 2 IR assignments of 2-[(2-ethoxy-3,4-dioxocyclobut-1-en-yl)amino]propanamide.

$\nu[cm^{-1}]$	Assignment
3399	ν^{as}_{NH2}
3296, 3078	ν^{s}_{NH2}
3352	ν_{NH}
1811	$\nu^{as}_{CO(squarate fragment)}$
1700	$\nu^{s}_{CO(squarate fragment)}$
1610	$\nu_{C=C(squarate fragment)}$
1688	$\nu_{C=O}$(Amide I)
1666	δ_{NH2}
1509	δ_{NH}
798	$\gamma_{C=O}$
680	γ_{NH}

4 Conclusion

2-[(2-Ethoxy-3,4-dioxocyclobut-1-en-yl)amino]propanamide (N-alaninamidoamide of squaric acid ethyl ester) has been structurally characterized by polarized IR-LD spectroscopy of oriented crystals suspended in a nematic liquid crystal. Experimental results are compared with theoretical and single crystal X-ray data to demonstrate this approach to obtaining structural information as well as understanding the complicated IR spectra of these compounds.

References

[1] D. Chemla and J. Zyss: *Nonlinear Optical Properties of Organic Molecules and Crystals*, Vol. 1, D. Chemla, J. Zyss (Eds.), Academic Press, New York, 1988, pp. 23–187.

[2] H.S. Nalwa, T. Watanabe and S. Miyata: *Nonlinear Optics of Organic Molecules and Polymers*, H.S. Nalwa, S. Miyata (Eds.), CRC Press, Boca Raton, 1997, pp. 89–329.

[3] T. Kolev, R. Petrova and M. Spiteller: "(R)-2-[(2-Ethoxy-3,4-dioxocyclobut-1-en-1-

yl)- amino]-3 phenylpropanamide hemihydrate", *Acta Cryst.*, Vol. 60E, (2004), pp. o634–o636.

[4] T. Kolev, J. Benet-Buchholz and M. Spiteller: "Crystal structure of alaninamide ester amide of squaric acid", *Acta Crystallogr.*, (2006) submitted.

[5] T. Kolev, J. Benet-Buchholz and M. Spiteller: "Crystal structure of prolinamide ester amide of squaric acid", *Acta Crystallogr.*, (2006) submitted.

[6] T. Kolev, J. Benet-Buchholz and M. Spiteller: "Crystal structure of tryptophanamide ester amide of squaric acid", *Acta Crystallogr.*, (2006) submitted.

[7] T. Kolev, E. Cherneva, M. Spiteller, W.S. Sheldrick and H. Mayer-Figge: "L-Methioninamide ester amide of diethylsquaric acid", *Acta Crystallogr.*, Vol. E62, (2006), pp. o1390–o1392 .

[8] T. Kolev, B.B. Koleva, E. Cherneva, M. Spiteller, W.S. Sheldrick and H. Mayer-Figge: "Crystal structure, IR-LD spectroscopic, theoretical and vibrational analysis of valinamide ester amide of squaric acid", *Struct. Chem.*, (2006) in press.

[9] T. Kolev, D. Yancheva, M. Spiteller, W.S. Sheldrick and H.Mayer-Figge: "L-Prolinamidium hydrogensquarate", *Acta Cryst.* Vol. E62, (2006), pp. o463–o465.

[10] T. Kolev, M. Spiteller, W.S. Sheldrick and H. Mayer-Figge: "1-(Aminocarbonyl)ethylammonium hydrogensquarate monohydrate", *Acta Cryst.*, Vol. E61, (2006), pp. o4292–o4294.

[11] T. Kolev, M. Spiteller, W.S. Sheldrick, H. Mayer-Figge and T. van Almsick: "L-Tyrosinamide hydrochloride monohydrate", *Acta Cryst.*, Vol. E61, (2006), pp. o3819–o3821.

[12] T. Kolev, M. Spiteller, W.S. Sheldrick and H. Mayer-Figge: "L-Arginineamide bis(hydrodensquarate)", *Acta Cryst., E,* (2006), in press.

[13] Y. In, M. Fujii, Y. Sasada and T. Ishida: "Structural studies on C-amidated amino acids and peptides: Structures of hydrochloride salts of C-amidated Ile, Val, Thr, Ser, Met, Trp, Gln and Arg and corresponding C-unamidated counterparts", *Acta. Cryst.*, Vol. B57, (2001), pp. 72–81.

[14] B.A. Eipper and R.E. Mains: "Peptide alpha-amidation", *Ann. Rev. Physiol.*, Vol. 50, (1988), pp. 333–344.

[15] R. Kulathila, K.A. Merkler and D.J. Merkler: "Enzymatic formation of C-terminal amides", *Nat.Prod. Rep.*, Vol. 16, (1999), pp. 145–148.

[16] D. Merkler: "C-terminal amidated peptides: Production by the in vitro enzymatic amidation of glycine extended peptides and the importance of the amides for bioactivity", *J. Enzymme Microb. Technol.*, Vol. 16, (1994), pp. 450–458.

[17] S. Suwan, M. Isobe, O. Yamashita, H. Minakata and K. Imai: "Silkworm diapause hormones – activity relationships indispensable role of C-terminal amides", *Insect Biochem. Mol. Biol.*, Vol. 24, (1994), pp. 1001–1007.

[18] X. Xie, A.B. Comeau and C.T. Seto: "Squaric acid derivatives: A new class of protein tyrosine phosphatase inhibitors", *Org. Lett.*, Vol. 6, (2004), pp. 83–86.

[19] J.R. Porter, S.C. Archibald, K. Child, D. Critchley, J.C. Head, J.M. Linsley, T.A.H. Parton, M.K. Robinson, A. Shock, R.J. Taylor, G.J. Warrellow, R.P. Alexander and

B. Langhman: "Squaric acid derivatives as VLA-4 integrin antagonists", *Bioorg. Med. Chem. Lett.*, Vol. 12, (2002), pp. 1051–1054.

[20] M. Burak, A.B. Comeau and C.T. Seto: "Squaric acid-based peptidic inhibitors of matrix metalloprotease-1", *J. Org. Chem.*, Vol. 70, (2005), pp. 10792–10802.

[21] A.M. Gilbert, M.M. Antane, T. Argentieri, J.A. Butera, G.D. Francisco, C. Freeden, E.G. Gundersen, R. Graceffa, D. Herbst, B. Hirth, J. Lebbox, C. McFarlane, N. Wesley, D. Quagliato, J. Sheldon. D. Warga, A. Wojdan and M. Woods: "Design and SAR of Novel Potassium Channel openers targeted for urge urinary incontinance. 2. Selective and potent benzylamino cyclobutenediones", *J. Med. Chem.*, Vol. 43, (2000), pp. 1203–1214.

[22] B.B. Ivanova, M.G. Arnaudov and P.R. Bontchev: "Linear-dichroic infrared spectral analysis of Cu(I)-homocysteine complex", *Spectrochim. Acta, Part A*, Vol. 60(4), (2004), pp. 855–862.

[23] T. Kolev, B.B. Koleva, M. Emgenbroich, M. Spiteller, W.S. Sheldrick and H. Mayer-Figge: "Crystal structure and linear-dichroic infrared (IR-LD) spectral analysis of N,N'-diethyl-4-vinylbenzamidinium squarate", *Struct. Chem.*, (2006), in press.

[24] B.B. Ivanova: "Solid state linear-dichroic infrared (IR-LD) spectral characterization of α- and β-polymorphs of glycine", *Centrl. Europ. J. Chem.*, Vol. 4, (2006), pp. 111–117.

[25] B.B. Ivanova, M.G. Arnaudov and St.T. Todorov: "Linear-dichroic infrared and NMR spectral analysis of Au^{3+}-complex with the tripeptide glycyl-methionyl-glycine", *J. Coord. Chem.*, (2005) in press.

[26] B.B. Ivanova: "Stereo-structural and IR-spectral characterization of histidine containing dipeptides by means of solid state IR-LD spectroscopy and ab initio calculations", *J. Mol. Struct.*, Vol. 782, (2006), pp. 122–129.

[27] B.B. Ivanova and M.G. Arnaudov: "Solid state linear-dichroic infrared spectral and theoretical analysis of methionine containing tripeptides", *Spectrochim. Acta, Part A*, (2005), in press.

[28] B.B. Ivanova, M.G. Arnaudov, St. Todorov, W.S. Sheldrick and H. Mayer-Figge: "Structural analysis of the tripeptide glycyl-methionyl-glycine (H-Gly-Met-Gly-OH) and its hydrochloride", *Struct. Chem.*, (2005), in press.

[29] B.B. Ivanova: "IR-LD spectroscopic characterization of L-Tryptophan containing dipeptides", *Spectrochim. Acta, Part A*, (2005) in press.

[30] B.B. Ivanova, D.L. Tsalev and M.G. Arnaudov: "Validation of reducing-difference procedure for the interpretation of non-polarized infrared spectra of n-component solid mixtures", *Talanta*, Vol. 69, (2006), pp. 822–828.

[31] B.B. Ivanova, V.D. Simeonov, M.G. Arnaudov and D.L. Tsalev: "Linear-dichroic infrared spectroscopy – validation and experimental design of the orientation technique as suspension in nematic liquid crystal", *Spectrochim Acta Part A*, (2006), submitted.

[32] *DALTON, a molecular electronic structure program*, Release 2.0 (2005), http://www.kjemi.uio.no/software/dalton/dalton.html

[33] M.G. Arnaudov, B.B. Ivanova and Sh.G. Dinkov: "A linear dichroic infrared (IR-LD) solid state spectral study of 4-aminopyridine", *Vibrational Spectrosc.*, Vol. 37(1), (2005), pp. 145–147.

[34] N. Roeges: *Guide to the complete interpretation of infrared spectra of organic structures*, Wiley, New York, 1993, pp. 1–337.