

Effects of length and number of aromatic rings in carboxylic acid ligands on structure and optical properties of lead(II) coordination polymers

Alireza Hashemzadeh¹ · Mostafa M. Amini¹ · Ezzatollah Najafi² · Hamid Reza Khavasi¹

Received: 14 January 2017/Accepted: 18 April 2017 © Springer Science+Business Media Dordrecht 2017

Abstract To systematically examine the effects of the length and number of aromatic rings in carboxylic acid ligands on the structure and properties of lead(II) coordination polymers, terephthalic acid (L^1) and 4,4-biphenyl dicarboxylic acid (L^2) as primary ligands and 1-(dimethylamino)propan-2-ol (L³) as ancillary ligand were used for preparation of two new lead(II) coordination polymers: $[Pb_2L_2^1L^3(DMF)]_n$ (1) and $[PbL^{2}L^{3}]_{n}$ (2). Single-crystal X-ray diffraction analysis was used to determine the crystal structure of the prepared compounds. The results showed that the length of the π -conjugation system of the aromatic carboxylic acid ligands was a primary factor controlling the structure of the coordination compounds. Connecting Pb(II) atoms using ligands L^1 and L^3 led to formation of compound 1 with two-dimensional network structure, while use of ligands L^3 and L^2 resulted in formation of compound 2 with zigzag one-dimensional (1D) polymeric network structure. Study of the thermal behavior of the prepared compounds revealed that the structure and type of the ligands in the coordination compounds affected their thermal stability. Investigation of the optical properties of the compounds demonstrated that changing the length of the π conjugation system of the aromatic carboxylic acid ligands in the structure of the coordination compounds can be used to tune their photophysical properties.

Electronic supplementary material The online version of this article (doi:10.1007/s11164-017-2960-1) contains supplementary material, which is available to authorized users.

Mostafa M. Amini m-pouramini@sbu.ac.ir

Ezzatollah Najafi ezzat.najafi@gmail.com

¹ Department of Chemistry, Shahid Beheshti University, Tehran 1983963113, Iran

² Department of Chemistry, Payame Noor University (PNU), Tehran 19395-3697, Iran

Keywords Lead(II) coordination polymer \cdot Effect of ligand \cdot Photoluminescence \cdot Thermal behavior

Introduction

During the last two decades, great effort has been devoted to preparation of novel metal coordination compounds with multidimensional networks, which involves self-assembly of organic multitopic ligands with suitable functional groups and metallic centers. Concomitantly, this interest is also due to their unique structural topologies and potential applications in many fields, such as lasers, telecommunication technology, transistors, and optical sensors for special probes, and in bioanalysis [1–4]. Investigation of the molecular structure of a large number of coordination compounds of main and transition metal ions has shown that selection of an appropriate ligand and knowledge of the nature and number of binding modes and geometry are important to improve the molecular recognition ability of such coordination compounds. Changing the length, symmetry, and flexibility of the organic ligands provides the ability to form new classes of compounds with unique arrangements and applications [5–7].

Studies have shown that the length and number of aromatic rings of the carboxylic acid ligands can affect the coordination ability and mode of related carboxylic groups, also providing convenient conditions for formation of intra- and/ or internetwork π - π stacking and C-H- π interactions to form molecular solids, which are characterized by strong interactions between single molecular units [8–13]. These noncovalent weak interactions have been deeply investigated in the fields of structural chemistry, structural biology, and pharmaceutical science [14–18].

Due to their widespread use as ligands for synthesis of coordination polymers, the chemistry of organic carboxylic acids is considered very important. To date, many coordination compounds formed of carboxylate groups with main and transition metal ions with interesting structure and topology have been reported. Moreover, because of their conjugated π -system, coordination compounds with aromatic carboxylic acid ligands are currently of interest for development of fluorescent materials and application as model compounds for electroluminescence (EL), chemosensors, and photoinduced electron transfer (PET) sensors [19-22]. To the best of the authors' knowledge, the relationship between the length and number of aromatic rings of aromatic carboxylic acid ligands and the structure, optical properties, and thermal behavior of resulting metal coordination polymers has not been widely studied. In continuation of our interest in this direction, two new lead(II) coordination polymers with 4,4-biphenyl dicarboxylic acid and terephthalic acid ligands with different aromatic rings were synthesized in this work. The crystal structure of the prepared compounds was determined, and their optical properties and thermal behavior investigated.

Synthesis

Two new lead(II) coordination polymers were synthesized using terephthalic acid (L^1) and 4,4-biphenyl dicarboxylic acid (L^2) ligands (Scheme 1) under hydrothermal conditions. It is noteworthy that efforts to prepare crystals of compounds 1 and 2 suitable for structural analysis by X-ray diffraction were not successful. To solve this problem, 1-dimethylamino-2-propanol (L^3) was introduced as ancillary ligand into the structure of the prepared lead(II) coordination polymers. Use of this ancillary ligand led to formation of high-quality crystals suitable for structural analysis. This result shows that inclusion of ancillary ligands can be a useful approach to improve the crystal quality of coordination compounds. The crystal structure of the coordination compounds was assessed to evaluate the effects of the length and number of aromatic rings of the carboxylic acid ligands on their structure.

Characterization of lead coordination polymers 1 and 2

The structure of the prepared compounds was verified by elemental (CHN) analysis and single-crystal X-ray diffraction analysis. The distinct difference between the infrared (IR) spectra of complexes **1** and **2** and the free ligands as well as the presence of the stretching vibration bands of Pb–O at about 750 cm⁻¹ and Pb–N at about 420 cm⁻¹ unambiguously indicate coordination of the aromatic carboxylic acid ligands and 1-dimethylamino-2-propanol to Pb(II) ion. Relatively weak



Scheme 1 Line drawings of prepared lead(II) coordination polymers

stretching vibration bands of aromatic and aliphatic C–H bonds were observed in the IR spectra of the complexes in the range of 3000–3050 and 2930–3000 cm⁻¹, respectively. The Pb–O stretching vibration band appeared at wavenumber similar to values found for other lead(II) complexes [23–26].

The ¹H nuclear magnetic resonance (NMR) spectrum of complex **2** was recorded to provide information on metal-ligand binding and additional structural details in solution, while that of complex 1 was not recorded because of its insolubility in common organic solvents. The ¹H NMR spectrum of complex 2 exhibited the anticipated aliphatic and aromatic peaks with exact integration values, albeit shifted somewhat downfield in comparison with those of the free ligands. This shift can be related to electron density transfer from the ligands to the lead atom as acceptor. According to single-crystal X-ray structural analysis, both compounds crystallized in monoclinic system in space group $P2_1/c$ (Table 1). The asymmetric unit of lead(II) coordination polymer 1 has two crystallographically independent lead atoms, Pb1 and Pb2, two terephthalic acid (L^1) ligands, one 1-dimethylamino-2propanol (L^3) ligand, and one DMF molecule (Fig. 1). The coordination number of seven for Pb1 is achieved through five oxygen atoms from terephthalate and the nitrogen and oxygen atoms of chelating 1-dimethylamino-2-propanol ligand. In contrast, Pb2 is six-coordinated by five carbonyl oxygen atoms from four ligands and one oxygen atom from DMF, resulting in a different coordination environment from that of Pb1 (Fig. 1). The coordination environment of the Pb1 ion can be described as a distorted mono-capped trigonal prism, while each Pb2 cation lies at the center of a distorted octahedron.

The coordination sphere of both Pb(II) atoms resulting from the arrangement of the donor oxygen and nitrogen atoms obviously indicates an apparent vacancy, revealing that the lone pair of electrons is stereochemically active for Pb1 and Pb2 in the structure of the prepared lead(II) complex (Fig. 2). Comparison of the Pb-O bond lengths opposite versus adjacent to the putative lone pair, for both lead ions, confirms this property. As shown in Scheme 2, the terephthalate anions adopt two different coordination modes. In mode \mathbf{a} , anion L1 is coordinated to three symmetry-related Pb2 atoms in a chelating and bis-monodentate mode through carboxylate groups. In mode **b**, carboxylate groups act in hexadentate bridging mode, coordinated to one Pb2 and three symmetry-related Pb1 ions. The Pb1...Pb1 and Pb2...Pb2 distances separated by the L¹ ligand were 4.655 and 3.787 Å. The Pb–O bond length lay in the range of 2.315(18)–2.84(3) Å, while that of Pb–N was 2.73(2) Å (Table S1, Electronic Supporting Information). As analyzed using Cambridge Structure Data 2017 with the aid of Conquest (version 1.19) and Mercury (version 3.9) software (Figs. S1, S2), these values are in accordance with those reported for other Pb(II)-O and Pb(II)-N donor complexes. Comparison of these Pb–O bond distances with similar carboxylate-based ligands also reveals that these values are similar to previously reported values (Fig. S3). In the structure of the prepared complexes, weak inter- and intramolecular interactions are the principal agent controlling the packing. As shown in Fig. 1, linking of Pb atoms by L^1 ions leads to formation of two-dimensional (2D) layers. Connection between the 2D coordination layers via hydrogen-bonding interactions (Table S2) and C-H $\cdots\pi$

Complex	1	2
Empirical formula	$C_{24}H_{28}N_2O_{10}Pb_2$	C ₁₉ H ₂₁ NO ₅ Pb
Formula weight	918.88	550.57
Crystal color	Colorless	Yellow
Crystal size (mm)	$0.14 \times 0.13 \times 0.10$	$0.21 \times 0.20 \times 0.19$
Temperature (K)	298(2)	298(2)
Wavelength (Å)	0.71073	0.71073
Crystal system	Monoclinic	Monoclinic
Space group	$P2_1/c$	$P2_I/c$
<i>a</i> (Å)	11.9186 (15)	11.5003 (11)
<i>b</i> (Å)	16.642 (2)	12.1076 (11)
<i>c</i> (Å)	14.666 (2)	14.9719 (15)
β (°)	107.333 (10)	110.023 (7)
V (Å ³)	2776.8 (7)	1958.7 (3)
Ζ	4	4
Absorption coefficient (mm ⁻¹)	12.166	8.641
Calculated density (mg/m ³)	2.198	1.867
<i>F</i> (000)	1720	1056
θ range for data	1.79–27.00	1.88-29.26
Index ranges	$-15 \le h \le 15,$	$15 \le h \le 15$,
	$-21 \le k \le 21,$	$-16 \le k \le 15,$
	$-16 \leq l \leq 1$	$-20 \le l \le 16$
Reflections collected	6072	5268
Unique reflections	5861	2766
Restraints/parameters	0/332	1/241
Goodness of fit on F^2	0.916	0.884
Final <i>R</i> indices $[I > 2\sigma(I)]$	$R_1 = 0.0963, w_{R1} = 0.1939$	$R_1 = 0.0567, w_{R1} = 0.1020$
R indices (all data)	$R_2 = 0.2036, w_{R2} = 0.2310$	$R_2 = 0.1297, w_{R2} = 0.1192$

Table 1 Crystal data and refinement details for lead(II) complexes

interactions with distance of 2.867 Å (Fig. 3) led to growth of the structure of the complex into a three-dimensional (3D) coordination polymer.

The asymmetric unit of **2** contains one unique Pb(II) atom, one biphenyl-4,4'dicarboxylate (\mathbf{L}^2), and one 1-dimethylamino-2-propanol (\mathbf{L}_3) in which the Pb(II) ion is coordinated through four carboxylate oxygen atoms from \mathbf{L}^2 in a bidentate chelating coordination mode and two nitrogen and oxygen atoms from \mathbf{L}^3 (Fig. 4). Compound **2** forms a zigzag 1D polymeric network made up of a hemidirected coordination sphere of Pb(II) caused by stereochemically active lone pairs of Pb(II) with Pb… π interactions with the nearby aromatic ring (distance 3.659 Å) (Figs. 5, 6). In the chain, the Pb…Pb distance bridged by the biphenyl-4,4'-dicarboxylic acid is about 15.79 Å. Checking the Pb–O and Pb–N distances using the Cambridge Structural Database 2017 with use of Conquest (version 1.19) and Mercury (version



Fig. 1 ORTEP view of lead(II) complex 1



Fig. 2 Presence of apparent vacancy in coordination sphere of Pb1 and Pb2 in 1

3.9) software revealed that they have similar values to other Pb(II)–O and Pb(II)–N donor complexes (Table S3; Figs. S1–S3). The ligands from adjacent chains are also paired to furnish strong O–H…O and CH…O hydrogen bonds (Table S4). These interactions show a significant effect on the formation and stabilization of the three-dimensional supramolecular structure.



Fig. 3 C-H··· π interaction in complex 1







Fig. 5 Zigzag state of 1D coordination polymer 2



Fig. 6 Pb… π interactions in structure of coordination polymer 2 with hemidirected Pb(II) coordination sphere

It is clear that the only variable factor in the preparation of these compounds was the length and number of aromatic rings of the carboxylic acid ligands. The results of crystal structure analysis showed that this factor had a significant effect on the coordination number and geometry of the corresponding Pb(II) atoms in the structure of the resulting coordination polymers. These factors also influence the coordination mode of the carboxylate groups of the respective ligands. Ligands L^1 and L^2 have completely different coordination modes in the structure of compounds 1 and 2, respectively. The most important point when comparing the structure of compounds 1 and 2 is the connection of Pb(II) atoms by L^1 ligand in the structure of compound 1. This connection led to formation of one 2D supramolecular network, while the connection of lead atoms by L^2 ligand in the structure of compound 2 resulted in a zigzag 1D polymeric network. As a result, choice of a suitable ligand with intermediate flexibility, length, and several coordination sites can lead to formation of new coordination polymers with unforeseen and fascinating structure. It seems essential to choose a proper ligand in order to control the structure of the compounds for design and preparation of coordination polymers with particular structural topology. Development of such ligands opens a new horizon for research into supramolecular coordination compounds with fascinating structural topology, outstanding physical properties, and applications.

Powder X-ray diffraction analysis and thermal study of prepared coordination polymers

The high purity of the prepared compounds was confirmed by comparison of their powder X-ray diffraction patterns with those simulated from their single-crystal data (Fig. S4). Investigation of the thermal behavior of compounds used to fabricate optical devices is essential, as they must show relatively high thermal stability. To evaluate the effects of the structure and ligand of the coordination polymers on the thermal behavior, thermal analysis of the prepared compounds was performed in air atmosphere from room temperature up to 800 °C (Figs. S5, S6). Decomposition of the framework and loss of organic components from the prepared complexes resulted in an intense exothermic peak in the differential thermal analysis (DTA) curves together with significant weight loss in their thermogravimetric analysis (TGA) curves in the temperature range of 400-550 °C. The residue after thermal analysis can be attributed to formation of lead(II) oxide particles. These thermal analysis results show that the structure of coordination compounds can have a significant impact on their thermal stability. As illustrated by the thermograms in Figs. S1 and S2, coordination polymer 1 exhibited relatively better thermal stability than coordination polymer 2. Furthermore, these results show that the prepared coordination polymers had appropriate thermal stability for fabrication of optical devices such as organic light-emitting diodes (OLEDs).

Optical properties

Brief literature review reveals that control of the chemical and physical properties of materials is critical for device performance, so much effort has been made by scientists to control them [27–31]. Over the past two decades, according to increasing demand for optical devices, synthesis and design of compounds with good optical properties have attracted much attention.

Control of the optical properties of luminescent compounds is essential for preparation of optical devices to address applications effectively. Considerable efforts have already been made in this field, including the introduction of different substituents on ligands used to prepare coordination compounds, altering the central metal, and use of ancillary ligands [32-36]. In this work, to prepare coordination compounds with rare structural topology and control their optical properties, two ligands with similar structure but different π -conjugation systems, viz. 4,4-biphenyl dicarboxylic acid and terephthalic acid, were used to prepare two new lead(II) coordination polymers. The solid-state absorption spectra of the prepared coordination polymers and related ligands are shown in Fig. 7. Bands observed in the absorption spectra of the ligands can be related to spin-allowed $\pi - \pi^*$ transitions. The similar absorption spectra of the ligands and corresponding complexes reveal that the origin of the absorption is the same for both. Comparison of the absorption spectra of the ligands reveals that the absorption band of 4,4-biphenyl dicarboxylic acid is red-shifted relative to that of terephthalic acid, which could be due to the different π -conjugation length of these ligands, the only variable factor in their structures. The similar shift in the absorption spectra of the complexes indicates that



the optical properties of the ligands affect the properties of the compounds. Overall, the results show that the ligand chosen can strongly influence the optical properties of the resulting coordination compound and thereby the fabrication of optical devices.

The bandgap of the prepared compounds was calculated from the absorption edge [37] of 329 and 342 nm for compound 1 and 2, respectively (Fig. 8), yielding values of 3.77 and 3.62 eV. The wider bandgap of complex 1 relative to complex 2 shows that the absorption properties of these optical compounds can be controlled over a broad wavelength range via the length of the π -conjugation system of the ligand in their structure.

The room-temperature solid-state photoluminescence spectra showed peaks at 430 and 470 nm for complex 1 and 2, respectively (Fig. 8), corresponding to spinallowed π - π ^{*} transitions of the ligands. The maximum in the emission spectrum of complex 1, similar to the absorption spectra, showed a blue-shift relative to that of complex 2.

The absolute quantum yield of the prepared complexes 1 and 2 in solid state was 0.54 and 0.62, respectively, as calculated according to Moreno [38]. The higher quantum yield of complex 2 relative to complex 1 shows that the π -conjugation



length of the ligand is an important parameter to control the optical properties of the resulting coordination compound. The thermal stability and optical property results reveal that these complexes have good potential as fluorescent materials for preparation of luminescence devices such as light-emitting diodes.

Experimental

Materials and methods

Lead(II) nitrate, terephthalic acid (L^1), and 1-dimethylamino-2-propanol (L^2) were purchased from Sigma-Aldrich and used without further purification. All solvents were dried before use according to standard procedures [39]. Elemental analysis of compounds was carried out using a Thermo Finnigan Flash-1112EA microanalyzer. A Bomem MB-series FT-IR instrument was used to record infrared spectra. NMR spectra were obtained on a Bruker AVANCE 300 operating at 300.3 MHz. Solidstate luminescence and absorption spectra of the prepared compounds were obtained on USB2000 and Shimadzu 2100 spectrometers, respectively. X-ray diffraction patterns were obtained on a STOE diffractometer using Cu K_{α} radiation at 60 keV and 15 mA with scan rate of 3° min⁻¹. Thermal analysis (TGA) was carried out on a Bahr STA-503 instrument in air at heating rate of 10 °C min⁻¹.

Crystallographic measurements were carried out on a STOE IPDS-II diffractometer using graphite-monochromated Mo K_{α} radiation at 100 K. Unit cell parameters and orientation matrices were obtained by least-squares refinement. The structures were solved by the direct method and refined using the full-matrix leastsquares procedure on F^2 . SHELXL97 crystallographic software was used for all refinements [40].

Preparation of biphenyl-4,4'-dicarboxylic acid

Acetyl chloride (8.6 mL, 0.12 mol) was added to solution of anhydrous aluminum chloride (13.32 g, 0.1 mol) in CH₂Cl₂ (20 mL) and stirred for 20 min at 0 °C. Solution of biphenyl (6.16 g, 40 mmol) in CH₂Cl₂ (80 mL) was added to the resulting acetylating complex during 1 h at 0 °C with vigorous stirring. Stirring the resulting acetylated AlCl₃ complex for 0.5 h at 0 °C then overnight at room temperature led to formation of 1,1'-([1,1'-biphenyl]-4,4'-diyl)bis(ethan-1-one). Biphenyl-4,4'-dicarboxylic acid was obtained by reflux of the prepared diketone (5.0 g, mmol), fuming HNO₃ (10 mL), and acetic acid (100 mL) for 6 days. Biphenyl-4,4'-dicarboxylic acid was filtered and washed with water and ethanol several times, then dried at room temperature (yield 75 %, m.p. > 270°C). FT-IR (KBr, cm⁻¹): 766, 843, 1102, 1111, 1178, 1279, 1396, 1530, 1607, and 1696. ¹H NMR (300 MHz, DMSO-*d*₆): δ = 8.03, 8.06 (d, 2H), 7.85, 8.87 (d, 2H), 13.06 (s, 1H) ppm.

Synthesis of complexes 1 and 2

To prepare complex **1**, $[Pb_2L_2^1L^3(DMF)]_n$, $Pb(NO_3)_2$ (0.04 g, 0.12 mmol), and 1-(dimethylamino)propan-2-ol (1.0 mL) were added to 1:2 methanol/DMF (15.0 mL) solution of terephthalic acid (0.02 g, 0.12 mmol) in a 20-mL glass tube. The solution was transferred to a glass vessel and heated hydrothermally from room temperature to 80 °C at 2 °C/min, kept at 80 °C for 72 h, then allowed to cool to room temperature during 18 h. After filtration, yellow needle-like crystals were obtained (yield 73 %, m.p. > 270°C). Anal. Calc. (%) for $C_{24}H_{28}N_2O_{10}Pb_2$: C, 31.37; H, 3.07; N, 3.05. Found (%): C, 31.36; H, 3.06; N, 3.08. IR (KBr, cm⁻¹): 3030 (w), 2991 (w), 1664 (m), 1535 (s), 1369 (s), 818 (w), 751 (m), 429 (w). [PbL²L³]_n (2) was synthesized in the same manner but with biphenyl-4,4′-dicarboxylic acid replacing terephthalic acid (yield 80 %, m.p. > 270°C). Anal. Calc. (%) for $C_{19}H_{21}N_1O_5Pb_1$: C, 41.45; H, 3.84; N, 2.54. Found (%): C, 41.48; H, 3.82; N, 2.52. IR (KBr, cm⁻¹): 3035 (w), 2966 (w), 1662 (m), 1577 (s), 1384 (s), 851 (m), 767 (m), 414 (w). ¹H NMR (CDCl₃, ppm): 8.04, 4.35, 3.75, 2.24, 1.10, 0.07.

Conclusions

4,4-Biphenyl dicarboxylic acid was prepared to investigate the effect of the length of the π -conjugation system of aromatic carboxylic acid ligands on the structure, optical properties, and thermal behavior of two new lead(II) coordination polymers with 4,4-biphenyl dicarboxylic acid or terephthalic acid as primary ligand and 1-(dimethylamino)propan-2-ol (\mathbf{L}^3) as ancillary ligand. Study of the crystal structure of the prepared compounds revealed that the length of the π -conjugation system of the aromatic carboxylic acid ligand affected the topology of the resulting coordination compound. Differential thermal and thermogravimetric analyses revealed that the thermal behavior of the coordination compounds depended on their crystal structure. Based on the optical properties and quantum yield of the coordination compounds, it can be concluded that altering the length of the π conjugation system may represent a new approach to control their optical properties and enable their application for fabrication of optical devices.

Acknowledgement We thank the Graduate Study Councils of Shahid Beheshti University and Payame Noor University for supporting this study.

References

- 1. Y. Hanifehpour, A. Morsali, B. Soltani, B. Mirtamizdoust, S.W. Joo, Ultrason. Sonochem. 34, 519 (2017)
- 2. J.H. Lee, S.Y. Im, S.W. Lee, Polyhedron 118, 125 (2016)
- 3. S.S. Sreejith, N. Mohan, N. Aiswarya, M.R.P. Kurup, Polyhedron 115, 180 (2016)
- 4. Q. Zhou, J. Qian, C. Zhang, J. Mol. Struct. 1119, 340 (2016)
- 5. H.J. Im, S.W. Lee, Polyhedron 110, 24 (2016)

- J. Ngoune, J.J. Anguile, J. Nenwa, G. Djimassinga, C. Pettinari, E. Álvarez, L. Pandolfo, Inorg. Chim. Acta 453, 263 (2016)
- 7. R. Tatikonda, E. Kalenius, M. Haukka, Inorg. Chim. Acta 453, 298 (2016)
- 8. M. Arıcı, O.Z. Yeşilel, M. Taş, J. Solid State Chem. 245, 146 (2017)
- 9. J. Cheng, S. Wang, Z. Shi, H. Sun, B. Li, M. Wang, M. Li, J. Li, Z. Liu, Inorg. Chim. Acta 453, 86 (2016)
- 10. J.-M. Hu, R. Guo, Y.-G. Liu, G.-H. Cui, Inorg. Chim. Acta 450, 418 (2016)
- 11. K. Swarnalatha, S. Kamalesu, R. Subramanian, J. Mol. Struct. 1123, 416 (2016)
- 12. C.H. Yoder, E.L. Christie, J.L. Morford, Polyhedron 114, 23 (2016)
- T. Zhang, H.-Q. Huang, H.-X. Mei, D.-F. Wang, X.-X. Wang, R.-B. Huang, L.-S. Zheng, J. Mol. Struct. 1100, 237 (2015)
- K.A. Benavides, L.J. Treadwell, G.D. Campbell, R.N. McDougald Jr., G.T. McCandless, J.Y. Chan, Polyhedron 114, 56 (2016)
- 15. M. Chahkandi, J. Mol. Struct. 1111, 193 (2016)
- 16. F. Liu, C. Ma, D.J. McClements, Y. Gao, Food Hydrocolloids 63, 625 (2017)
- B. Naskar, R. Modak, D.K. Maiti, S.K. Mandal, J.K. Biswas, T.K. Mondal, S. Goswami, Polyhedron 117, 834 (2016)
- 18. N. Ramanathan, K. Sundararajan, K. Vidya, E.D. Jemmis, Spectrochim. Acta Part A 157, 69 (2016)
- 19. Y.-J. Wu, D.-C. Hu, X.-Q. Yao, Y.-X. Yang, J.-C. Liu, Inorg. Chim. Acta 453, 488 (2016)
- 20. L. Wang, Z.H. Yan, Z. Xiao, D. Guo, W. Wang, Y. Yang, CrystEngComm 15, 5552 (2013)
- 21. Z.H. Yan, L.L. Han, Y.Q. Zhao, X.Y. Li, X.P. Wang, L. Wang, D. Sun, CrystEngComm 16, 8747 (2014)
- 22. Y. Sun, Y. Sun, H. Zheng, H. Wang, Y. Han, Y. Yang, L. Wang, CrystEngComm 18, 8664 (2016)
- 23. L. Aboutorabi, A. Morsali, Ultrason. Sonochem. 32, 31 (2016)
- 24. L. Aboutorabi, A. Morsali, Coord. Chem. Rev. 310, 116 (2016)
- 25. T. Hajiashrafi, A. Morsali, M. Kubicki, Polyhedron 100, 257 (2015)
- 26. N.-Y. Li, W. Ma, S.-J. Wang, D. Liu, Inorg. Chem. Commun. 58, 1 (2015)
- 27. A. Hakimifar, A. Morsali, Inorg. Chim. Acta 435, 25 (2015)
- 28. T. Huang, Z.-C. Tu, H. Wang, X. Shangguan, L. Zhang, N.-H. Zhang, N. Bansal, Carbohydr. Polym. 156, 294 (2017)
- 29. Y. Li, X. Zhou, Z.L. Chen, H.H. Zou, F.P. Liang, Polyhedron 119, 505 (2016)
- R. Machado, D.A. Ochoa, V.B. dos Santos, E. Cerdeiras, L. Mestres, J.E. García, Mater. Lett. 183, 73 (2016)
- 31. L. Yang, Y. Yu, X. Wang, M. Zhu, Q. Gao, Y. Dai, Y. Bian, Inorg. Chem. Commun. 73, 30 (2016)
- 32. S. Altürk, D. Avcı, Ö. Tamer, Y. Atalay, O. Şahin, J. Phys. Chem. Solids 98, 71 (2016)
- 33. E.M. El-Menyawy, J. Alloys Compd. 683, 393 (2016)
- 34. A. Moulahi, F. Sediri, Optik (Munich, Ger.) 127, 7586 (2016)
- 35. M. Novaković, M. Popović, K. Zhang, Z. Rakočević, N. Bibić, Opt. Mater. 62, 57 (2016)
- 36. Z. Xu, Y. Li, Z. Liu, Mater. Des. 108, 333 (2016)
- 37. S. Chander, M.S. Dhaka, Mater. Lett. 182, 98 (2016)
- 38. L.A. Moreno, J. Vis. Exp. 63, 3066 (2012)
- 39. W.L. Armarego, C.L.L. Chai, *Purification of Laboratory Chemicals* (Butterworth-Heinemann, Oxford, 2013)
- 40. G.M. Sheldrich, Acta Crystallogr. A64, 112 (2008)