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Vibrational spectroscopy investigation using ab initio and density functional theory analysis on the structure of 3-(6-benzoyl-2-oxobenzo [d]oxazol-3(2H)-yl)propanoic acid

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Abstract

The molecular structure, vibrational frequencies and infrared intensities of the 3-(6-benzoyl-2-oxobenzo[d]oxazol-3(2H)-yl)propanoic acid were calculated by the HF and DFT methods using 6–31G(d) basis set. The FT-infrared spectra have been measured for the title compound in the solid state. We obtained 11 stable conformers for the title compound, however the Conformer 1 is approximately 3.88 kcal/mol more stable than the Conformer 11. The comparison of the theoretical and experimental geometry of the title compound shows that the X-ray parameters fairly well reproduce the geometry of the Conformer 1. The harmonic vibrations computed of this compound by the B3LYP/6–31G(d) method are in a good agreement with the observed IR spectral data. Theoretical vibrational spectra of the title compound were interpreted by means of PEDs using VEDA 4 program.

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1. Introduction

Pain is clinical status that human beings have been coping with for centuries. Commonly used nonsteroidal antiinflammatory drugs on the market show the same side effects to a certain extent, including gastrointestinal disorders, kidney damage and hematological toxicities. Therefore, the design of new active anti-inflammatory compounds has attracted the attention of medicinal chemists. As a result, there are many heterocyclic compounds have been investigated for anti-inflammatory activity and they are separated from the above side effects have been a challenge for many years.

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It was previously reported that various derivatives of 2-benzothiazolinone, 2-benzoxazolinone, and oxazolopyridazinone derivatives exhibit a variety of pharmacological effects, including analgesic and anti-inflammatory activity [1-8]. Early studies, 2-benzothiazolinone derivatives have been reported to be potent analgesic and anti-inflammatory agents. For instance, 6-benzoyl-2-benzothiazolinone was screened for analgesic activity and reported as a peripheral acting by release of an endogenous circulating opoid-like substance with a certain anti-inflammatory and antipyretic activity [9]. Among other 2-benzothiazolinone derivatives, tiaramide is a wellknown analgesic and anti-inflammatory agent [2,3,9–16]. Doğruer et al. reported that (2-benzoxazolinon-3-yl), (2benzothiazolinon-3-yl)acetamides [17] and 6-acyl derivatives of these acetamides [18] alleviate the induced pain and suppress the induced inflammation with no observed toxicity. Based on these reports, it is very clear that 2-benzothiazolinone structures are very important heterocyclic cores for anal-

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gesic and anti-inflammatory activity. In addition, the title compound, 3-(6-benzoyl-2-oxo-2,3-dihydro-2-benzothiazol-3-yl)propanoic acid, shows higher analgesic activity than aspirin (acetylsalicylic acid), and has an anti-inflammatory activity as good as indometacin (1-(4-chlorobenzoyl)-5-methoxy-2-methyl-1-*H*-indole-3-acetic acid) [16]. The crystal structure of 3-(6-benzoyl-2-oxobenzo[*d*]oxazol-3(2*H*)-yl)propanoic acid has been determined by X-ray diffraction [19] however so far no ab initio studies have been made on the conformation and vibrational spectra of the title compound in the gas phase.

In the present work, the ab initio studies of molecular conformation and vibrational spectra of the title compound have been made using the basis set 6–31G(d) at the HF and DFT/B3LYP levels. Using the ab initio force constants, harmonic vibrational frequencies, infrared intensities and theoretical band assignment have been calculated to interpreted the observed infrared spectra.

2. Experimental

2.1. Synthesis of

3-(6-benzoyl-2-benzothiazolinon-3-yl)propanenitrile

Acrylonitrile (12.0 mmol) was added to the solution of 6-acyl-2-benzothiazolinone derivative (10.0 mmol) and triethylamine (12.0 mmol) in 50 mL water (Scheme 1). After heating (6 h) at 50–60 °C while stirring, the mixture was stirred at room temperature for further 18 h. A solid precipitate formed which was filtered, washed with water to neutral pH, dried, and recrystallized from methanol (yield 86%), m.p. 376–377 K. Anal.



Scheme 1. Synthetic route of the title compound.

required for $C_{17}H_{12}N_2O_2S$. Calc. C, 66.22%; H, 3.92%; N, 9.08%; found C, 66.05%; H, 3.95%; N, 9.08%.

2.2. Synthesis of

3-(6-benzoyl-2-benzothiazolinon-3-yl)propanoic acid

3-(6-acyl-2-benzothiazolinon-3-yl)propanenitrile (10.0 mmol) was added to (50 mL) of a *N*,*N*-dimethylformamid/water/ sulphuric acid mixture (1:1:2). After stirring at room temperature for 2 h, the mixture was refluxed for 4 h, after cooling to the room temperature; it was poured into ice water (100 g). The precipitate formed was filtered by suction filtration, washed with water, dried, and re-crystallized from ethanol/water (yield 81%), m.p. 456–457 K, ¹H NMR (DMSO-*d*₆) δ : 12.39 (1H, s, COO*H*),



Fig. 1. The experimental and calculated (B3LYP/6-31G(d) level) FT-IR spectra of 3-(6-benzoyl-2-oxobenzo[d]oxazol-3(2H)-yl)propanoic acid.

8.11 (1H, d, 2-benzothiazolinone-H(7)), 7.74 (3H, m, 2-benzothiazolinone-H(4), benzoyl-H(3,5)), 4.22 (2H, t, N– CH_2), 2.68 (2H, t, CH_2 –CO). Anal. required for $C_{17}H_{13}NO_4S$. Calc. C, 62.37%; H, 4.00%; N, 4.28%; found C, 62.20%; H, 3.98%; N, 4.20%.

2.3. Instrumentation

Melting points were determined using an Electrothermal-9300 Digital Melting Points Apparatus (Electrothermal Inc., Essex, UK). The ¹H NMR spectra were recorded on Bruker



Conformer 11

Fig. 2. Eleven stable conformers of the title compound calculated at HF/6–31G(d) level.

Table 1
Energies of the different conformations of the title compound

Conformer	HF			B3LYP				
	<i>E</i> (a.u.)	ΔE (kcal/mol)	Dipole (debye)	<i>E</i> (a.u.)	ΔE (kcal/mol)	Dipole (debye)		
1	-1402.83586	0.00000	5.3797	-1409.52457	0.00000	5.3801		
2	-1402.83576	0.06532	1.6513	-1409.52441	0.10090	2.0635		
3	-1402.83571	0.09839	6.0643	-1409.52405	0.32731	6.8343		
4	-1402.83561	0.16158	3.2814	-1409.52394	0.39809	2.7669		
5	-1402.83542	0.28087	0.8458	-1409.52390	0.41792	0.5571		
6	-1402.83287	1.88021	5.0760	-1409.52187	1.69497	2.8439		
7	-1402.83266	2.00879	2.7728	-1409.52158	1.87381	2.6890		
8	-1402.83253	2.09488	1.1694	-1409.52131	2.04832	1.0512		
9	-1402.83218	2.31081	6.8290	-1409.52114	2.14972	6.0372		
10	-1402.82981	3.79669	2.4450	-1409.51965	3.08603	2.6065		
11	-1402.82968	3.88090	7.3375	-1409.51945	3.21084	6.4767		

400 MHz NMR spectrometer. Chemical shifts are reported in parts per million relative to internal standard tetramethylsilane. Microanalyses were performed by TÜBITAK Analytical Laboratory (Ankara, Turkey). The room temperature attenuated total reflection Fourier transform infrared (FT-IR ATR) spectrum of the 3-(6-benzoyl-2-oxobenzo[*d*]oxazol-3(2*H*)-yl)propanoic acid was recorded using Varian FTS1000 FT-IR spectrometer with Diamond/ZnSe prism (4000–525 cm⁻¹; number of scans: 250; resolution: 1 cm⁻¹) in the solid (Fig. 1).

2.4. Calculations details

The conformation analysis study was performed by Spartan 06 program package [20]. All the other calculations were performed with the Gaussian 03W program package on a double Xeon/3.2 GHz processor with 8 GB Ram [21]. The molecular structure of the title compound, in the ground state, are optimized by using HF and B3LYP methods with the standard 6–31G(d) basis set. The vibrational frequencies were also calculated with these methods. The frequency values computed at these levels contain known systematic errors [22]. Therefore, we have used the scaling factor values of 0.8953 and 0.9614 for HF and B3LYP, respectively [23–25]. The assignment of the calculated wave numbers is aided by the animation option of GaussView 3.0 graphical interface for Gaussian programs, which gives a visual presentation of the shape of the vibrational modes [26]. Furthermore, theoretical vibrational spectra of the title compound were interpreted by means of PEDs using VEDA 4 program [27].

Fig. 3. The crystal structure of the title compound, with displacement ellipsoids drawn at the 50% probability level [19].

3. Results and discussion

3.1. Conformational stability

The title compound was submitted to a rigorous conformation analysis around the free rotation bonds. This study was performed by Spartan 06 program [20]. Finally, we found that the structure of the title compound has eleven conformations. The conformers of the title compound show in Fig. 2. For comparison, the total energy and the relative energies of all of the conformer of the title compound calculated at the HF/6–31G(d) and B3LYP/6–31G(d) level of theory are given in Table 1. These relative energies clearly suggested that the Conformer 1 is so stable. Also, the comparison of the theoretical and experimental geometry of the title compound shows that the X-ray parameters fairly well reproduce the geometry of the Conformer 1 (Fig. 3). Therefore, further in this paper, we focus on this particular form of the title compound.

3.2. Molecular geometry

The optimized structure parameters of the title compound calculated by ab initio and DFT method listed in Table 2 are in accordance with atom numbering scheme given in Fig. 3. The crystal and molecular structure of the title compound have been reported previously [19]. The geometric structure is monoclinic, the space group $P2_1/c$, with the cell dimensions; a = 9.352(5) Å, b = 12.921(5) Å, c = 12.908(5) Å, $\beta = 104.370(5)^{\circ}$ and $V = 1511.0(12) \text{ Å}^3$. The structure parameters obtained by X-ray single crystal diffraction method are given in Table 2. Also, Table 2 compares the calculated geometric parameters with the experimental data. Based on this comparison, the bond lengths and angles calculated for the title compound showing good agreement with experiment. However, according to our calculations, the optimized both bond lengths and bond angles obtained by DFT method show the best agreement with the experimental values. The larges difference between experimental and calculated DFT/B3LYP-6-31G(d) bond length and bond angle is 0.042 Å and 1.12°, respectively.

The C=O and C–OH bond lengths obtained both X-ray single crystal diffraction method and theoretical calculation method

Table 2
Optimized and experimental geometries of the title compound in the ground state

Bond lengths (Å)	Experimental	Calculated		Bond angle ($^{\circ}$)	Experimental	Calculated		
		HF	B3LYP			HF	B3LYP	
S1-C10	1.743(4)	1.762	1.766	C10-S1-C14	91.44(16)	90.80	90.89	
S1-C14	1.781(4)	1.779	1.813	C11-N1-C15	125.3(3)	125.10	125.10	
O1-C7	1.226(4)	1.198	1.227	C14-N1-C15	118.5(3)	119.42	118.89	
O2-C14	1.213(5)	1.189	1.211	C11-N1-C14	116.2(3)	115.47	115.91	
O3-C17	1.198(5)	1.189	1.212	C2-C1-C6	120.2(3)	120.28	120.31	
O4-C17	1.330(5)	1.327	1.353	C1C2C3	120.3(4)	120.00	120.09	
N1-C11	1.384(5)	1.388	1.391	C2-C3-C4	120.8(4)	120.04	119.95	
N1-C15	1.471(5)	1.456	1.462	C3-C4-C5	119.2(3)	119.97	120.01	
N1-C14	1.379(5)	1.370	1.390	C4-C5-C6	120.7(3)	120.36	120.48	
C1-C2	1.384(5)	1.386	1.395	C1C6C5	118.8(3)	119.33	119.13	
C1-C6	1.394(4)	1.390	1.403	C5-C6-C7	118.3(3)	117.94	117.69	
C2-C3	1.359(5)	1.384	1.395	C1-C6-C7	122.6(3)	122.62	123.04	
C3-C4	1.392(5)	1.387	1.398	O1-C7-C6	119.1(3)	119.85	119.68	
C4-C5	1.381(5)	1.382	1.391	C6-C7-C8	121.3(2)	120.58	120.72	
C5-C6	1.393(5)	1.392	1.404	O1-C7-C8	119.5(3)	119.58	119.60	
C6-C7	1.492(4)	1.500	1.500	C7-C8-C9	117.8(2)	117.56	117.15	
С7—С8	1.484(5)	1.499	1.498	C7-C8-C13	123.4(3)	123.07	123.39	
C8–C9	1.398(5)	1.395	1.406	C9-C8-C13	118.7(3)	119.24	119.31	
C8-C13	1.400(4)	1.389	1.404	C8-C9-C10	119.6(3)	119.40	119.54	
C9-C10	1.384(5)	1.372	1.384	S1-C10-C9	128.3(2)	128.04	127.93	
C10-C11	1.405(4)	1.396	1.412	C9-C10-C11	120.4(3)	121.09	120.86	
C11-C12	1.379(5)	1.383	1.397	S1-C10-C11	111.3(3)	110.87	111.20	
C12-C13	1.376(5)	1.387	1.394	N1-C11-C12	127.6(3)	127.13	127.10	
C15-C16	1.509(5)	1.526	1.532	C10-C11-C12	120.2(3)	119.98	119.93	
C16-C17	1.491(5)	1.506	1.533	N1-C11-C10	112.2(3)	112.90	112.97	
r		0.9966	0.9969	C11-C12-C13	119.1(3)	118.74	118.94	
				C8-C13-C12	121.9(3)	121.52	121.38	
				S1-C14-O2	125.1(3)	124.66	125.42	
				O2-C14-N1	126.0(3)	125.40	125.58	
				S1-C14-N1	108.9(2)	109.95	108.99	
				N1-C15-C16	112.2(3)	111.68	111.90	
				C15-C16-C17	111.0(3)	111.68	111.32	
				O3-C17-C16	124.4(4)	125.17	125.31	
				O4-C17-C16	112.8(3)	112.04	111.68	
				O3-C17-O4	122.8(4)	122.08	123.01	
				r		0.9964	0.9973	

in this study are characteristic of a typical carboxylic group in carboxylic acids. As expected, the hydroxyl proton in the carboxylic acid group is in the *cis* orientation. It is involved in a weak–strong hydrogen bond with the O2 atom (O4–H40···O2^{*i*}; O4–H40: 0.82 Å, H40···O2: 1.90 Å, O4···O2: 2.723(4) Å, 04–H40···O2: 176°, *i*: 1 - x, 1/2 + y, 3/2 - z) (Fig. 4). This hydrogen bond does not lead to any significant distortion of the carboxylic group geometry in the solid form. Similar results are observed in the theoretical calculations (Table 2).

3.3. Vibrational assignments

Table 3 lists the wavenumbers of the bands observed in the FT-IR spectra of the 3-(6-benzoyl-2-oxobenzo[d]oxazol-3(2H)-yl)propanoic acid. The theoretical frequencies and infrared intensities calculated by HF and hybrid DFT(B3LYP) methods of the title compound are gathered in Table 3. The last column of Table 3 shows the detailed vibrational assignment obtained from the calculated potential energy distribution (PED).

Comparison of the frequencies calculated at HF and B3LYP with experimental values reveals the overestimation of the calculated vibrational modes due to neglect of anharmonicity in real system. Inclusion of electron correlation in density functional theory to a certain extend makes the frequency values smaller in comparison with the Hartree–Fock frequency data. Reduction in the computed harmonic vibrations, though basis set sensitive are only marginal as observed in



Fig. 4. The hydrogen bond in the crystal structure of the title compound.

Table 3
Vibrational wavenumbers obtained for the title compound at 6-31G(d) level ^a

Number Experimental		HF				B3LYP				Assignments, PED (%) ^b	
		Wave numb	ber	IR intensit	y	Wave number IR intensi		IR intensit	y		
		Unscaled	Scaled ^c	Absolute	Relative	Unscaled	Scaled ^d	Absolute	Relative		
1	3454	4050	3626	139	25	3685	3543	56	9	ν _{OH} , 100	
2	3113	3410	3053	1	0	3231	3107	4	1	v _{CH} , R2, sym, 97	
3	3098	3409	3052	6	1	3228	3103	1	0	$\nu_{\rm CH}$, R2, asym, 90	
4	3098	3406	3049	7	1	3227	3102	8	1	v _{CH} , R1, svm, 97	
5	3098	3395	3040	11	2	3219	3095	9	1	V _{CH} , R1, asym. 83	
6	3084	3392	3037	9	2	3212	3088	8	1	$v_{\rm CH}$ R2 asym 94	
7	3084	3385	3031	44	8	3209	3085	36	6	$\nu_{\rm CH}, R2, asym, 91$	
8	3067	3374	3021	11	2	3108	3075	11	2	$\nu_{\rm CH}, R1, asym, 05$	
0	3053	3367	3010	0	0	3197	3064	0	0	$\nu_{\rm CH}, R1, asym, 95$	
10	3028	3354	3003	5	1	3168	3046	3	0	$\nu_{\rm CH}, {\rm KI}, {\rm asym}, {\rm 70}$	
10	2021	2201	2055	10	2	2119	2008	3	1	$\nu_{\rm CH}, C15, asym, 97$	
12	2981	2281	2935	10	2	2112	2996	2	1	$\nu_{\rm CH}$, C15 sym, C16 asym, 98	
12	2961	2221	2937	2	1	2064	2992	2	1	$\nu_{\rm CH}$, C15 sym, C10 asym, 97	
13	2939	3231	2893	0	1	3064	2946	4	1	$\nu_{\rm CH}$, C16 sym, 99	
14	1731	2027	1815	375	0/	1841	1770	251	38	$\nu_{\rm C=0}, 03, 85$	
15	1729	1959	1/54	564	100	1806	1/36	654	100	$\nu_{\rm C=0}, 02, 88$	
16	1642	1954	1749	548	97	1734	1667	148	23	$\nu_{\rm C=0}, 01, 86$	
17	1596	1809	1620	23	4	1658	1594	22	3	$\nu_{\rm C=C}, {\rm R1}, 40$	
18	1588	1799	1611	137	24	1646	1583	142	22	$\nu_{\rm C=C}, {\rm R}2, 42$	
19	1575	1781	1595	5	1	1636	1573	12	2	$\nu_{\rm C=C}, R1, 47 + \delta_{\rm CCC} 10$	
20	1557	1770	1585	52	9	1620	1557	41	6	$\nu_{\rm C=C}, R2, 61$	
21	1480	1670	1495	9	2	1538	1479	0	0	$\delta_{\rm CH}, R1, 55$	
22	1471	1661	1487	83	15	1525	1466	52	8	$\nu_{\rm CN}, 14 + \delta_{\rm CH}, 30$	
23	1449	1645	1473	24	4	1514	1455	22	3	δ_{CH} , sciss, C15, 80	
24	1424	1617	1448	19	3	1495	1437	6	1	δ_{CH} , sciss, C16, 88	
25	1416	1612	1443	25	5	1490	1433	19	3	δ _{CH} , R1, 53	
26	1404	1595	1428	133	23	1460	1404	25	4	$\nu_{\rm C=C}, R2, 45$	
27	1379	1580	1415	10	2	1447	1391	64	10	$\delta_{\rm CH}$, wagg, C15, C16, 25	
28	1366	1529	1369	155	27	1422	1367	131	20	$\nu_{\rm CN}, 17 + \delta_{\rm CH}, R2, 27$	
29	1326	1516	1357	19	3	1393	1339	14	2	ν_{C-O} , 14 + δ_{COH} , 15 + δ_{CH} , C15, wagg, 29	
30	1318	1474	1320	25	4	1369	1316	8	1	$\nu_{C=C}$, R1, 35 + δ_{CH} , R1, 50	
31	1314	1471	1317	151	27	1366	1313	75	11	$\delta_{\rm CH}, R2, 50 + \delta_{\rm CNC}, 11$	
32	1303	1440	1289	3	1	1350	1298	31	5	$\nu_{C=C}$, R1, 22 + δ_{CH} , R1, 11	
33	1295	1425	1276	11	2	1343	1291	52	8	$\delta_{\rm CH}$, twist, C15, 54	
34	1267	1409	1261	399	71	1317	1266	26	4	δ _{CH} , R2, 55	
35	1256	1382	1237	126	22	1306	1256	18	3	δ_{COH} , 34 + δ_{CH} , wagg, C15, C16, 29	
36	1243	1345	1204	7	1	1293	1243	506	77	$\nu_{\rm C=C}, 39$	
37	1224	1332	1193	6	1	1265	1216	68	10	$\delta_{\rm CH}$, wagg, C16, 28	
38	1172	1309	1172	317	56	1213	1166	35	5	$\delta_{\rm CH}, R1, 73$	
39	1163	1303	1167	22	4	1204	1157	42	6	$v_{C=C}$, R2, 14 + δ_{CH} , R2, 11	
40	1144	1289	1154	153	27	1192	1146	1	0	δ _{CH} , R1, 77	
41	1137	1279	1145	31	5	1184	1139	107	16	$\nu_{C=C}$, R2, 14 + δ_{CH} , R2, 18	
42	1130	1240	1110	3	1	1178	1133	191	29	$v_{C-0}, 31 + \delta_{COH}, 17$	
43	1114	1227	1099	9	2	1162	1117	89	14	δ _{CH} , R 2, 20	
44	1081	1211	1084	4	1	1114	1071	3	0	v_{C-C} R1 38 + δ_{CH} R1 12	
45	1063	1185	1061	1	0	1112	1069	4	1	$\delta_{\rm CH}$ rock C16 33	
46	1041	1157	1036	13	2	1069	1028	8	1	$V_{\rm CH}$, 100k, 210, 55	
47	1026	1150	1030	6	1	1060	1019	8	1	$\nu_{\rm C-C}$, C15–C16, 19 + $\delta_{\rm CH}$,	
18	1018	1135	1016	0	0	1058	1017	3	1	rock, C15, C16, 20	
40	1018	1133	1010	2	0	1038	082	18	3	$V_{C=C}, R1, 57$	
50	088	11152	000	0	2	1021	980	10	0	δ_{coc} 65 + ν_{c} a R 1 11	
51	963	1114	007	3	0	1007	060	2	0	$v_{\rm cu}, 0.5 + v_{\rm =0}, {\rm R}_{1}, {\rm H}_{1}$	
52	944	1005	080	0	0	087	0/0	∠ 18	3	$\gamma_{\rm CH}, {\bf R}_1, 0.5$	
53	044	1095	077	3	1	082	045	31	5	γCH , $K1$, 21	
55	9 44 011	1072	911	5 11	1	90J 066	020	31 1	5	$\gamma_{\rm CH}, \mathbf{N}_1, 2_2$	
J4 55	911	1073	901	11	ے ج	900	928	1	1	$\gamma_{\rm CH}, \kappa_1, \kappa_2, \delta_0$	
33 50	911	1035	945	3U 2C	5	951	915	5	1	$\gamma_{\rm CH}, \kappa_1, \kappa_2, 13$	
50	880	1042	933	20	5	929	893	12	2	$\gamma_{\rm CH}$, C9, 75	
57	881	995	891	11	2	914	8/9	11	2	ν _{C-C} , C16–C17, 28	
58	860	970	868	12	2	888	853	20	3	v _{C-C} , C16–C17, 23	

Table 3 (Continued)

Number	Experimental	HF				B3LYP				Assignments, PED (%) ^b	
		Wave numb	ber	IR intensity	y	Wave number		IR intensit	y		
		Unscaled	Scaled ^c	Absolute	Relative	Unscaled	Scaled ^d	Absolute	Relative		
59	835	966	865	1	0	872	838	3	0	γ _{CH} , R1, 96	
60	793	939	841	18	3	839	807	10	2	γ _{CH} , R2, 59	
61	786	895	801	20	4	811	780	15	2	γ _{CH} , R1, R2, 57	
62	763	865	774	9	2	798	767	8	1	δ_{CH} , rock, C15, C16, 22	
63	732	835	748	54	10	766	736	36	6	$\delta_{\rm CCC}, {\rm R2}, 65 + \gamma_{\rm C}, 10$	
64	710	822	736	54	9	745	717	36	5	$\gamma_{\rm CH}, 10 + \gamma_{\rm C}, 28$	
65	704	792	709	37	7	719	692	22	3	$\delta_{\text{CCC}}, 21 + \gamma_{\text{CH}}, 11$	
66	696	773	692	6	1	714	687	18	3	$\delta_{\text{CCC}}, 19$	
67	682	769	688	11	2	704	677	2	0	$\delta_{\rm CCC}, 44 + \gamma_{\rm C}, 10$	
68	661	745	667	20	4	685	659	106	16	$\delta_{\text{CCC}}, 11 + \gamma_{\text{CH}}, 10$	
69	650	734	657	37	6	682	656	10	1	$\gamma_{\rm OH}, 53 + \gamma_{\rm C}, C17, 17$	
70	639	715	640	25	5	661	635	30	5	$\gamma_{\rm OCO}, 22 + \gamma_{\rm C}, C14, 21$	
71	620	709	635	113	20	644	619	5	1	$\gamma_{\rm OCO}, 12 + \gamma_{\rm C}, C14, 64$	
72	608	677	606	1	0	631	606	1	0	$\delta_{\text{CCC}}, \text{R1}, 78$	
73	578	660	591	1	0	610	587	2	0	$\delta_{\text{CCC}}, 12$	
74	541	618	553	70	12	571	549	67	10	$\delta_{\text{OCO}}, 25 + \delta_{\text{CCC}}, 14$	
75	528	593	531	13	2	549	528	9	1	γ _C , C11, 64	
76	_	575	515	27	5	535	515	26	4	$\delta_{\text{CNC}}, 15 + \delta_{\text{CCC}}, 14$	
77	-	570	510	25	4	532	511	13	2	$\tau_{\rm OH}, 29 + \gamma_{\rm C}, C17, 31$	
78	_	556	498	34	6	512	492	25	4	$\nu_{\rm CS}$, 23 + $\delta_{\rm SCC}$, 19 + $\delta_{\rm CCC}$, 23	
79	_	509	456	7	1	465	447	11	2	$\delta_{\text{OCC}}, 48 + \delta_{\text{CCN}}, 18$	
80	-	501	449	12	2	457	439	11	2	$\delta_{\text{SCC}}, 31 + \delta_{\text{OCS}}, 17 + \delta_{\text{CCC}},$ 11	
81	_	483	432	4	1	446	428	3	0	$\tau_{\rm CC}, 18 + \gamma_{\rm C}, 13$	
82	-	477	427	5	1	437	420	4	1	$\tau_{\rm CC}, 27 + \gamma_{\rm C}, 24$	
83	-	458	410	0	0	422	405	1	0	$\tau_{\rm CH}, 30 + \tau_{\rm CC}, 56$	
84	_	421	377	2	0	392	377	1	0	$\nu_{\rm CC}, {\rm C6-C7}, 18 + \delta_{\rm OCC}, 18$	
85	_	395	354	7	1	365	351	4	1	$\delta_{\rm CNC}, 10$	
86	-	375	336	4	1	345	332	3	0	δ_{OCS} , 17 + δ_{CNC} , 16	
87	-	332	297	1	0	304	292	1	0	$\delta_{\rm NCC}, 14 + \delta_{\rm CNC}, 25$	
88	_	288	258	4	1	271	260	4	1	$\delta_{CCC}, 23$	
89	-	251	225	2	0	235	225	1	0	$v_{\rm CC}, 16$	
90	_	215	192	1	0	198	191	1	0	$\tau_{\rm CC}, 38 + \gamma_{\rm C}, 15$	
91	_	199	178	0	0	187	180	0	0	$\tau_{\rm CC}, 20$	
92	_	186	167	4	1	177	170	4	1	δ_{OCC} , 14 + δ_{CCC} , 42	
93	_	177	158	2	0	164	157	1	0	$\delta_{CCC}, 28$	
94	_	141	126	0	0	131	126	0	0	$\tau_{\rm CN}, 35 + \gamma_{\rm C}, 12$	
95	_	106	95	3	1	96	92	4	1	$\tau_{\rm CN}, 22 + \tau_{\rm CC}, 11 + \nu_{\rm C}, 13$	
96	_	96	86	2	0	85	81	0	0	$\tau_{\rm CC}, 42$	
97	_	81	73	0	0	75	73	0	0	$\tau_{\rm CC}, 29 + \gamma_{\rm C}, 12$	
98	_	53	47	1	0	52	50	0	0	$\delta_{CCC}, 35 + \tau_{CC}, 39$	
99	_	38	34	1	0	38	36	1	0	$\tau_{\rm CC}, 35 + \nu_{\rm N}, 36$	
100	_	33	30	2	0	36	35	1	Õ	$t_{\rm CC}, 53 + \gamma_{\rm N}, 11$	
101	_	29	26	0	0	26	25	0	0	tcc. 86	
102	-	22	20	0	0	18	17	0	0	$\delta_{\rm CNC}, 11 + \tau_{\rm CC}, 11 + \tau_{\rm CN}, 49$	

^a Harmonic frequencies (in cm⁻¹) and IR intensities (km mol⁻¹).

^b ν , stretching; δ , in-plane bending; γ , out-of-plane bending; τ , torsion; sym, symmetric; asym, asymmetric; R1: C7–C8–C9–C10–C11–C12; R2: C14–C15–C16–C17–C18–C19; PED less than 10% are not shown.

^c Scaling factor = 0.8953.

^d Scaling factor = 0.9614.

the DFT values using 6-31G(d). Any way not withstanding the level of calculations, it is customary to scale down the calculated harmonic frequencies in order to improve the agreement with the experiment. Therefore, in our study, we have used the scaling factor values of 0.8953 for calculated wave numbers for HF and 0.9614 for calculated wave numbers for B3LYP method [23–25]. Experimental fundamentals are in better agreement with the scaled fundamentals which are found to have a good correlation for DFT/B3LYP (r=0.9999) than HF method. The calculated frequencies (scaled) do not differ so much from the experimental ones that the maximum difference between two spectra is not more than 24 cm^{-1} (except $v_{\text{O-H}}$ and $v_{\text{C=O}}$) for DFT/B3LYP method. Also, the average absolute error of the calculated frequencies was found less than 0.7% for DFT/B3LYP method.

In order to investigate the performance and vibrational frequencies for the title compound, the mean deviation, mean absolute deviation, average absolute error, root mean square value and correlation coefficient between the calculated harmonic and observed fundamental vibrational frequencies for each method were also calculated and given in Table 4. The root mean square (RMS) values were obtained in this study using the following expression [28]:

$$\text{RMS} = \sqrt{\frac{1}{n-1} \sum_{i}^{n} (\nu_i^{\text{calc}} - \nu_i^{\text{exp}})^2}$$

These results indicate that the B3LYP calculations approximate the observed fundamental frequencies much better than the HF results. The small difference between experimental and calculated vibrational modes is observed. It must be due to the fact that hydrogen bond vibrations present in crystal lead to strong perturbation of the infrared frequencies (and intensities) of many other modes. Also, we state that the experimental results belong to solid phase and theoretical calculations belong to gaseous phase.

 v_{O-H} stretching vibration occurs in the region 3500- 3000 cm^{-1} . The IR band appearing at 3454 cm^{-1} is assigned to v_{O-H} stretching mode of vibrations. This vibration mode calculated at 3543 and 3626 cm^{-1} (scaled) for DFT and HF methods, respectively. The difference between experimental and calculated v_{O-H} stretching mode is about 89 cm⁻¹ (DFT/B3LYP) and 172 cm^{-1} (HF). This striking discrepancy can come from the formation of intermolecular hydrogen bonding with O-H because the crystal structure of the title compound has an intermolecular O4–H40···O2^{*i*} (*i*: 1 - x, 1/2 + y, 3/2 - z) hydrogen bonds (Fig. 4). OH out-of-plane bending occurs between 875 and 975 cm^{-1} . Theoretically computed value of 650 cm^{-1} (DFT) is not in good agreement for OH out-of-plane bending vibration for the title compound. In the same way, this discrepancy is come from the formation of intermolecular hydrogen bonding (O4-H40...O2).

The characteristic ν_{CH} stretching vibrations of heteroaromatic structure are expected to appear in 3000–3100 cm⁻¹ frequency ranges. The ν_{CH} stretching vibrations of the title

Table 4

Mean deviation, mean absolute deviation, average absolute error, correlation coefficient and root mean square values between the calculated and observed fundamental vibrational frequencies for different scaling factor values

Scaling factor	HF		DFT/B3L	DFT/B3LYP		
	1.0000	0.8953	1.0000	0.9614		
Mean deviation	174.32	6.20	60.68	2.94		
Mean absolute deviation	174.32	25.91	60.68	8.00		
Average absolute error	12.70	1.79	4.16	0.60		
RMS _{mol}	196.18	37.20	72.61	14.00		
RMSover	168.23	31.90	62.27	12.00		
r	0.9991	0.9991	0.9999	0.9999		

compound were assigned to five bands observed at 3113, 3098, 3084, 3067, and 3053 cm^{-1} in the infrared spectrum. The B3LYP calculated wavenumbers of these bands very well reproduced the experimental ones. The difference between experimental and calculated ν_{CH} is about 6, 3, 4, 8, and 11 cm^{-1} .

Three more bands at 3028, 2981 and 2939 cm⁻¹ were observed in the spectrum. First band is asymmetric v_{C-H} stretching band for C15 atom, the second band is a mix band as symmetric and asymmetric v_{C-H} stretching band for -CH₂-groups, and the last band is symmetric v_{C-H} stretching band for C16 atom. These assignments were also supported by the literature [29,30]. The in-plane and out-of-plane bending vibrations of C–H group have also been identified for the title compound and they are presented in Table 3.

The identification of ν_{C-N} vibrations as a difficult task since the mixing of vibrations is possible in this region. However, with the help of theoretical calculations (VEDA 4) the ν_{C-N} vibrations are identified and assigned in this study. The infrared bands appearing at 1471 and 1366 cm⁻¹ were designated to ν_{C-N} stretching vibrations.

The vibrational modes concerning the bond angle bending (HCH): scissoring, wagging, twisting and rocking are well defined in all the calculations. As seen from Table 3, the bands observed at 1449 and 1424 cm⁻¹ in FT-IR spectrum correspond to scissoring deformation of $-C(15)H_2$ and $-C(16)H_2$ group in the title compound, respectively [31,32]. The theoretically computed values of scissoring deformation vibration modes show a good agreement with the experimental values. The wagging, twisting and rocking vibrational modes are distributed in a wide range [31-34]. Twisting and wagging vibrational modes of the -CH2- groups were assigned in the range of $1375-1224 \text{ cm}^{-1}$. The above result is in close agreement with the literature values [31–35]. These vibrational modes are described in the tables by mean of the general symbol δ_{CH} . The infrared bands in this region are superposed with very intensive bands. The rocking -CH2- is assigned in the wavenumber range of $1060-760 \text{ cm}^{-1}$ and the wavenumber shift of these bands is due to the atom nature in which the $-CH_2$ -group is bonded. The -CH₂-rocking vibrational modes are intensive bands in which can be appreciating the vibrational coupling with other vibrational modes [32,33]. These bands are assigned using calculated potential energy distribution.

The characteristic region of the benzoxazol derivatives spectrum is $1500-1650 \text{ cm}^{-1}$ like as benzimidazole derivatives. The vibrational frequencies and intensities for all substituted benzoxazol derivatives in this range differ from the position of the substituent [36]. Generally, two bands observed in $1500-1650 \text{ cm}^{-1}$ range for benzoxazol derivatives. The observed vibrational frequencies (1588 and 1557 cm^{-1}) are generally intense because of the conjugation between the benzene and imidazole rings. Also, we obtained another vibrational frequency at 1596 and 1575 cm^{-1} which is come from 6-benzoyl substitute group. The vibrational spectra of benzoxazol derivatives show a very intensive band around the 700 cm⁻¹. This vibrational mode is the most intensive in this region. It may be ascribed to the out-of-plane γ_{CH} bending frequency.

fore, the infrared band appearing at 700 cm^{-1} was designated to out-of-plane γ_{CH} bending vibration. This result confirmed by Sullivan [37].

4. Conclusion

The frequency assignment for the 3-(6-benzoyl-2oxobenzo[d]oxazol-3(2H)-yl) propanoic acid which is a benzoxazol derivatives have been done for the first time from the FT-IR spectrum recorded for this compound. The conformation stability, equilibrium geometries and harmonic frequencies of the title compound were determined and analyzed both at HF and DFT level of theories utilizing 6-31G(d) basis set. The difference between the observed and scaled wave number values of most of the fundamentals is very small. Any discrepancy noted between the observed and the calculated frequencies may be due to the fact that the calculations have been actually done on a single molecule in the gaseous state contrary to the experimental values recorded in the presence of intermolecular interactions. The IR spectrum of the title compound was interpreted in terms of the potential energy distribution (PED) analysis.

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References

- M.C. Bermann, J.P. Bonte, I. Lesieur-Demarquilly, M. Debaert, D. Lesieur, M. Leinot, J. Benoit, C. Labrid, Eur. J. Med. Chem. 17 (1982) 85.
- [2] C. Şafak, H. Erdoğan, E. Palaska, R. Sunal, S. Duru, J. Med. Chem. 35 (1982) 1296.
- [3] T. Takashima, Y. Kadoh, S. Kumada, Arzneim. -Forsch. 22 (1972) 711.
- K. Tsurumi, Y. Hiramatsu, M. Nozaki, M. Hayashi, H. Fujimura, Arzneim.
 -Forsch. 22 (1972) 716.
- [5] M.C. Vinaud, P. Jamoneau, C. Flouzat, J.G.B. Espiard, B. Pfeiffer, P. Renard, D.H. Caignard, G. Adam, G.J. Guillaumet, J. Med. Chem. 38 (1995) 1278.
- [6] D.S. Doğruer, M.F. Şahin, S. Ünlü, S. Ito, Arch. Pharm. Pharm. Med. Chem. 333 (2000) 79.
- [7] P. Renard, D. Lesieur, C. Lespagnol, M. Cazin, C. Brunet, J.C. Cazin, Eur. J. Med. Chem. Chim. Ther. 15 (1980) 453.
- [8] B. Gong, F. Hong, C. Kohm, L. Bonham, P. Klein, Bioorg. Med. Chem. Lett. 14 (2004) 1455.
- [9] S.H. Fereira, B.B. Lorenzetti, M. Devissaguet, D. Lesieur, Y. Tsouderos, Br. J. Pharmacol. 114 (1995) 303.
- [10] S. Ünlü, H. Erdoğan, R. Sunal, H.Ü. J. Fac. Pharm. 12(1) (1992) 23.
- [11] S. Ünlü, H. Erdoğan, R. Sunal, B. Gümüşel, H.Ü. J. Fac. Pharm. 12(1) (1992) 75.
- [12] H. Erdoğan, S. Ünlü, Arch. Pharm. 322 (1989) 75.
- [13] K. Tsurumi, Y. Hiramatsu, M. Nozaki, M. Hayashi, H. Fujimura, Arzneim. -Forsch. 22 (1972) 724.
- [14] Fujisawa Pharmaceutical Co. Ltd., Jpn. Kokai Tokkyo Koho JP 59 53,475; 84 53,475. 1984 Chem. Abstracts, 1984, 101, 90983d.

- [15] H. Nakamura, A. Shimoda, K. Ishii, T. Kadokawa, Arch. Int. Pharmacodyn. 282 (1986) 16.
- [16] S. Ünlü, T. Önkol, Y. Dündar, B. Ökçelik, E. Küpeli, E. Yeşilada, N. Noyanalpan, M.F. Şahin, Arch. Pharm. Pharm. Med. Chem. 336 (2003) 353.
- [17] D.S. Doğruer, S. Ünlü, E. Yeşilada, M.F. Şahin, Il Farmaco 52 (1997) 745.
- [18] D.S. Doğruer, S. Ünlü, M.F. Şahin, E. Yeşilada, Il Farmaco 53 (1998) 80.
- [19] A. Aydın, T. Önkol, C. Arıcı, M. Akkurt, M.F. Şahin, D. Ülkü, Acta Cryst. E59 (2003) 0616–0618.
- [20] Y. Shao, L.F. Molnar, Y. Jung, J. Kussmann, C. Ochsenfeld, S.T. Brown, A.T.B. Gilbert, L.V. Slipchenko, S.V. Levchenko, D.P. O'Neill, R.A. DiStasio, R.C. Lochan, T. Wang, G.J.O. Beran, N.A. Besley, J.M. Herbert, C.Y. Lin, T. Van Voorhis, S.H. Chien, A. Sodt, R.P. Steele, V.A. Rassolov, P.E. Maslen, P.P. Korambath, R.D. Adamson, B. Austin, J. Baker, E.F.C. Byrd, H. Dachsel, R.J. Doerksen, A. Dreuw, B.D. Dunietz, A.D. Dutoi, T.R. Furlani, S.R. Gwaltney, A. Heyden, S. Hirata, C-P. Hsu, G. Kedziora, R.Z. Khalliulin, P. Klunzinger, A.M. Lee, M.S. Lee, W.Z. Liang, I. Lotan, N. Nair, B. Peters, E.I. Proynov, P.A. Pieniazek, Y.M. Rhee, J. Ritchie, E. Rosta, C.D. Sherrill, A.C. Simmonett, J.E. Subotnik, H.L. Woodcock III, W. Zhang, A.T. Bell, A.K. Chakraborty, D.M. Chipman, F.J. Keil, A.Warshel, W.J. Hehre, H.F. Schaefer, J. Kong, A.I. Krylov, P.M.W. Gill, M. Head-Gordon (Phys. Chem. Chem. Phys. 8 (2006) 3172). Spartan 06, Wavefunction Inc., Irvine, CA 92612, USA, 2006.
- [21] M.J. Frisch, G.W. Trucks, H.B. Schlegel, G.E. Scuseria, M.A. Robb, J.R. Cheeseman, V.G. Zakrzewski, J.A. Montgomery, Jr., R.E. Stratmann, J.C. Burant, S. Dapprich, J.M. Millam, A.D. Daniels, K.N. Kudin, M.C. Strain, O. Farkas, J. Tomasi, V. Barone, M. Cossi, R. Cammi, B. Mennucci, C. Pomelli, C. Adamo, S. Clifford, J. Ochterski, G.A. Petersson, P.Y. Ayala, Q. Cui, K. Morokuma, P. Salvador, J.J. Dannenberg, D.K. Malick, A.D. Rabuck, K. Raghavachari, J.B. Foresman, J. Cioslowski, J.V. Ortiz, A.G. Baboul, B.B. Stefanov, G. Liu, A. Liashenko, P. Piskorz, I. Komaromi, R. Gomperts, R.L. Martin, D.J. Fox, T. Keith, M.A. Al-Laham, C.Y. Peng, A. Nanayakkara, C. Gonzalez, M. Challacombe, P.M.W. Gill, B. Johnson, W. Chen, M.W. Wong, J.L. Andres, C. Gonzalez, M. Head-Gordon, E.S. Replogle, J.A. Pople, Gaussian 03, Revision C.02, Gaussian Inc., Pittsburgh, PA, 2003.
- [22] B. Foresman, E. Frisch, Exploring Chemistry with Electronic Structure Methods: A Guide to Using Gaussian, Gaussian Pitttsburg, PA, 1993.
- [23] A.P. Scott, L. Radom, J. Chem. 100 (1996) 16502.
- [24] H. Arslan, Ö. Algül, Y. Dündar, Vibrat. Spectrosc. 44 (2007) 248.
- [25] NIST Computational Chemistry Comparison and Benchmark Database, NIST Standard Reference Database Number 101, Release 12, August 2005, Editor: Russell D. Johnson III, http://srdata.nist.gov/cccbdb.
- [26] R. Dennington, T. Keith, J. Millam, K. Eppinnett, W.L. Hovell, R. Gilliland, GaussView, Version 3.07, Semichem Inc., Shawnee Mission, KS, 2003.
- [27] M.H. Jamróz, Vibrational Energy Distribution Analysis VEDA 4, Warsaw, 2004.
- [28] V. Krishnakumar, S. Dheivamalar, R. John Xavier, V. Balachandran, Spectrochim. Acta A 65 (2006) 147.
- [29] H. Arslan, T. Ozpozan, Asian J. Chem. 18 (3) (2006) 1815.
- [30] V. Krishnakumar, R. Ramasamy, Spectrochim. Acta Part A 62 (2005) 570.
- [31] R. Kimmelma, M. Hotokka, J. Mol. Struct. (Theochem) 418 (1997) 189.
- [32] H. Arslan, A. Demircan, Acta Chim. Slov. 54 (2007) 341.
- [33] M. Silverstein, G. Clayton Basseler, C. Morill, Spectrometric Identification of Organic Compounds, Wiley, New York, 1981.
- [34] N. Sundaraganesan, C. Meganathan, B. Anand, C. Lapouge, Spectrochim. Acta A 66 (2007) 773.
- [35] O.V. Cabral, C.A. Téllez, S.T. Giannerini, J. Felcman, Spectrochim. Acta A 61 (2005) 337.
- [36] D.J. Rabiger, M.M. Joullie, J. Org. Chem. 29 (1964) 476.
- [37] D.G.O. Sullivan, Spectrochim. Acta Part A 16 (1960) 762.