1-(2-NITROPHENYL)PIPERAZINE: NMR, RAMAN, FTIR AND DFT STUDIES

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ABSTRACT

Structure of 1-(2-nitrophenyl)piperazine (NPP, $C_{10}H_{13}N_3O_2$) was characterized by nuclear magnetic resonance (NMR), Fourier transform infrared (FTIR) and Raman techniques. The conformational analysis, nuclear magnetic shielding tensors, normal mode frequencies and corresponding vibrational assignments of NPP were examined by the density functional theory (DFT), using the Becke-3-Lee-Yang-Parr (B3LYP) functional and the 6-31G(d) and 6-311++G(d,p) basis sets. Reliable vibrational assignments were investigated by the total energy distributions (TED) obtained with the scaled quantum mechanical (SQM) method. The hydrogen of NH group in piperazine and the phenyl fragment of NPP equatorially oriented relative to piperazine. There is a good agreement between the experimentally determined nuclear magnetic shielding tensors and vibrational frequencies of NPP and those predicted theoretically.

Keywords: 1-(2-nitrophenyl)piperazine, NMR, Vibrational Spectra, DFT

1. INTRODUCTION

Piperazine derivatives have found important applications in various fields of science. For example, they were used as ligands in different complexes [1, 2]. Further, N-aryl piperazines, particularly in neuroscience field, were used as key components for a diversity of biologically active compounds [3]. In addition to that, m-chlorophenyl piperazine known as serotonin receptor agonists had been subjected to many clinical tests [4]. As well as piperazine, the molecular systems containing nitrobenzene were used in several ways including explosives and biologically important processes [5].

DFT has been widely used for the prediction of structural parameters, vibrational and nuclear magnetic shielding properties of different types of molecular systems [6-10]. In the present work, the geometrical structures, FTIR, Raman and $^1H/^{13}C$ NMR spectroscopic properties of NPP were examined by both experimental and computational point of views. Based on the available data in the literature [11], some structural presumptions were made and those structures were optimized with B3LYP functional and 6-31G(d) basis set. Following to find out the minimum energy condition to the most optimized structure of NPP, vibrational wavenumbers and nuclear magnetic shielding tensors were computed by B3LYP/6-311++G(d,p) method. From the experimental and theoretical findings, the structural and spectroscopic discussions were reported here.

2. MATERIALS AND METHODS

A commercial sample of NPP was purchased and used without further treatment. NMR measurements were performed by a Bruker Avance II 500 NMR spectrometer and deuterated chloroform used as solvent. FTIR spectrum was recorded with Bruker Optics IFS66v/s FTIR spectrometer with a resolution of 2 cm^{-1}. Raman spectrum was recorded with a Bruker Senterra Dispersive Raman microscope spectrometer using 785 nm excitation from a 3B diode laser in the region of 3700–400 cm^{-1}.
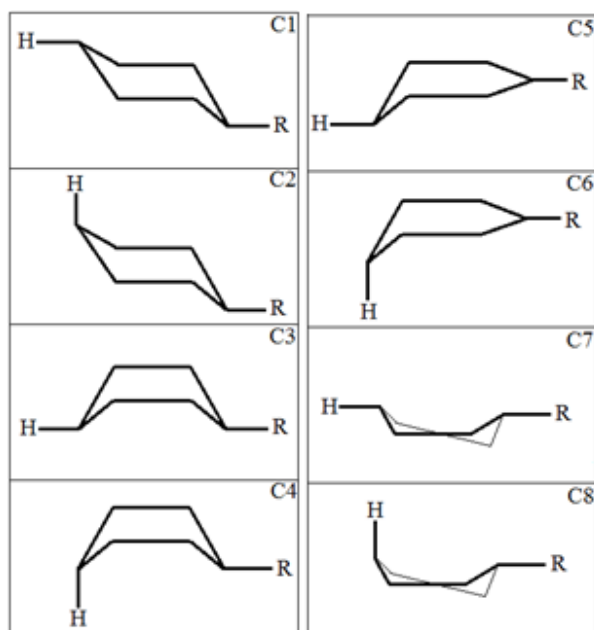
Figure 1. Eight different conformations constructed of NPP

Taking into account the previously reported [11] possible conformers of the piperazine, eight different structures labelled with C1 to C8 were built for NPP before the optimization process as seen in Figure 1. All structures were optimized with B3LYP/6-31G(d) level of theory. After the optimization, it was found that C1 conformer of NPP with C_1 point group yielded with the lowest optimization energy. The optimized structure can be seen in Figure 2. For each optimization process no geometric restrictions were applied. After having found the most stable conformer, vibrational frequencies (in the gas phase) and nuclear magnetic shielding tensors (in deutorated chloroform, $CDCl_3$) were calculated with B3LYP/6-311++G(d,p) method. TED calculations were completed with SQM program. All other calculations were carried out by Gaussian 09 program [12-14].
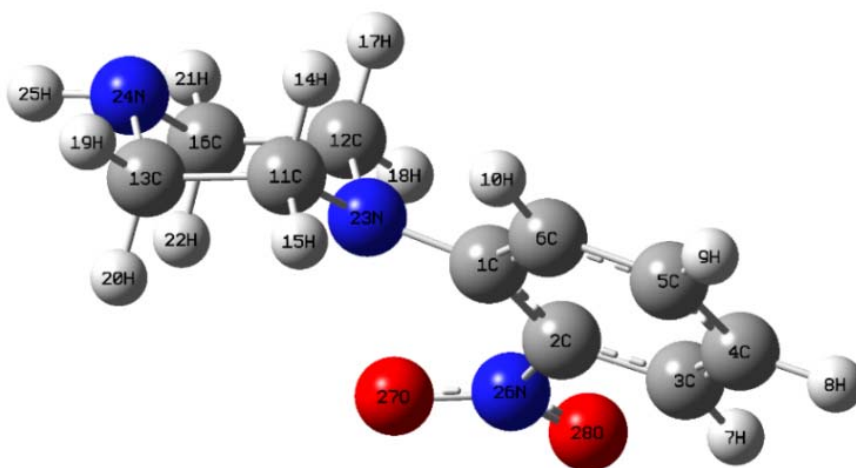

Figure 2. Optimized structure of NPP

3. RESULTS AND DISCUSSIONS

3.1. Geometric Structures

To the best of our knowledge, crystal data of NPP have not been reported elsewhere. Therefore, the molecular parameters found in this research were compared with previously reported structural parameters of piperazine [15] and benzene [16]. For example, C–C, C–N and C–H bond lengths for piperazine were reported before as 1.540 Å, 1.467 Å and 1.110 Å, respectively [15]. The average values of these bond lengths were found in this work as 1.530 Å, 1.466 Å and 1.099 Å, respectively. The C–C and C–H bond length for benzene were reported before as 1.399 Å and 1.101 Å [16]. By making an analogy with benzene, the average values of C–C and C–H bond lengths of the phenyl fragment of NPP were calculated as 1.406 Å and 1.085 Å. C–C–N, C–N–C and H–C–H bond angles for piperazine were given to the literature as 110.4º, 109.0º and 109.1º [15], the average of those were calculated in this study were found as 109.6º, 111.1º and 108.3º, respectively. N–H bond distance was calculated as 1.018 Å which is close to the value reported for N–H bond length for ammonia (1.30 Å) [17]. It is seen here that the calculated values in this study are very close to the previously reported data.

3.2. Vibrational Studies

NPP consists of 28 atoms, so it has 78 normal vibrational modes. All the experimental vibrational modes observed and corresponding theoretical data are given in Table 1. In the literature, NH stretching vibrations for various types of piperazine derivatives were reported as 3245, 3390, 3449 cm^{-1} [8, 18, 19]. In this work, it is found as 3173 cm^{-1} in the IR spectrum as shown in Figure 3. 785, 632 and 532 nm lasers with various power levels available with the Raman spectrometer yielded no interpretable NH stretching bands in the Raman spectrum for NPP. Aromatic CH stretching bands generally appear as weak bands because of the decrease in the dipole moment resulting from the reduction of the negative charges of the carbon atoms [20, 21].

The very weak bands at 3080, 2996 cm^{-1} (IR) and 3076 cm^{-1} (R) were assigned to CH stretching vibrations arising from phenyl ring. In previous works, some of CH stretching vibrations of phenyl for different compounds were reported as quite weak bands at 3086, 3071, and 2984 cm^{-1} [22-24]. The bands seen at 2949, 2915, 2834 cm^{-1} (IR) and 2954, 2833 cm^{-1} (R) can be attributed to CH stretching vibrations due to the piperazine ring since in the literature free piperazine and its various derivatives have the following CH stretching adsorption bands: 2950, 2945, 2925, 2831 and 2825 cm^{-1} [23-25]. During the investigation of previously published works, it was seen that C-C stretching bands were reported as 1597, 1570, 1481 for biphenyl, 1600, 1579, 1498 for 1-phenylpiperazine, 1598, 1481, 1454 for 1-(4-nitrophenyl)piperazine, 1588, 1479, 1455 for nitrobenzene and 1600, 1463 cm^{-1} for N-(4-nitrophenyl)-β-alanine.

Therefore, in this work the υ(C-C) bands with TED contributions given in parenthesis observed at 1603 cm^{-1} (53%), 1566 cm^{-1} (59%) and can be attributed to C-C stretching arising from the nitrophenyl fragment of NPP. There are possible two stretching modes for NO$_2$ group as antisymmetric and symmetric vibrations. In the literature -NO$_2$ stretching bands for compounds similar in structure to the title molecule were observed at following wavenumbers: 1530, 1523, 1502 (for symmetric vibrations) and 1365, 1350, 1347 cm^{-1} (for antisymmetric vibrations) [22, 24, 26, 27]. In present work, these bands appeared at 1519 (IR&R) and 1348 (IR), 1342 (R) cm^{-1}, respectively. The bands appeared at 1487 (IR&R) and 1452 (IR), 1446 (R) cm^{-1} seem to have δC-C-H (28%) + υC-C (15%) and δH-C-H(20) + τH-C-C-H (14) respectively, as can be seen in Table 1. The rest of the vibrations seem to occur as the mixed type of stretching, bending and torsional vibrations as given in Table 1.
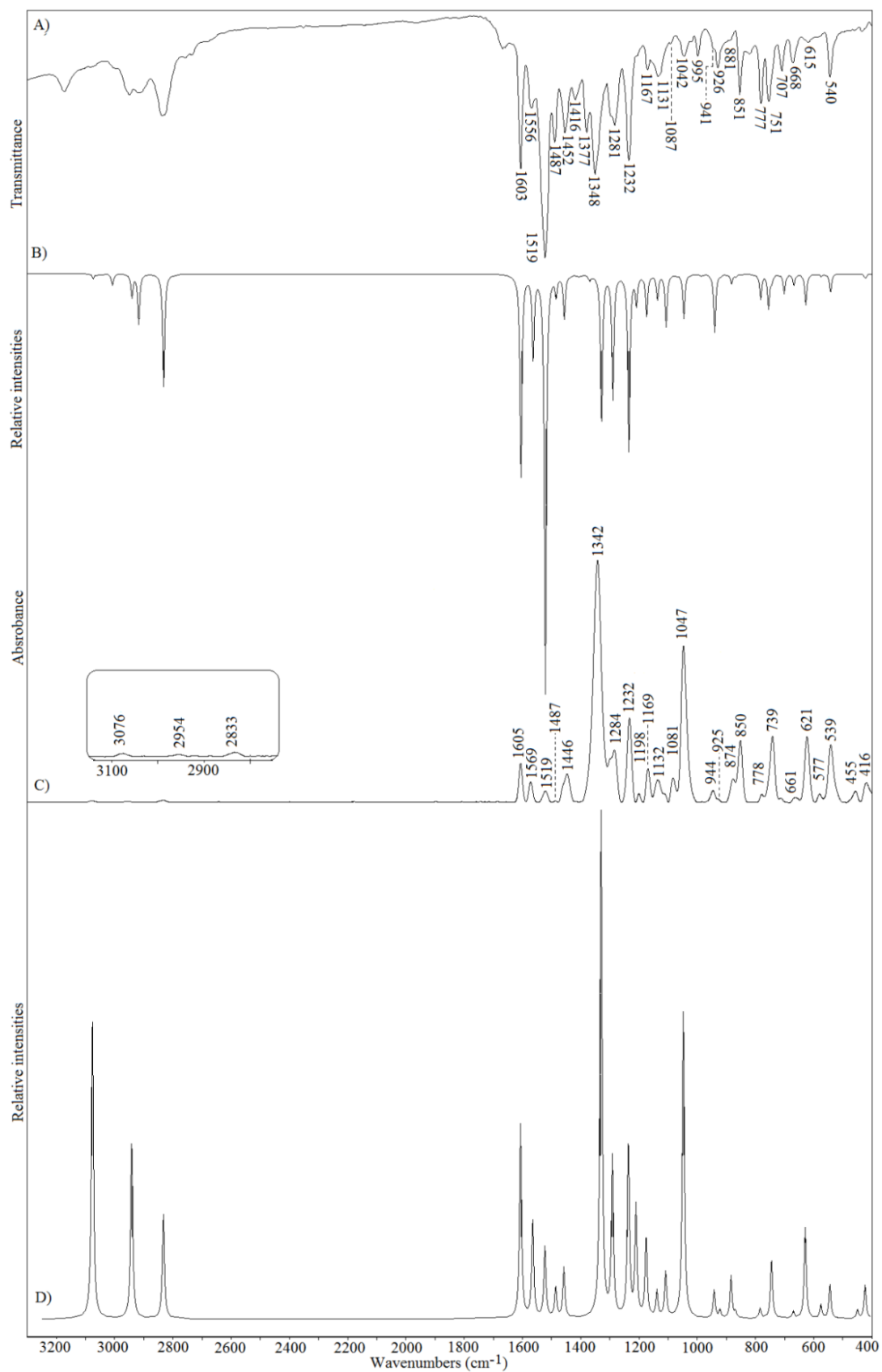
Figure 3. Experimental (A, C) and calculated (B, D) vibrational spectra of NPP

Table 1. Comparison of experimental and computed vibrational wavenumbers (cm^{-1})

Mode	Assignments	Experimental		B3LYP / 6-31G(d)		
	TED ($\geq$ 10 %)	IR	Raman	SQM	I_{IR}	I_R
υ_1	υN-H(100)	3173	-	3173	0.49	-
υ_2	υC-H(96)	3080	3076	3074	3.67	97.84
υ_3	υC-H(99)	2996	-	3008	8.80	-
υ_4	υC-H(97)	2949	2954	2941	17.63	55.13
υ_5	υC-H(95)	2915	-	2918	37.49	-
υ_6	υC-H(95)	2834	2833	2832	85.75	31.35
υ_7	υC-C(53)	1603	1605	1604	154.72	42.25
υ_8	υC-C(59) + δC-C-H(12)	1566	1569	1562	64.17	21.60
υ_9	υN-O(57) + υC-C(10)	1519	1519	1520	315.21	15.46
υ_{10}	δC-C-H(28)+ υC-C(15	1487	1487	1483	14.70	6.54
υ_{11}	δH-C-H(20)+ τH-C-C-H(14)	1452	1446	1455	32.86	10.54
υ_{12}	δC-C-H(15)+ τC-N-C-H(15)	1416	-	1405	0.91	-
υ_{13}	υC-N(17)+ δC-C-H(15)	1377	-	1367	3.80	-
υ_{14}	υN-O(55)	1348	1342	1327	115.75	104.35
υ_{15}	δN-C-H(25)	1281	1284	1288	93.45	32.11
υ_{17}	υC-N(18)	1232	1232	1233	134.94	36.40
υ_{18}	δN-C-H(25)	-	1198	1207	-	21.95
υ_{19}	δC-C-H(60) + υC-C(15)	1167	1169	1172	31.68	16.45
υ_{20}	υC-N(48)	1131	1132	1135	18.83	5.17
υ_{21}	*	1087	1081	1105	39.34	8.96
υ_{22}	υC-C(30)	1042	1047	1044	33.37	59.81
υ_{23}	τH-C-C-H(50)+ τH-C-C-H(15) +τC-C-C-H(12)	995	-	988	1.46	-
υ_{24}	υC-N(43)	941	944	938	43.91	5.29
υ_{25}	υC-C(46)+ υC-N(11)	926	925	918	0.90	1.60
υ_{26}	δO-N-O(24)+ δC-N-O(12)+ υN-O(11)	881	874	880	7.63	7.94
υ_{27}	τH-C-C-N(13)+ τH-C-C-C(18)	851	850	865	2.33	1.13
υ_{28}	τH-C-C-C(54)+ τH-C-C-N(12) +τO-N-C-C(16)	777	778	780	18.77	1.90
υ_{29}	υC-N(14)+ τO-N-C-C(18)	751	-	753	25.97	-
υ_{30}	τO-N-C-C(17)+ υC-N(10)	-	739	741	-	10.97
υ_{31}	τO-N-C-C(35)	707	-	699	14.78	-
υ_{32}	δN-C-H(20)	668	661	666	8.27	1.29
υ_{33}	δC-C-C(20)	615	621	625	23.39	15.85
υ_{34}	δO-N-C(32)+ δC-C-N(20)+ υC-C(11)	-	577	571	-	2.39
υ_{35}	τC-C-C-C(27)+ τC-C-C-H(16)	540	539	540	14.21	6.00
υ_{36}	τC-C-C-C(12)	-	455	445	-	1.46
υ_{37}	τN-C-C-N(6)	-	416	419	-	5.72

I_{IR}: Infrared intensity; I_R: Raman scattering activity; ν, δ, τ: stretching, bending and torsion, respectively; *: TED $\leq$ 5, so not given here.

3.3. NMR Studies

Stretching in ^{13}C NMR spectrum of NPP, the eight carbon peaks were observed (Figure 4 and Table 2) which implies that based on the chemical shielding assessments, the eight of ten carbon atoms were

chemically shielded almost the same amount. In addition to that, C11 & C12 and C13 & C16 carbon couples gave singlets implying that like C11 and C12, C13 and C16 have the same resonance frequency in NMR spectrum.

Table 2. Experimental and calculated NMR chemical shifts for C1 and C2 conformers.

Nucleus	Exp.	Equatorial (C1)	Axial (C2)	Equatorial+	Axial+
H7	7.77	8.54	8.55	8.35	8.36
H9	7.49	7.77	7.77	7.60	7.60
H10	7.16	7.13	7.09	6.99	6.95
H8	7.05	7.10	7.11	6.95	6.96
CH2*	3.04	3.10	3.02	3.08	2.99
NH	1.90	1.41	0.74	1.43	0.79
MAE		0.28	0.39	0.24	0.36
C1	146.4	157.7	157.8	150.5	150.6
C2	143.5	148.2	148.1	141.3	141.5
C5	133.5	143.2	143.2	136.5	136.5
C3	126.0	136.6	136.5	130.1	130.1
C4	121.9	125.0	125.1	119.0	119.1
C6	121.0	126.9	126.9	121.1	120.8
C11,12**	53.0	56.3	57.6	52.8	54.1
C13,16**	46.2	51.1	50.9	47.8	47.7
MAE		6.7	6.8	2.3	2.4

MAE: Mean absolute errors; +: Values are after the transformation of σ (absolute shieldings) into δ (chemical shifts) [27, 28]; **: Average values were used for CH_2 of piperazine fragment.

The most shifted carbon peaks to the lowest magnetic field region on the ppm (part per million) scale were found as C1 and C2 carbon atoms since they are directly attached to electronegative nitrogen atom so the electron density around those carbons were deshielded more compared to the other carbon atoms in NPP.
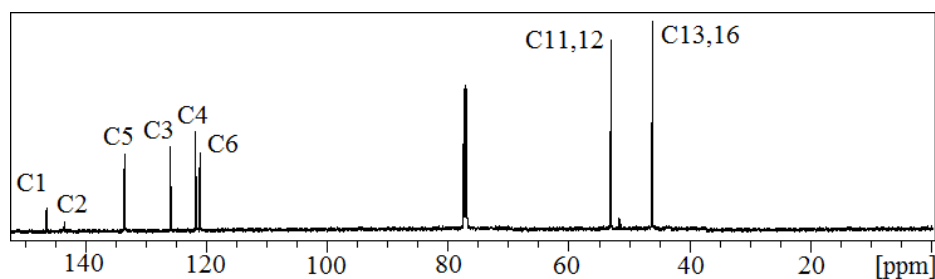

Figure 4. ^{13}C NMR spectrum of NPP

In ^{1}H NMR spectrum (Figure 5), since H7 and H10 have only one neighboring hydrogen atom they mainly appear as doublets at 7.77 and 7.16 ppm, respectively (Table 2). On the other hand, H9 and H8 appear as triplets due to two neighboring hydrogen atoms at 7.49 and 7.05 ppm, respectively. Hydrogen atoms on piperazine ring except hydrogen of –NH, all appeared at 3.04 ppm. Therefore, they have all nearly the same resonance frequency. Hydrogen of –NH fragment gave a slightly broadened singlet at 1.90 ppm.

In HETCOR NMR spectrum (Figure 6) connections between C5→H9, C3→H7, C4→H8, C6→H10, C11,12 & C13,16 → H14,15 &H17-22 can be clearly observed.
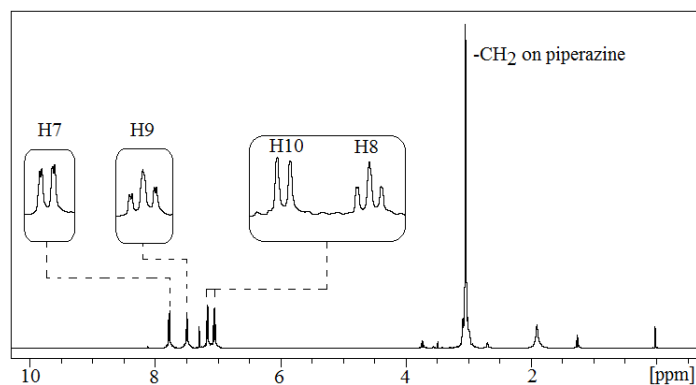
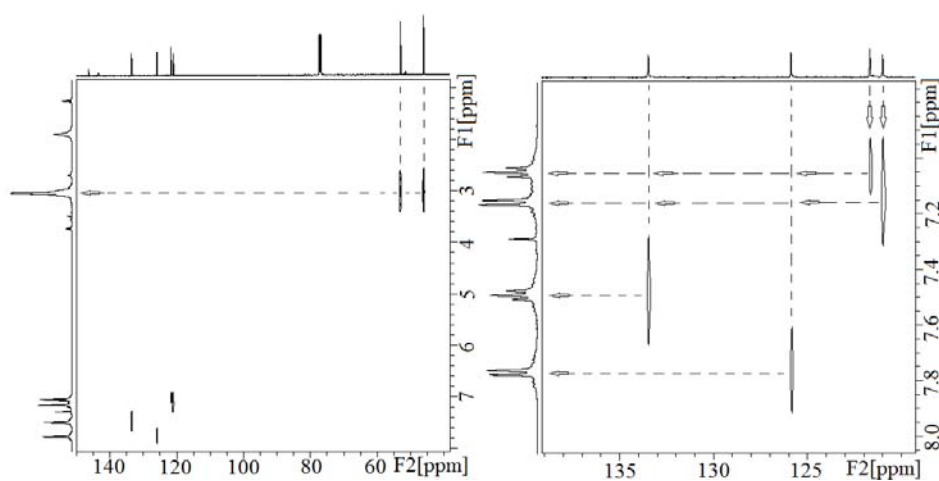**Figure 5.** ^{1}H NMR spectrum of NPP

Figure 6. HETCOR NMR spectrum of NPP

4. CONCLUSIONS

In the frame work of the present research, the experimental and theoretical NMR, FTIR and Raman spectra of NPP were investigated. In brief, following conclusions can be summarized:

i. B3LYP/6-311++G(d,p)//6-31G(d) level of theory produced acceptable results in the calculation of chemical shifting values for ^{13}C, ^{1}H nuclei and the vibrational frequencies of NPP.

ii. Computed chemical shifts were analysed in two different way. In Table 2, first, no transformation was performed. Second, the transformations given below were applied to transform σ (absolute shieldings) into δ (chemical shifts): ^{13}C NMR: $\delta^{13}C = 175.7 - 0.963\ \sigma^{13}C$ [28] and ^{1}H NMR: $\delta^1H = 31.0 - 0.97\ \sigma^1H$ [29]. It was observed that after the transformation, the experimental and calculated values showed better agreement with each other and yielded with smaller mean absolute error values.

iii. The calculated NMR results indicate that the position of hydrogen atom which is directly connected to the nitrogen atom in piperazine molecule and the related chemical shifting value of it strongly depend on the orientation of the hydrogen atom in space that is whether it is connected in equatorial or axial positions. The comparison of the experimentally observed and calculated chemical shifting value of the mentioned hydrogen atom shows that it is oriented in the equatorial position within NPP. In compliance with the NMR findings, within the examined structures, C1 (equatorial–equatorial) conformer was found having the lowest optimization energy in the gas phase.

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