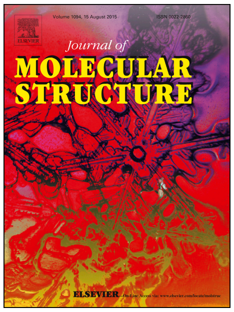


Synthesis, experimental characterization and theoretical calculation of novel charge transfer complex between (S, S)-bis-N,N-sulfonyl bis –l-phenylalanine dimethylester and 2,3-dichloro-5,6-dicyano-1,4-benzoquinone (DDQ)

Messaouda Mohamdi, Nadjia Bensouilah, Nadia Trad, Mohamed Abdaoui

PII: S0022-2860(19)30981-0
DOI: https://doi.org/10.1016/j.molstruc.2019.126890
Reference: MOLSTR 126890

To appear in: *Journal of Molecular Structure*

Received Date: 5 January 2019
Revised Date: 7 July 2019
Accepted Date: 1 August 2019

Please cite this article as: M. Mohamdi, N. Bensouilah, N. Trad, M. Abdaoui, Synthesis, experimental characterization and theoretical calculation of novel charge transfer complex between (S, S)-bis-N,N-sulfonyl bis –l-phenylalanine dimethylester and 2,3-dichloro-5,6-dicyano-1,4-benzoquinone (DDQ), *Journal of Molecular Structure* (2019), doi: https://doi.org/10.1016/j.molstruc.2019.126890.

Synthesis, experimental characterization and theoretical calculation of novel charge transfer complex between (S, S)-bis-N,N-sulfonyl bis –L-phenylalanine dimethylester and 2,3-dichloro-5,6-dicyano-1,4-benzoquinone (DDQ)

Messaouda Mohamdi[1], Nadjia Bensouilah[1,2,*], Nadia Trad[1], Mohamed Abdaoui[1]

[1] Laboratory of applied chemistry (LAC), University of May 8th, 1945, BP 401, 24000 Guelma, Algeria.

[2] laboratory of applied organic chemistry , faculty of chemistry (LAOC), USTHB, BP 32, El-Alia, 16111 Bab-Ezzouar, Algiers, Algeria

Abstract:

Charge transfer complex (CTC) formed between (S, S)-bis-N, N-sulfonyl bis-L-phenylalanine dimethylester as donor and 2,3-dichloro-5,6-dicyano-*p*-benzoquinone (DDQ) as acceptor, has been studied spectrophotometrically. Benesi-Hildebrand and molar ratio methods were applied in order to determine association constant (K_{CT}), molar extinction coefficient (ε_{CT}) and stoichiometric ratio, respectively. The solid CT complex has been synthesized and its structure was characterized via spectroscopic techniques (UV–vis and FT-IR). In order to determine the equilibrium geometries, DFT/CAM-B3LYP has been employed. Moreover, TD-DFT method was used to investigate the electronic structures of donor, acceptor and their complex. Natural bond orbital (NBO) analysis has been used to study the atomic charges and molecular bonding interactions of the interesting complex. These studies show that non-bonding interactions are important in charge transfer complex.

Keywords: Sulfonamides**,** DDQ, CTC, DFT-CAM-B3LYP, TD-DFT, NBO.

[*] *Corresponding author:*
Doctor Bensouilah Nadjia
Tel : 00213 0661 49 56 39

**laboratory of applied organic chemistry , faculty of chemistry (LAOC), USTHB, BP 32, El-Alia, 16111 Bab-Ezzouar, Algiers, Algeria*

Email: nadjia.bensouilah@yahoo.fr

1. Introduction:

Charge transfer complexes CTC are held together by weak intermolecular forces such as hydrogen bonding and van der Waals forces. Hydrogen bond plays an extremely significant role on determining the structural stability of many chemical complexes and biological macro molecules [1, 2]. The hydrogen bond is observed when a hydrogen atom related to an electronegative atom (HX; where X is an element with an electronegativity greater than H) is approximate to a free electron pair which is generally carried by another electronegative atom (acceptor) [3].

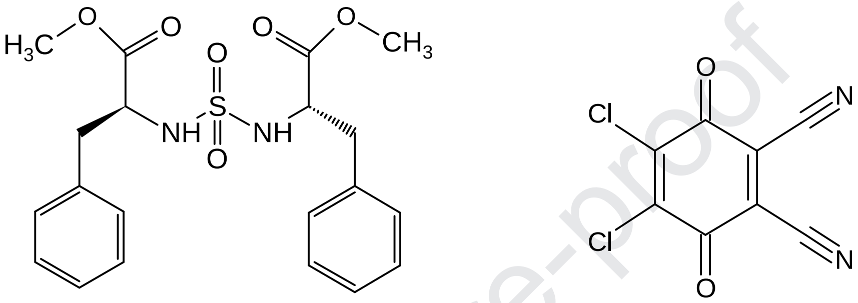
These CTC-interactions have been the subjects of many chemical and biological studies, in particular with acceptors of biological interests like DDQ [4, 5]. 2,3-dichloro-5,6-dicyano-1,4-benzoquinone (DDQ) is a strong electron acceptor as mild oxidizing agent and its extraordinary potency as a dehydrogenating agent is discovered [6]. It is structurally characterized by the presence of potentially three different halogen bonding acceptor sites; the carbonyl oxygen atoms, the nitrogen atoms and the chlorine atoms [7].

The studies of interaction of drug as electron donor with different acceptors are important in the area of research [8-11]. In fact, it is shown that the drug-acceptor complexes can enhance the activity of antibacterial agents especially against both Gram-positive and Gram-negative bacteria as well as fungi [12-15].

Compounds including N–SO_2–N fragment possesses antiviral action [16] .The most important biological activity of sulfamide derivatives is due to the fact that the sulfamide belongs to important essential structures which are used in human medicine with various types of pharmacological agents having antibacterial properties [17,18], Protease inhibitors such as HIV Protease [19, 20], as nonhydrolyzable components in peptidomimetics [21] and certain analogues of symmetric N, N'-substituted sulfamides show anticonvulsant activity [22]. According to these researchs, it is interesting for us to invest the characteristics of its electron donor nature to form stable complexes of the CTC type.

The presence of the ion pairs of oxygen and nitrogen electrons and the aromatic ring in (S, S)-bis-N, N-sulfonyl bis –L-phenylalanine dimethylester facilitate the hydrogen-bonding and charge transfer interaction with acceptors. The results show a tremendous increase in the stability of their Tetracyanoethylene TCNE and chloranil after complexation [23]. The purpose of the present study is to explore a definite relation between the oxidation-reduction potentials of DDQ and their reactivity in charge-transfer reaction with (S, S)-bis-N, N-sulfonyl bis –L-phenylalanine dimethylester.

The structures of donor and acceptor are shown in scheme 1. The new complex formed between (S, S)-bis-N,N-sulfonyl bis-L-phenylalanine dimethylester and DDQ was synthesized and characterized using elemental analyses, electronic absorption spectroscopy and Fourier transform infrared FT- IR technique. The geometrical parameters, electronic spectroscopic properties, the Natural population analysis (NPA) for the investigated donor, DDQ and their complex and the Natural bond orbital (NBO) were performed by CAM-B3LYP level of theory.



Scheme 1. Chemical structures of (S, S)-bis-N,N-sulfonyl bis –L-phenylalanine dimethylester and 3-dichloro-5,6-dicyano-1,4-benzoquinone (DDQ).

2. Experimental:

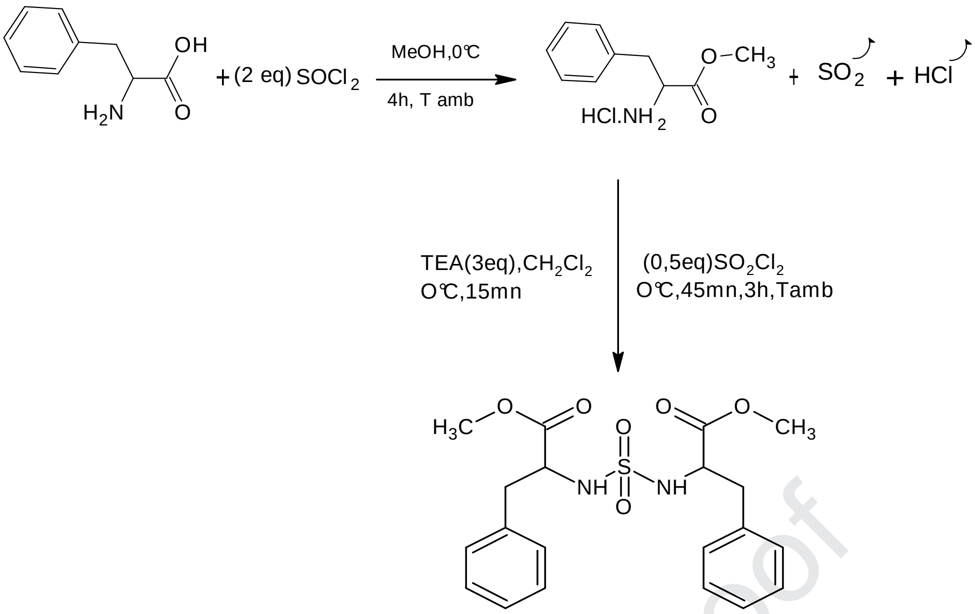
2.1. Chemicals and materials:

(S, S)-bis-N, N-sulfonyl bis –L-phenylalanine dimethylester was prepared according to the known method [21, 24]. 2,3-dichloro-5,6-dicyano-1,4-benzoquinone (DDQ) was obtained from Aldrich Chemical. Chlororm and acetonitrile of analytical grade obtained respectively from: Merck and Fluka groups were used without any further purification. The UV–vis spectrum was recorded on UV Probe PC software within 190 nm – 1100 nm range using a Perkin-Elmer Precisely Lambda 25 UV/Vis double beam Spectrometer fitted with a quartz cell of 1.0 cm path length. The FT-IR of the compounds was measured on JASCO/FT-IR Model 410 spectrophotometer in the range of: 400–4000 cm^{-1} with 30 scans and 2 cm^{-1} resolution using KBr pellet technique. The ^1H NMR spectrum of the donor was recorded on JEOL EX-400MHz device (400 MHz 1H).

2.3. General procedure for the synthesis of the donor:

The synthesis of (S, S)-bis-N,N-sulfonyl bis –L-phenylalanine dimethylester in two steps was outlined in Scheme 2. The synthesis consists of an esterification reaction followed by sulfamoylation. Starting by the preparation of L-phenylalanine methyl hydrochloride, the synthesis of aminoester is usually performed as follows: 1 equivalent of phenylalanine ($C_9H_{11}O_2N$) dissolved in anhydrous methanol at 0°C was added dropwise to 2 equivalents of thionyl dichloride ($SOCl_2$) in the same solvent, after 30 min the reaction was followed to more than 4 h at at room temperature. Once the reaction is complete the solvent and the excess thionyl dichloride were evaporated in vacuum, the crude product is taken up in ether to obtain a white powder of amino ester hydrochloride. The second step begins by the deprotection of the amino ester hydrochloride : at 0°C, 1 equivalent of triethylamine (TEA) ($C_6H_{15}N$) was added dropwise to 1 equivalent of amino ester hydrochloride.

The reaction mixture is left under magnetic stirring for 15 min. After this step, the amino ester in dichloromethane was added dropwise (at 0°C) to a mixture of 0.5 equivalent sulfuryl chloride (SO_2Cl_2) in the presence of triethylamine (3 equivalents). The mixture was stirred for 45 min at room temperature. The resulting mixture was accomplished by treatment with HCl 0.1N and water. The organic layer was separated and dried over anhydrous Na_2SO_4. The obtained organic solution was filtered, concentrated in vacuum and purified by chromatography on silica gel to obtain the final product: (S, S)-bis-N, N-sulfonyl bis –L-phenylalanine dimethylester. Spectroscopic evidences concerning illustration of the structure of the donor are given as follows: FT-IR (KBr, ν en cm^{-1}): 3329 cm^{-1}(NH), 1736 cm^{-1}(C=O) et 1362 cm^{-1} (SO_2). (See Fig.6 (a)) ^1H RMN (400MHz, DMSOd6, δ : ppm): 7.08-7.21 (m, 10H, 2ArH), 4.45 (d, 2H, NH), 3,84 (m, 2H, CH*), 3.67 (s, 6H, OCH_3), 3.29-3.04 (m, 4H, $2CH_2Bn$).(See Fig.1)



Scheme 2. Synthesis of *(S, S)-bis-N,N-sulfonyl bis –L-phenylalanine dimethylester*

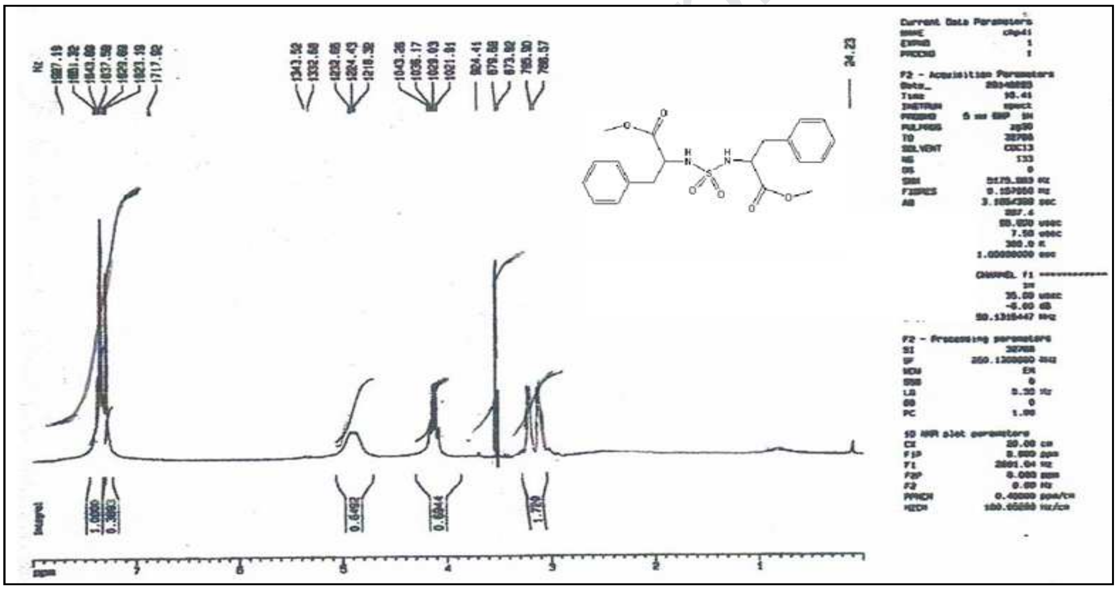


Fig.1. The ^{1}H NMR spectra of *(S, S)-bis-N,N-sulfonyl bis –L-phenylalanine dimethylester.*

2.4. Photometric measurements:

Solutions for spectroscopic measurements (1.00 10^{-4} mol /l) were prepared by mixing an appropriate constant volume of donor and acceptor stock solutions with acetonitrile. Acetonitrile which was chosen as a principal reaction medium was found to be an ideal solvent for the study of CT complexes [25]. For highlighting the formation of a stable complex, the stoichiometry of the CT complex in solution was determined by molar ratio method [26] and the association constant was determined using Benesi- Hildebrand equation

[27-29] (The concentration of DDQ is kept constant (1.00 x 10^{-5} mol /l) whereas, the donor concentration is varied from (1.00 x10^{-5} to 1.00 x10^{-4} mol /l)).

3. Theoretical calculations:

Quantum chemical calculations were carried out using the Gaussian-09 software package [30] with the help of Gauss View 5.0 [31]. The molecular structures of bis-L-aminoesters sulfones, DDQ and their complex have been optimized by using DFT/ CAM-B3LYP method [32] with 6-31++G (d, p) basis set in gas phase and in acetonitrile as solvent using PCM model [33]. The bond length and bond angle of the optimized structures are classified. The absorption spectra of DDQ, donor and their complex were calculated using the time-dependent density functional theory (TD-DFT) method using the PCM model on optimized geometries. The calculation of different HOMO and LUMO energies was also performed at the same level of theory. NBO calculations were employed to calculate the second-order perturbation stabilization energy (E^2) of DDQ complex. The atomic charges in free molecule and in their complex were calculated by the NPA. Finally, the natural NBO atomic charges [34-36] were analyzed to correlate the properties of both partners before and after complexation.

4. Results and discussion:

4.1. Determination of molar ratio:

Representative of spectrophotometric titration plot based on the characteristic absorption bands are depicted in Fig. 2. In order to obtain the stoichiometry of the resulting complex, the varying molar ratio method (Skoog, 1985) was followed. Then, 0.20, 0.40, 0.80, 1.00, 1.20, 1.60, 2.00, 2.40 ml of a solution of 1.00 x 10^{-4} M of the donor was added to 1.00 ml of a solution of 1.00 x 10^{-4} M of the acceptor. The absorbance obtained in the spectra assigned to the formed CT complexes were measured and plotted as a function of the [D]/[A] ratio according to the known method. As can be seen, the spectrophotometric titration plot confirmed the formation of donor-DDQ complex at a ratio of 1:1.

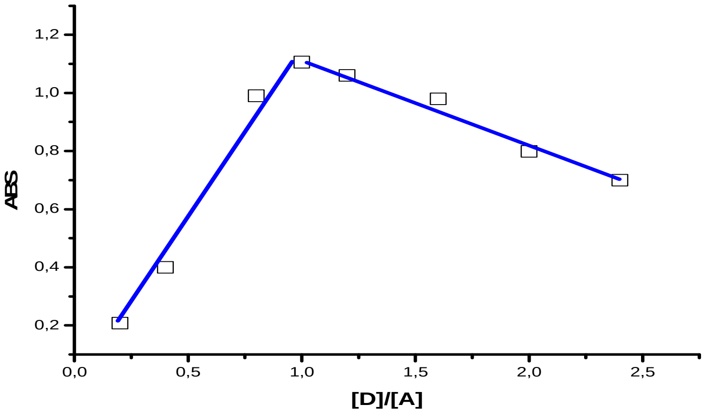


Fig. 2. Spectrophotometric titration curve of bis-L-aminoester sulfone with DDQ in acetonitrile at 298 K.

4.2. Formation constants and energy (E_{CT}) of CT-complex:

The electronic absorption spectra of DDQ (kept fixed at 1.00 x 10^{-5} M) in the presence of various donor concentrations has been followed by an increase in absorbance at 208 nm (see Fig. 3). An important observation from Fig. 3 is the unchanging of the maximum of wavelengths of the complex bands upon going from: 4.00 x10^{-5} to10^{-4} M of donor. This is consistent with the appearance of stable complex. The band maxima as obtained in the present study indicate the formation of electron donor acceptor complex between DDQ and donor in acetonitrile. The formation constant for the complexation process can be obtained by a proper analysis of the absorbance data. Benesi–Hildebrand equation [37-39] was used to calculate both formations constant (K_{CT}), and extinction coefficient (ε_{CT}) of the CT complex in acetonitrile. The equation is written as follows:

$$\frac{[\mathbf{A}]}{\mathbf{ABS}} = \frac{\mathbf{1}}{\boldsymbol{K_{CT}.\varepsilon_{CT}}} \cdot \frac{\mathbf{1}}{[\mathbf{D}]} + \frac{\mathbf{1}}{\boldsymbol{\varepsilon_{CT}}} \qquad \mathbf{(1)}$$

ABS is the absorbance of the detected CT bands while [D] and [A] are the initial molar concentrations of the donor and acceptor, respectively. From the previous equation, and by plotting the values of [A]/ABS versus 1/[D], straight line (with a regression coefficient : R = 0.99) was obtained with a slop of ($1/K_{CT}.\varepsilon_{CT}$) and intercept of 1/ ε_{CT} as shown in Fig. 4. The Values of K_{CT} and $\mathcal{E}_{CT}$ of the formed CT complex are respectively equal to $9.56.10^{3}$ L.mol^{-1} and $1.36.10^{5}$ L .mol^{-1}.cm^{-1}.

The results show that the [D→DDQ] complex shows a higher formation constant. This high K_{CT} value indicates a strong interaction between both partners. Therefore, it confirms the expected high stability of the formed CT-complex as a result of the expected high donating power of donor and high electron affinity of DDQ.

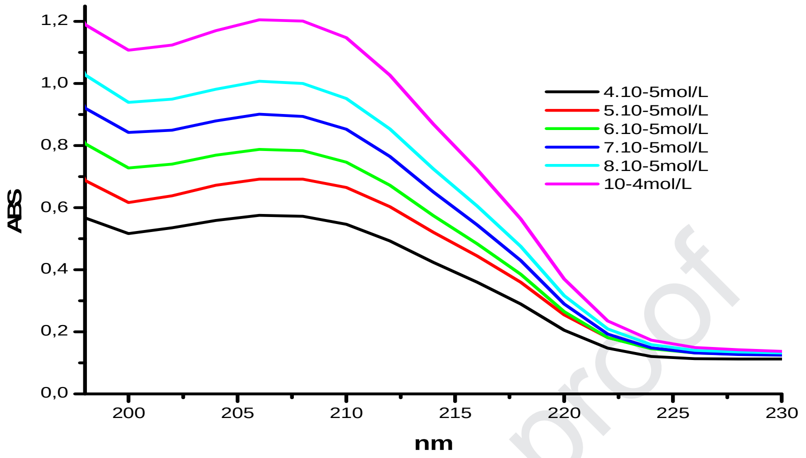


Fig.3. Electronic absorption spectra of 10^{-5} M DDQ with different concentrations of donor ranging from: $4x10^{-5}$ to 10^{-4} M in acetonitrile as solvent**.**

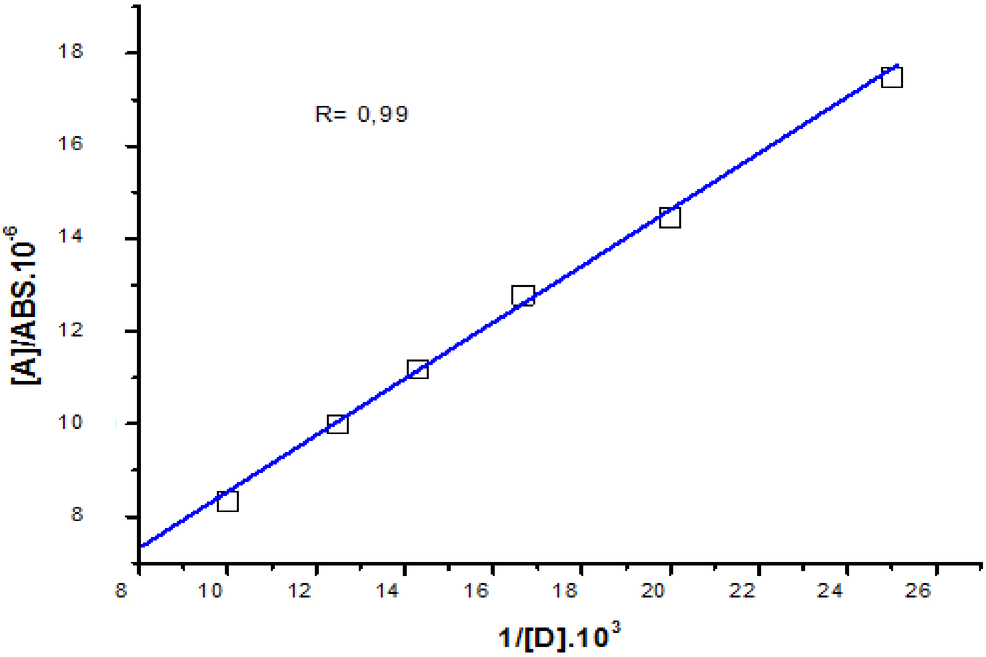


Fig.4. Benesi–Hildebrand plots for (S, S)-bis-N,N-sulfonyl bis-L-phenylalanine dimethylester donor with DDQ. (Solvent: acetonitrile)

4.3. Preparation of solid complex:

Literature research revealed that the color changes observed upon the mixture of donor with various electron acceptors is due to formation of CT complex [40, 41]. The solid CT-complex (1:1 according to the obtained ration molar complex) is formed by the addition of a saturated solution of the donor to a saturated solution of acceptor in $CHCl_3$ at room temperature with stirring. When they are mixed together, they give no immediate color change. However, a dark yellow color started to develop after 15–30 min and became bluish dark orange with time. The resulting precipitate was filtered and analyzed with FT-IR and UV-Vis measurements.

4.4. Spectral analysis:

4.4.1. Observation of CT bands:

The absorption spectra of donor, acceptor and its obtained CT complex in CH_3CN are presented in Fig. 5(a). The electron absorption spectra of donor in acetonitrile solution exhibit three bands. Two strong bands are at 196, 208 nm accompanied by week intensity at 258 nm, while that of DDQ shows four strong absorptions (208, 226, 272, 280 nm) and week intensity at 348 nm.

Interestingly, when donor and DDQ are mixed together, hyperchromic and hypochromic effect can be assigned to the formation of charge transfer complex. It is associated with the electronic transitions at 196, 208, 234, 258, 270, 280 and 346 nm. In parallel, the band observed at 226 nm and associated to free DDQ was shifted to 237 nm in CTC complex (bathochromic shift). This red shift at longer wavelength confirms intermolecular charge transfer between the two partners. This observed behavior suggests strong intermolecular charge transfer ability. Then, it is clear from the characteristic data presented in Fig. 5(b) that the absorption spectrum of solid complex in acetonitrile is in perfect agreement with that observed in Fig. 5(a). This result confirms the formation of CTC complex.

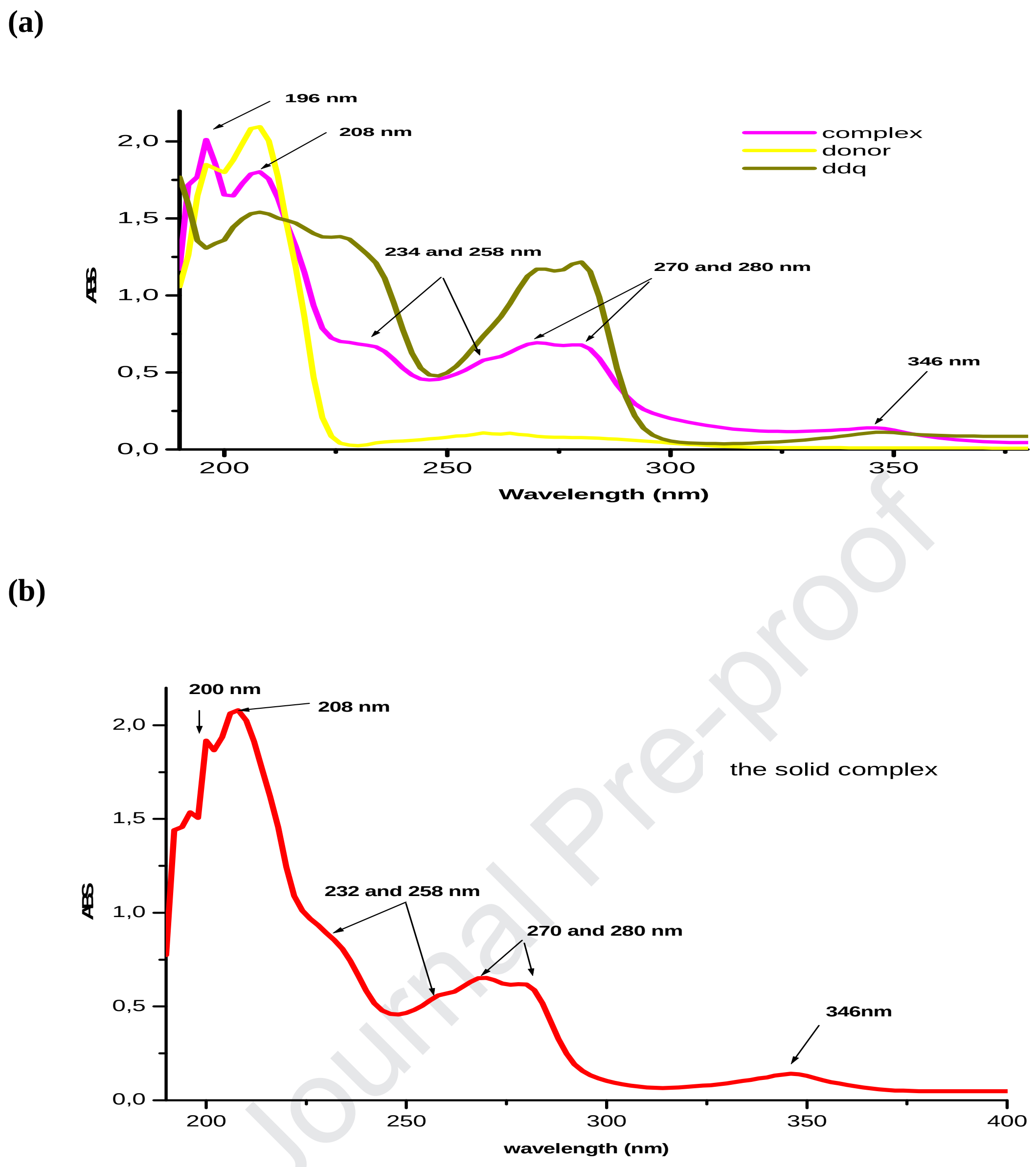


Fig.5. Electronic absorption spectra: a) [bis –L-aminoesters sulfones- DDQ] charge-transfer systems and free donor, acceptor in acetonitrile solvent, b) the solid complex in acetonitrile.

4.4.2. Infrared spectra:

As seen in Fig. 6, we note a shift in positions and changes in intensities of some characteristic peaks. This is due to the complexation of the donor with DDQ, where changes in both electronic structure and symmetry are expected. Fig. 6 shows the infrared absorption spectra of donor, DDQ and the formed complex (in solid state). In Table 1, we have dressed the most characteristic bands of acceptor, donor and their corresponding charge-transfer complex. Some of the significant shifts are:

When the donor interacts with DDQ acceptor, the characteristic band that results from the ν (C≡N) in free DDQ occurs at 2232 cm^{-1}, whereas, in its complex ν (C≡N) occurs at lower wavenumber values at 2031 cm^{-1}. It is known that (C≡N) group is an electron withdrawing group in DDQ. This observation clearly indicates that the (C≡N) group in the DDQ participates in the complexation process. Similarly for DDQ, the CO stretching frequencies that appeared at 1670 cm^{-1} of the free acceptor was shifted to 1694 cm^{-1} upon complex formation. In parallel, the CO stretching frequencies that appeared at 1735 cm^{-1} of the free donor was shifted to 1730 cm^{-1}. The characteristic bands of (SO_2) group at: 1362, 1342 and 1313 cm^{-1} in the free donor are also shifted and their intensities are affected.

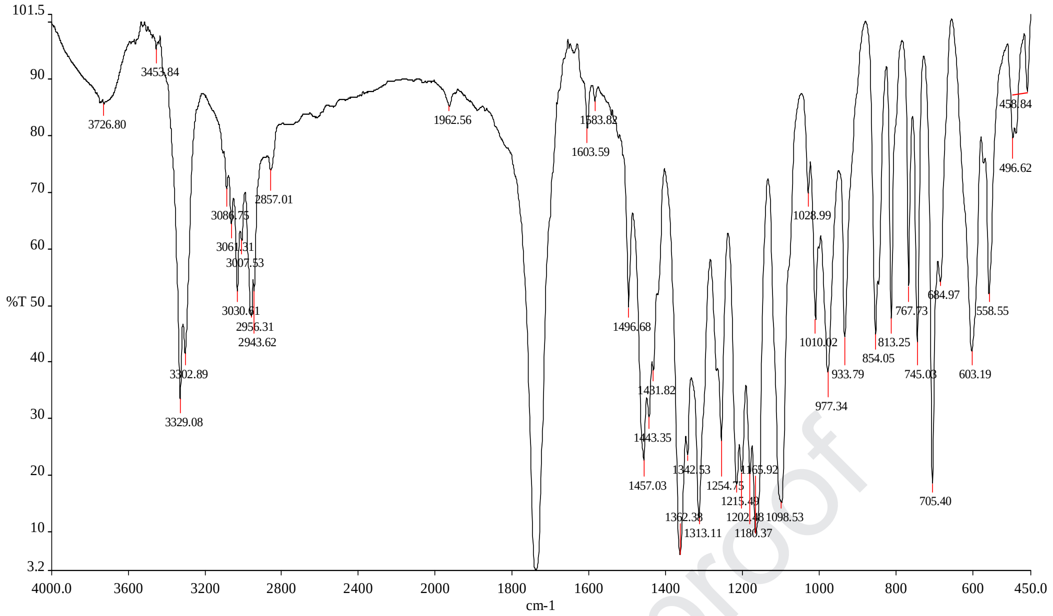
Additionally, the significant shift of the C-Cl stretching frequency was detected from 802 cm^{-1} towards lower frequency at 794 cm^{-1} after complexation.

Table 1 : Characteristic bands of infrared spectra of the acceptor, donor and their corresponding charge-transfer complex.

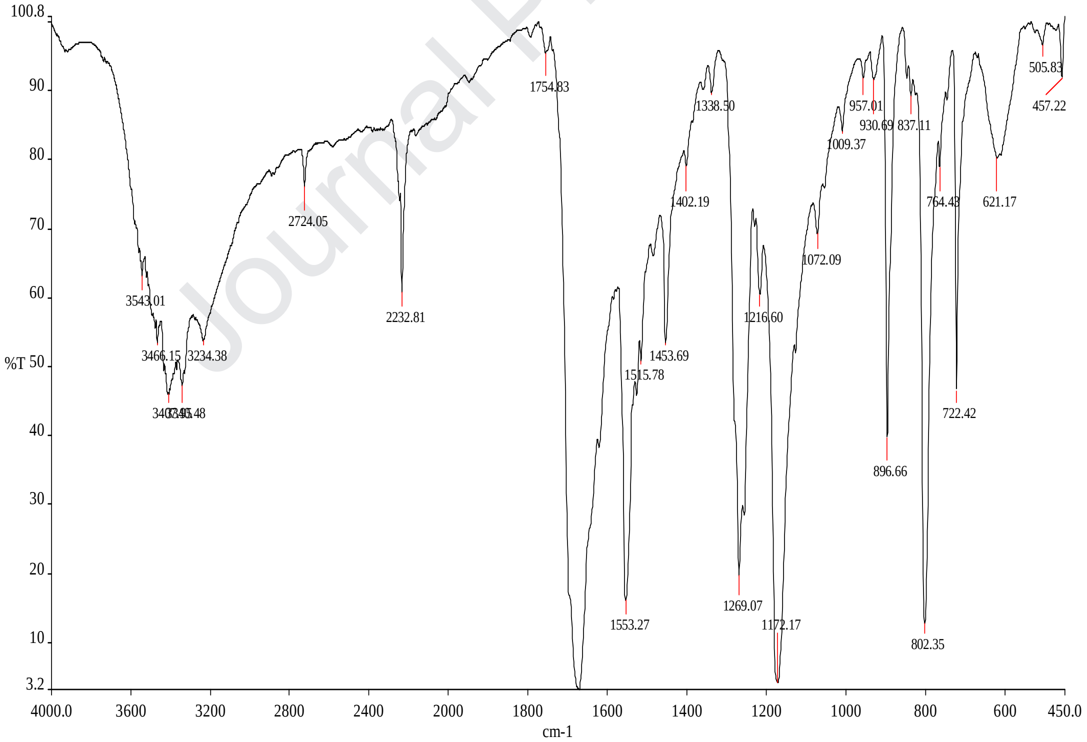
Donor	**DDQ**	**complex**	**Assignments**
3453w		3477br	ν (N-H) donor
3329s		3415br	
3302s			
	2232m	2031w	ν(C≡N) DDQ
1735vs,br		1730s	ν(C=O) donor
1603w		1617m	
		1637m	
	1670vs,br	1694s	ν (C=O) DDQ
1362vs		1356m	ν(SO_2) donor
1342s		1324w	
1313s			
	802vs	794m	ν(C-Cl) DDQ

s: strong, w: weak, m: medium, v: very, vs: very strong, br: broad.

(a)


101.5
90
80
70
60
%T 50
40
30
20
10
3.2
4000.0
3600
3200
2800
2400
2000
1800
1600
1400
1200
1000
800
600
450.0
cm-1
3726.80
3453.84
3329.08
3302.89
3086.75
3061.31
3007.53
3030.61
2956.31
2943.62
2857.01
1962.56
1603.59
1583.82
1496.68
1457.03
1443.35
1431.82
1362.38
1342.53
1313.11
1254.75
1215.49
1202.48
1180.37
1165.92
1098.53
1028.99
1010.02
977.34
933.79
854.05
813.25
767.73
745.03
705.40
684.97
603.19
558.55
496.62
458.84

(b)


100.8
90
80
70
60
%T 50
40
30
20
10
3.2
4000.0
3600
3200
2800
2400
2000
1800
1600
1400
1200
1000
800
600
450.0
cm-1
3543.01
3466.15
3234.38
340[illegible]
3345.48
2724.05
2232.81
1754.83
1553.27
1515.78
1453.69
1402.19
1338.50
1269.07
1216.60
1172.17
1072.09
1009.37
957.01
930.69
896.66
837.11
802.35
764.43
722.42
621.17
505.83
457.22

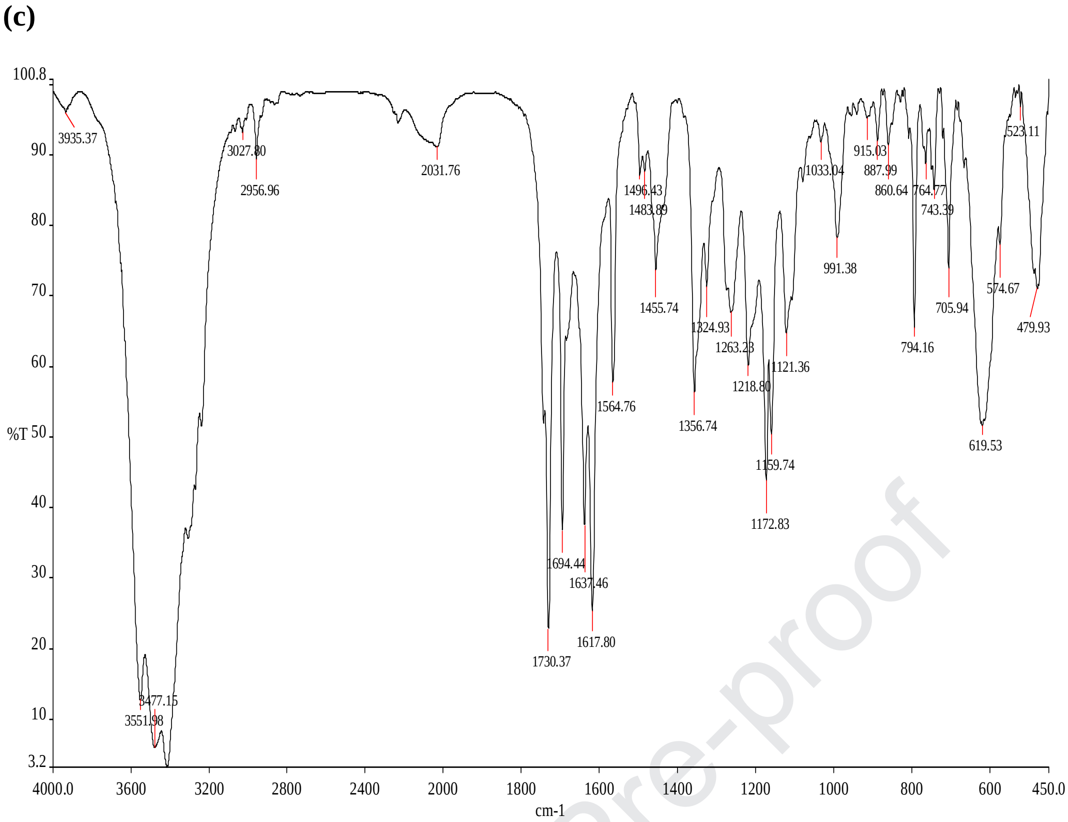


Fig.6. Experimental FT-IR spectra of donor (a), DDQ (b) and CTC complex (c).

4.5. Theoretical calculations:

We compare the optimized structural parameters (binding lengths and angles) of free molecule (donor and acceptor: DDQ) and those of its complex in vacuum and in solvent (see Tables 2 and 3). Fig.7 illustrates the most important intermolecular interactions. The binding energy ΔE of a complex formed [42, 43] by donor (D) and DDQ (A) can be obtained by the following equation:

$$\Delta E = E_{D\text{-}A} - (E_D + E_A) \qquad (2)$$

Where in our system $E_{D\text{-}A}$ is the minimized energy of the (D-A: Donor-Acceptor) complex. E_D and E_A are the energies of donor and DDQ molecules, respectively. The values of binding energy for complex obtained at CAM-B3LYP/631G++(d, p) in the vacuum and in acetonitrile are -9.91 and -3.75 Kcal/mol respectively. It should be noted that the value of the binding energy of the complex in acetonitrile is very low compared to vacuum.

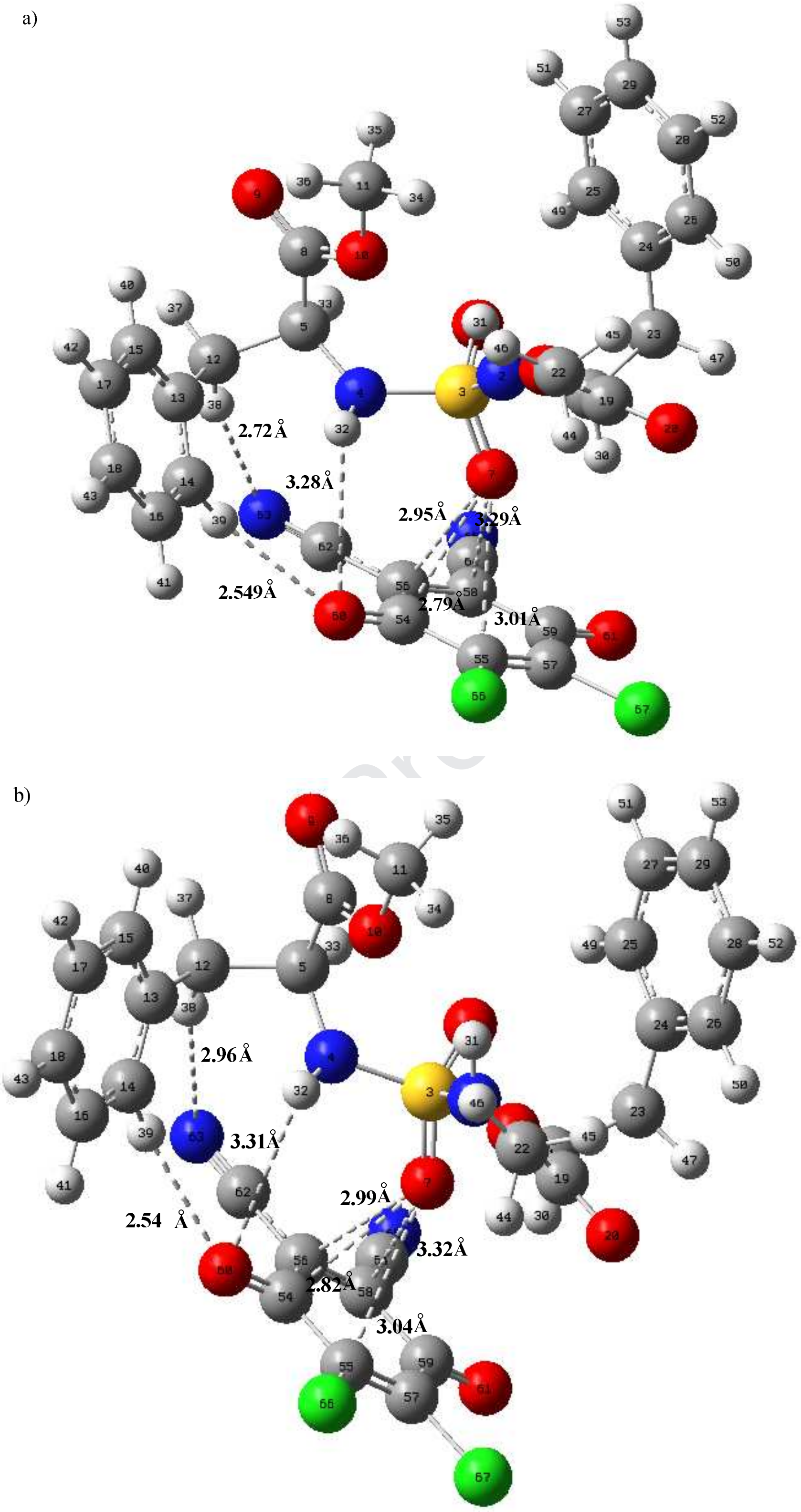


Fig.7. Optimized geometries of the complex in gas phase (a) and in acetonitrile (b) at CAMB3LYP/631G++(d,p) level of theory.

As can be seen from fig.7 the optimized structure of complex by a DFT method in gas phase, shows that O7...C54 inter-atomic distance is 2.793 Å and the O7…C56 distance was 2.969 Å, where the C54-C56 and C54-C55 bond lengths in the DDQ decrease slightly by 0,002 and 0,003 Å respectively in the complex. In addition the inter-atomic distances O7…C55 and O7…C58 as noted in complex are 3.017 Å and 3.294 Å respectively; witch the bond length for C58-C59 is decreased by 0,002 Å.

Apart from that, we noted an elongation of S3-O7 bond (1.462 Å) compared to the isolated donor molecule (1.452 Å) and a decrease in the bond angles O6S3O7 by 1.3° in complex (see Table 3). On the other hand, as displayed in Fig7 three bonding interactions are observed between O60…H39C14 with a bond distance of 2.549 Å. This bond distance is shorter than the N63…H38C12 and O60…H32 from (2.720 Å, 3.281 Å) respectively.

Whereas, the C54-C60 and N4-H32 distances: 1.013 Å in acceptor and 1.200 Å in donor increased with 0.002 and 0,001 Å respectively when they are compared to the complex. The most remarkable feature is that the charges on H39, H38 and H32 atoms are +0.158 e, +0.194 e and +0.425 e respectively. They are found to increase after complexation to be: +0.215 e, +0.242 e and +0.464 e respectively.

In the case of the solvent effect on the molecular structures modeled by PCM procedure; as displayed in Fig7; the most important point to be mentioned here is that the: O7...C54, O7…C56, O7…C55, O7…C58, N63…H38C12, O60…H32 interaction distances are increased by 0.035, 0.033, 0.023, 0.035, 0.24, 0.034 Å in comparison with the complex in vacuum, except the O60…H39C14 distance which decreases slightly by 0.006 Å. To elucidate these results and assess the solvent effect, we have investigated the charge NBO in vacuum and in CH3CN as solvent.

Table 2: Selected bond lengths (Å) of donor, of DDQ and of CTC complex calculated by using CAM-B3LYP/6-31G++(d,p) method.

Parameters	Donor	acceptor	complex
S3O7	1.452 (1.458)		1.462 (1.462)
S3O6	1.461 (1.463)		1.458 (1.462)
S3N2	1.660 (1.654)		1.653 (1.650)
S3N4	1.644 (1.637)		1.638 (1.636)
N4H32	1.013 (1.015)		1.015 (1.016)
N2H31	1.016 (1.017)		1.017 (1.017)
C54C55		1.493 (1.490)	1.490 (1.489)
C54C56		1.500 (1.499)	1.498 (1.498)

C55C57		1.346 (1.345)	1.344 (1.344)
C56C58		1.347 (1.344)	1.345 (1.343)
C58C59		1.500 (1.499)	1.498 (1.497)
C57C59		1.498 (1.490)	1.492 (1.488)
C54C60		1.207.208)	1.209 (1.209)
C59O61		1.207 (1.208)	1.207 (1.210)

All values between parenthesis correspond to the bond lengths in acetonitrile medium

Table 3: Selected bond angles of donor, of DDQ and of CTC complex calculated by using CAM-B3LYP/6-31G ++(d, p) method.

Parameters	Donor	acceptor	complex
O6S3O7	119.4 (117.9)		118.1 (117.5)
N2S3O6	113.1 (113.5)		114.1 (114)
N2S3O7	105.2 (105.4)		104.8 (105.1)
O6S3N4	105.4 (106)		106.2 (106.3)
O7S3N4	110.3 (110.2)		109.9 (110.2)
S3N2C1	118.8 (119.6)		119.4 (119.7)
C14C12C13	120.5 (120.6)		120.6 (120.6)
H38C12H37	108.1 (107.7)		107.9 (107.8)
C5N4H32	118.1 (117.6)		117.5 (117.5)
C16C14H39	119.7 (119.6)		119.5 (119.5)
C13C14H39	119.4 (119.5)		119.8 (119.7)
C1C3C9		116.3 (116.2)	115.9 (116.1)
C9C3C5		122.5 (122.7)	122.7 (122.6)
C3C5C6		121.2 (121.2)	120.9 (121.1)

All values between parentheses correspond to the bond lengths in acetonitrile medium

4.5.1. Electronic spectroscopic properties:

The comparison of absorption wavelengths λ_{max} between the experimental findings and theoretical results of DDQ, of the donor and of their complex in acetonitrile is presented in Table 4. While, experimental peaks maximum of the free molecules of Donor appeared at 196 nm and 208 nm TD-DFT predicted the calculated peaks maximum in acetonitrile at 204.79 nm, 205.20 nm and 210.90 nm. In parallel, the experimental values of $ʎ_{max}$(nm) of DDQ are as follows : 208, 226, 272, 280 and 348 nm and their corresponding calculated values are : 204.83, 224.64, 271.19, 276.90 and 370.73 nm. For CTC complex, the computed absorption maximum obtained at about 220.08 nm, 224.36 nm, 237.38 nm, 251.79 nm, 278.65 nm, 292.24 nm, 342.59 nm and at 347.66 nm are compared with the corresponding experimental values : 196, 208, 234, 258, 270, 280 and 346 nm respectively. Hence, the reasonable agreement between the theoretical and experimental results reflects well the suitability of CAM-B3LYP/6-311++G (d,p) method for this type of study.

Table 4: Experimental and computed UV-vis data of the free molecules and their complex in acetonitrile.

λ_{max}(nm) Theoretical			λ_{max}(nm) Experimental		
Donor	DDQ	complex	Donor	DDQ	complex
210.90			208		
	370.73	347.66		348	346
		342.59			/
	276.90	292.24		280	280
205.20			/		
	271.19	278.65		272	270
	224.64	251.79		226	258
204.79	204.83	237.38	196	208	234
	190.19	224.36		/	208
		220.08			196

The computed electronic values, such as absorption wavelength (λ_{max}), the transition energies, and oscillator strengths of electronic transitions for complex in acetonitrile are given in Table S1 (in supplementary data). The theoretical absorption spectra of DDQ, of the donor and of the complex are displayed in Fig 8. The primary strong band at 224.36 nm with the greater oscillator strength value at 0.3518 are assigned to the predominant transitions: HOMO-6 → LUMO+1 (59.15 %), HOMO-5 → LUMO+1 (26.50 %). The secondary strong band appeared at 278.65 nm (f = 0.3436) is mainly caused by the following transitions: HOMO -8 →LUMO (78.18 %) and HOMO -5 ->LUMO (8.65 %). The absorption at 292.24 nm has up to five configurations for electronic excitations: HOMO -6 → LUMO (29.90 %), HOMO -5 → LUMO (51.85 %), HOMO -14 →LUMO (3.12%), HOMO -8 → LUMO (4.72%), HOMO -7 → LUMO (2.68%).

In addition, the TD-DFT analysis has provided other maximum absorptions which have very small oscillator strength, the corresponding wavelengths are as follow: 347.66 nm (f = 0.0021), 342.59 nm (f = 0.0022), 251.79 nm (f=0.0082), 237.38 nm (f= 0.0191) and 220.08 nm (f=0.0099). Their transition contributions are also reassembled in Table S1. Then, we presented in Figure 9 some of the molecular orbitals and their corresponding energies based on the geometries optimized with CAM-B3LYP/6-31++G (d,p) method. The strong value of excitation energy was obtained at 224.36 nm. The strong value of Energy was obtained at

HOMO-6 and LUMO+1 at 224.36 nm: -9.55 eV and -1.50 eV and the calculated difference in energy ΔE for complex was: -8.05 eV.

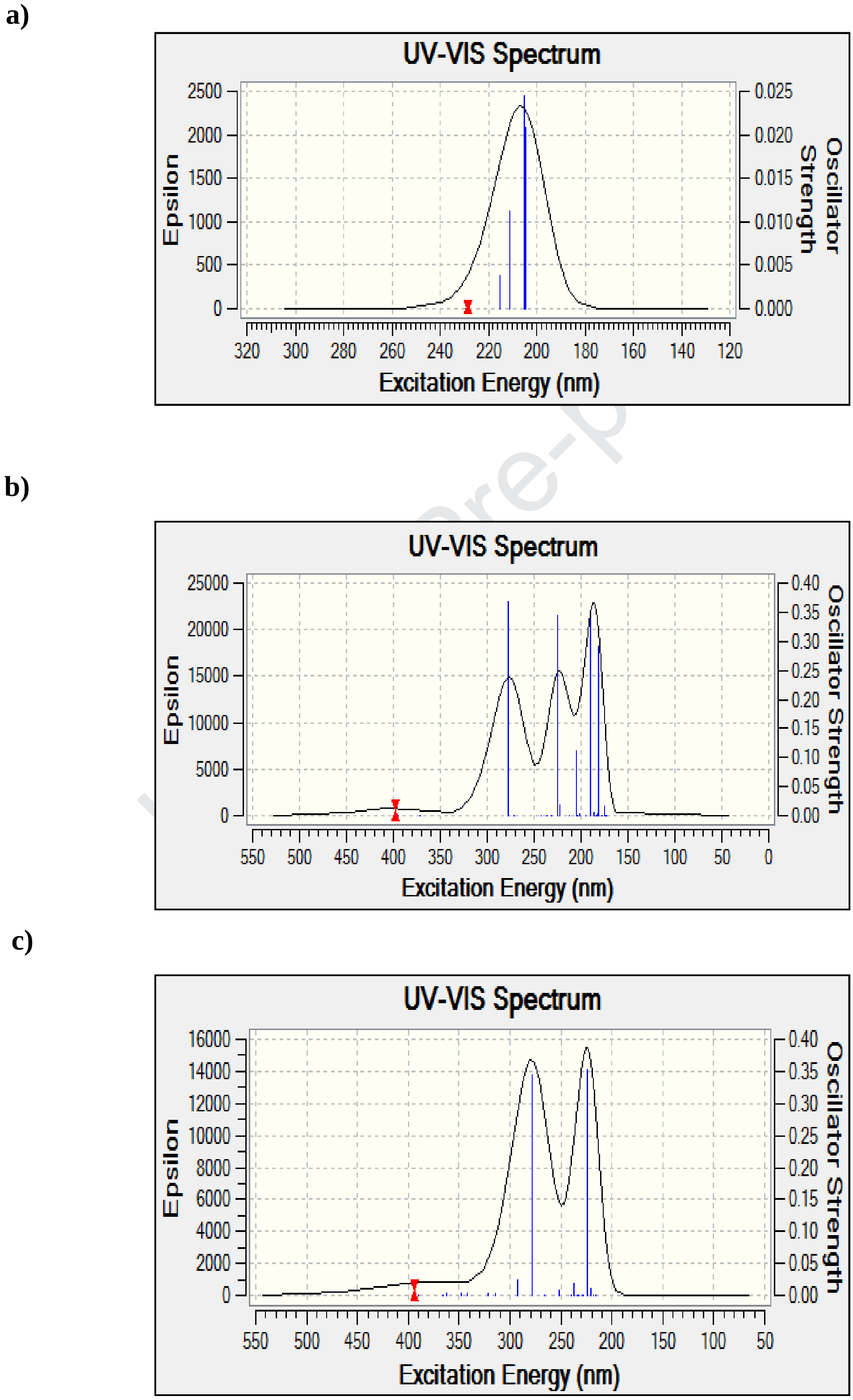


Fig.8. TD-DFT calculated absorption spectra of donor (a), DDQ (b) and their CTC complex (c).

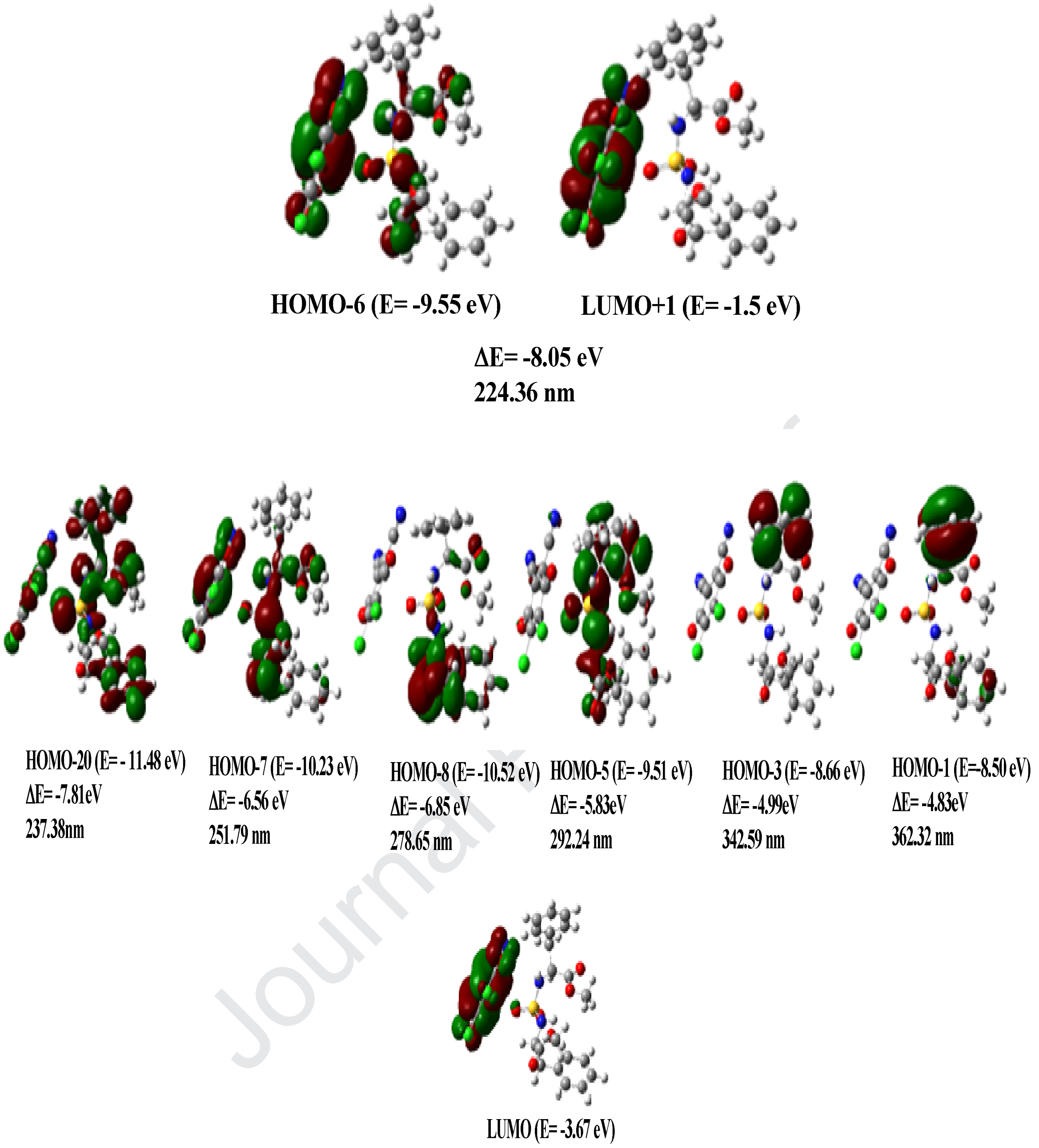


Fig.9. Theoretical electronic absorption transitions for complex in acetonitrile.

4.5.2. Charge analysis Natural bond orbital (NBO):

The NBO method is a valuable approach for the investigation of molecular bonding interactions, atomic charges, and to analyze the charge transfer process [44]. In the NBO analysis of X-H…Y hydrogen bonded systems, the interaction between the lone pair (LP) (Y) of the proton acceptor and σ* (X-H) anti-bond of proton donor is characterized by a significant $E^{(2)}$ stabilization energy [45]. The results of the NBO charges for donor, for DDQ and for their complex (in gas phase and in acetonitrile) were been performed by the B3LYP/6-31++G (d, p) method.

As apparent in the table S2, the NBO results show that the complexation increases the positive electronic charge of the H39, H38 and H32 atom and increases the negative electronic charge of the O60 and N63 atoms involved in hydrogen bonds. In addition, the NBO charge on the O61, N65, Cl66 and Cl67 atoms of complex are found to be more negative than that obtained for the individual DDQ molecule, suggesting that a charge is transferred from donor to DDQ. In addition, in the gas phase, the electronic charge NBO on the S3 atom of the complex increases from 2.503 e to 2.512 e. The result is opposite in acetonitrile where the charge of the S3 atom in the complex decreases by passing from 2.521e to 2.515 e. A comparison between the calculated NBO charge in vacuum and in acetonitrile as a solvent for DDQ complex was listed in Table S2. Other slight changes have also been observed.

In Tables 5, 6 we present some of the significant donor–acceptor interactions and their stabilization energies (E^2) in vacuum and in solvent. As shown in Table 5, the greater interaction is formed between LP(1)O7…BD*(2)C54-O60 (0.92 kcal/mol) and LP(3)O 7…. BD*(2)C54-O60 (1.47 kcal/mol). In case of DDQ and bis –L-aminoester sulfone, the NBO analysis clearly shows the existence of two inter-molecular hydrogen bonds between lone pairs : LP(1)O60, LP(2)O60 and LP(1)N63 and BD*(1)C14-H39, BD*(1)C14-H39 and BD*(1)C12-H38 respectively.

The corresponding E^2 values are 0.63, 0.37 and 0.35 kcal/mol in vacuum and 0.69, 0.30 and 0.08 kcal/mol in solvent. Consequently NBO analysis confirms the charge transfer nature between the donor molecule bis –L-aminoester sulfone and DDQ.

Table 5 : Donor–acceptor interactions and stabilization energies E^2 (kcal/mol) in vacuum.

Donor	**Acceptor**	**E^2 (kcal/mol) CAM-B3LYP 6-31++G (d,p)**
complex in vacuum		
bis –L-aminoester sulfone Donor and DDQ Acceptor		
BD(1)C12-H38	BD*(2)C62-N63	0.05
BD(1)C12-H38	BD*(3)C62-N63	0.08
LP(1)O7	BD*(1)C54-O60	0.06
LP(1)O7	BD*(2)C54-O60	0.92
LP(1)O7	BD*(2)C55-C57	0.09
LP(1)O7	BD*(2)C56-C58	0.09
LP(2)O7	BD*(2)C55-C57	0.08
LP(2)O7	BD*(2)C56-C58	0.23
LP(3)O7	BD*(2)C54-O60	1.47
LP(3)O7	BD*(2)C55-C57	0.13
LP(3)O7	BD*(2)C56-C58	0.22
DDQ Donor and bis –L-aminoester sulfone Acceptor		
BD(2)C54-O60	BD*(1)C14-H 39	0.07
BD(2)C55-C57	BD*(1)S3-O7	0.05

BD(2)C62-N63	BD*(1)C12-H38	0.15
BD(3)C62-N63	BD*(1)C12-H 38	0.21
LP(1)O60	BD*(1)C14-H39	0.63
LP(2)O60	BD*(1)C14-H39	0.37
LP(1)N63	BD*(1)C12-H38	0.35
BD*(2)C54-O60	BD*(1)S3-O7	0.06

Table 6 : Donor–acceptor interactions and stabilization energies E² (kcal/mol) in acetonitrile.

Donor	**Acceptor**	**E² (kcal/mol) CAM-B3LYP 6-31++G (d,p)**
complex in CAN		
bis –L-aminoester sulfone Donor and DDQ Acceptor		
BD(1)C14-H39	BD*(2)C54-O60	0.05
LP(1)O7	BD*(1)C54-O60	0.06
LP(1)O7	BD*(2)C54-O60	0.79
LP(1)O7	BD*(2)C55-C57	0.08
LP(1)O7	BD*(2)C56-C 58	0.09
LP(2)O7	BD*(2)C55-C57	0.09
LP(2)O7	BD*(2)C56-C58	0.20
LP(3)O7	BD*(2)C54-O60	1.32
LP(3)O7	BD*(2)C55-C57	0.13
LP(3) O7	BD*(2)C56-C58	0.20
DDQ Donor and bis –L-aminoester sulfone Acceptor		
BD(2)C54-O60	BD*(1)C14-H39	0.09
BD(2)C62-N63	BD*(1)C12-H38	0.07
BD(3)C62-N63	BD*(1)C12-H38	0.09
LP(1)O60	BD*(1)C14-H39	0.69
LP(2)O60	BD*(1)C14-H39	0.30
LP(1)N63	BD*(1)C12-H38	0.08
BD*(2)C54-O60	BD*(1)S3-O7	0.05

Conclusion:

In this study, we have synthesized a novel charge transfer complex CTC ((S, S)-bis-N, N-sulfonyl bis –L-phenylalanine dimethylester-DDQ). Elemental analyses, electronic absorption, FT- IR were used to characterize the donor, the acceptor and the new product. The binding ratio of complexation was determined to be 1:1 according to the photometric titrations. The obtained data show that the CT-complex has high values of K_{CT} and ε_{CT}. The confirmation of these results was also checked by theoretical calculations. The molecular geometrical parameters, the electronic properties, the natural population analysis (NPA) and Natural bond orbital (NBO) of the compounds have been calculated by using DFT (CAM-B3LYP) method with 6-31++G(d,p) basis set. The spectral data in acetonitile as a solvent were computed and compared to the experiment, indicating that TD-DFT/PCM calculations provide good results. Consequently, theoretical and experimental results have indeed confirmed the formation of charge transfer complex.

Acknowledgments:

This study was supported by the Algerian minister of higher education and scientific research through the CNEPRU research grants.

References:

[1] A.W. Acton, A.D. Allen, L.M. Antunes, A.V. Fedorov, K. Najafian, T.T. Tidwell, B.D. Wagner, Amination of pyridylketenes: experimental and computational studies of strong amide enol stabilization by the 2-pyridyl group, J. Am. Chem. Soc. 124 (2002) 13790-13794.

[2] N. Bensouilah, B. Boutemeur-Kheddis, H. Bensouilah, I. Meddour, M. Abdaoui ; Host-guest complex of nabumetone: β-cyclodextrin: quantum chemical study and QTAIM analysis, J. Incl Phenom Macrocycl Chem , DOI 10.1007/s10847-016-0690-4.

[3] A. Allerhand, Von Rauge Schleyer, P. A Survey of C-H Groups as Proton Donors in Hydrogen Bonding, J. Am. Chem.Soc., 1963, 85, 1715-1723.

[4] M. Pandeeswaran, KP. Elango, Solvent effect on the charge transfer complex of oxatomide with 2,3-dichloro-5,6-dicyanobenzoquinone, Spectrochim. Acta A 65 (2006) 1148.

[5] K. Ganesh, C. Balraj, A. Satheshkumar, Spectroscopic investigation on the mechanism of formation of molecular complexes of albendazole and trimethoprim with 2,3-dichloro-5,6-dicyano-1,4-benzoquinone.Spectrochim. Acta A 92 (2012) 46-55.

[6] E.A. Braude, A.G. Brook, R.P. Linstead, Hydrogen transfer. Part IV. The use of quinines of high potential as dehydrogenating reagents, J. Chem. Soc. (1954) 3569–3574.

[7] Y. Zhang, F. Zhang, K. Ma, G. Tang, Experimental and DFT studies on the vibrational and electronic spectra of 2,3-dichloro-5,6-dicyano-1,4-benzoquinone, Spectrochimica Acta Part A: Molecular and Biomolecular Spectroscopy 105 (2013) 352–358.

[8] A.M. Slifkin, Charge Transfer Interaction of Biomolecules. Academic Press, New York, USA, 1971.

[9] a) B. Pullman, Molecular Association in Biology, Academic Press, New York, USA,1968. b) K.A. Connors, Binding Constants, Wiley, New York, USA, 1987.

[10] A. Korolkovas, Essentials of Medicinal Chemistry, second Ed., Wiley, New York, USA, 1998 (Ch. 3).

[11] A. Majid, A. Adam. Synthesis, spectroscopic, thermal and antimicrobial investigations of charge-transfer complexes formed from the drug procaine hydrochloride with quinol, picric acid and TCNQ, Journal of Molecular Structure, 1030 (2012), 26-39.

[12] I.M. Khan, A. Ahmad, M.F. Ullah, Synthesis, crystal structure, antimicrobial activity and DNA-binding of hydrogen-bonded proton-transfer complex of 2,6-diaminopyridine with picric acid, J. Photochem. Photobiol. B 103 (2011) 42-49.

[13] I.M. Khan, A. Ahmad, M.F. Ullah, Synthesis, spectroscopic investigations, antimicrobial and DNA binding studies of a new charge transfer complex of o-phenylenediamine with 3,5-dinitrosalicylic acid, Spectrochim. Acta A 102 (2013) 82-87.

[14] I.M. Khan, A. Ahmad, M. Aatif, Synthesis, single-crystal characterization, antimicrobial activity and remarkable in vitro DNA interaction of hydrogen-bonded proton-transfer complex of 1,10-phenanthroline with 2,4,6-trinitrophenol, J. Photochem. Photobiol. B 105 (2011) 6-15.

[15] M. Saravanabhavan, K. Sathya, V.G. Puranik, M. Sekar, Synthesis, spectroscopic characterization and structural investigations of new adduct compound of carbazole with picric acid: DNA binding and antimicrobial studies, Spectrochim. Acta A. Mol. Biomol. Spectrosc. 118 (2014) 399-406.

[16] A.I. Esteban, E. De Clercq, and A. Martinez, *Bioorg. Med.Chem. Lett,* 1997, vol. 7, p 540.

[17] A. Andreani, M. Rambaldi, A. Locatelli, A.M. Isetta, Synthesis and mitogenic activity of new imidazo[2,1-*b*]thiazoles, Eur. J. Med. Chem. 26 (1991) 335–337.

[18] D.A. Horton, G.T. Bourne, and M.L. Smythe, The Combinatorial Synthesis of Bicyclic Privileged Structures or Privileged Substructures. Chem. Rev. 103 (2003) 893-930.

[19] (a) W. Schaal, A. Karlsson, G. Ahlse´n, J. Lindberg, H. O. Andersson, U. H. Danielson, B. Classon, T. Unge, B. Samuelsson, J. Hulte´n, A. Hallberg, Karle´n, A. Synthesis and Comparative Molecular Field Analysis (CoMFA) of Symmetric and Nonsymmetric Cyclic Sulfamide HIV-1 Protease Inhibitors . J. Med.Chem. 2001, 44, 155-169. (b) J. Hulten, H. O. Andersson, W. Schaal, H. U. Danielson, B. Classon, I. Kvarnstro¨m, Karle´n, T. Unge, B. Samuelson, Hallberg, A. Inhibitors of the C_2-Symmetric HIV-1 Protease: Nonsymmetric Binding of a Symmetric Cyclic Sulfamide with Ketoxime Groups in the P2/P2‘ Side Chains J. Med. Chem. 42 (1999) 4054-4061. (c) K. Ba¨ckbro, S. Lo¨wgren, K. Osterlund, J. Atepo, T. Unge, J. Hulte´n, N. M. Bonham, W. Schaal, A. Karle´n, Hallberg, A. Unexpected Binding Mode of a Cyclic Sulfamide HIV-1 Protease Inhibitor. J. Med. Chem. 40 (1997) 898-902. (d) P. K. Jadhav, F. Woerner, Synthesis of 8-membered cyclic sulfamides: Novel HIV-1 protease inhibitors, J. Tetrahedron Lett. 36 (1995) 6383-6386.

[20] R.M. Acheson , M.G. Bite ,J.E.G Kemp , Acidic epinephrine analogs derived from 1H, 3H-2, 1, 3-benzothiadiazole 2,2-dioxide and from trifluoromethanesulfonanilide. New synthesis of 1H, 3H-2, 1, 3-benzothiadiazole 2,2-dioxide, J. Med. Chem. 24 (1981) 1300-1304.

[21] J. M. Dougherty, Probst, D.A. Robinson, R.E. Moore, J.D. Klein, T.A. Snelgrove, K.A. Hanson, P.R. Ring-Closing, Metathesis Strategies to Cyclic Sulfamide Peptidomimetics, Tetrahedron, 56 (2000) 9781-9790.

[22] Luciana Gavernet, H. S. Cisneros, L.E. Bruno-Blanch, E.Guillerminal L, Synthesis of anticonvulsant sulfamides. Theoretical study of the related mechanism, Theor Chem Acc (2003) 110: 434–440, DOI 10.1007/s00214-003-0499-2.

[23] M. Mohamdi, N. Bensouilah , M. Abdaoui, Investigation of charge transfer complexes formed between (S, S)-bis-N,N-sulfonyl bis-L-phenylalanine dimethylester donor with tetracyanoethylene and chloranil as π-acceptors: Experimental and DFT studies, Journal of Theoretical and Computational Chemistry Vol. 15, No. 1 (2016) 1650009.

[24] M. Brenner and W.Huber, Preparation of α-amino acid esters by alcoholysis of the methyl esters, *Helv. Chim. Acta*, 36 (1953) 1109-1115.

[25] K. Sharmaa, S.P. Sharmab, S.C. Lahiri, Spectrophotometric, Fourier transform infrared spectroscopic and theoretical studies of the charge–transfer complexes between methyldopa [(S)-2 amino-3-(3,4-dihydroxyphenyl)-2-methyl propanoic acid] and the acceptors (chloranilic acid, o-chloranil and dichlorodicyanobenzoquinone) in acetonitrile and their thermodynamic properties, Spectrochimica Acta Part A 92 (2012) 212– 224.

[26] L. Shahada, A. Mostafa, E-M. Nour, H.S. Bazzi, Synthesis, spectroscopic, thermal and structural investigations of charge-transfer complexes of 4,40-trimethylenedipiperidine with chloranil, TBCHD, DDQ, TCNQ and iodine, J. Mol. Str. 933 (2009) 1–7.

[27] HA. Benesi, JH. Hildebrand,A spectrophotometric investigation of the interaction of iodine with aromatic hydrocarbons, J. Am. Chem. Soc. 71 (1949) 2703-2707.

[28] A. Mostafa, H.S. Bazzi, Synthesis and spectroscopic studies of the charge transfer complexes of 2- and 3-aminopyridine, Spectrochimica Acta Part A 74 (2009) 180–187.

[29] H. Fisli, N. Bensouilah, M. Abdaoui, Spectrofluorimetric determination of the antineoplastic agent lomustine based on the sensitizing effect of β-cyclodextrin ; Luminescence, The journal of biological and chemical luminescence , 2016; 31: 871–880.

[30] MJ. Frisch, GW. Trucks, HB. Schlegel, GE. Scuseria, MA. Robb, JR. Cheeseman, G. Scalmani, V. Barone, B. Mennucci, GA. Petersson, H. Nakatsuji, M. Caricato, Li X, H P. Hratchian, AF. Izmaylov, J. Bloino, G. Zheng, JL. Sonnenberg , M. Hada, M. Ehara, K. Toyota, R. Fukuda, J. Hasegawa, M. Ishida, T. Nakajima, Y. Honda, O. Kitao, H. Nakai, T. Vreven, JA Jr. Montgomery, JE. Peralta, F. Ogliaro, M. Bearpark, JJ. Heyd, E. Brothers, K N. Kudin, VN. Staroverov, R. Kobayashi, J. Normand, K. Raghavachari, A. Rendell, JC. Burant, SS. Iyengar, J. Tomasi, M. Cossi, N. Rega, JM. Millam, M. Klene, JE. Knox, JB. Cross, V. Bakken, C. Adamo, J. Jaramillo, R. Gomperts, RE. Stratmann, O. Yazyev, AJ. Austin, R. Cammi, C. Pomelli, JW. Ochterski, RL. Martin, K. Morokuma, VG. Zakrzewski, GA. Voth, P. Salvador, JJ. Dannenberg, S. Dapprich, AD. Daniels, O.

Farkas, JB. Foresman, JV. Ortiz, J. Cioslowski, DJ. Fox, (2009) Gaussian 09, Revision A.02. Gaussian Inc,Wallingford, CT.

[31] A. Frisch, A.B. Nielsen, A.J. Holder, Gauss View user manual, Gaussian, Inc., Pittsburgh, PA, 2000.

[32] T. Yanai, D.P. Tew, N.C. Handy, A new hybrid exchange-correlation functional using the Coulomb-attenuating method (CAM-B3LYP), Chem. Phys. Lett, 393 (2004) 51-57.

[33] P. Mach, G. Juhász, O. Kyse, Theoretical study of electronic absorptions in aminopyridines–TCNE CTcomplexes by quantum chemical methods, including Solvent, Springer-Verlag 2012, J Mol Model (2013) 19:4639–4650 DOI 10.1007/s00894-012-1437-9.

[34] J.E. Carpenter, F. Weinhold, Analysis of the geometry of the hydroxymethyl radical by the “different hybrids for different spins” natural bond orbital procedure, J. Mol. Struct. (Theochem) 169 (1988) 41-62.

[35] A. E. Reed, L.A. Curtiss, F. Weinhold, Intermolecular Interactions from a Natural Bond Orbital, Donor-Acceptor Viewpoint, Chem. Rev. 88 (1988) 899-926.

[36] N. Bensouilah, H. Fisli, H. Bensouilah, S. Zaater, M. Abdaoui, B. Boutemeur-Kheddis, Host-guest complex of *N*-(2-chloroethyl), *N*-nitroso, *N′*, *N′* -dicyclohexylsulfamid with β-cyclodextrin: Fluorescence, QTAIM analysis and structure-chemical reactivity, J. Mol. Str. 1146 (2017) 179-190.

[37] C. Meenakshi, P. Jayabal, V. Ramakrishnan, Molecular recognition of curcumin (Indian Ayurvedic medicine) by the supramolecular probe, p-t-butyl calix(8)arene, Spectrochimica Acta Part A: Mol. Biom. Spect. 127 (2014) 172–176.

[38] E. Asker, E. Uzkara, O. Zeybek, Effects of methyl substituent on the charge-transfer complexations of dicarbazolylalkanes with p-chloranil, tetracyanoethylene and tetracyanoquinodimethane, Spectrochimica Acta Part A 79 (2011) 1731– 1738.

[39] A. V. Zubkov and T. V. Ivanova, Approximate Equations for the Determination of Complexing Parameters: Applicability Criteria, Journal of Solution Chemistry, 11 (1982) 699–717.

[40] R. S. Mulliken, Molecular Compounds and their Spectra. II, J. Am. Chem. Soc. 74 (1952) 811–824.

[41]S.Y. AlQaradawi,H.S. Bazzi, A. Mostafa, N. El-Metwally, Novel charge transfer complexes of the donor 1,4,7,10,13,16-hexamethyl-1,4,7,10,13,16-hexaazacyclooctadecane and the acceptors iodine,TCNE, and TCNQ, Journal of Molecular Structure 998 (2011) 126–135.

[42] S. Sadaoui-Kacel, S. Zaater, N. Bensouilah, S. Djebbar, Novel repaglinide complexes with manganese (II), iron(III), copper(II) and zinc(II): spectroscopic, DFT characterization and electrochemical behavior, J. Str. Chem. 57 (2016) 1519-1530.

[43] N. Bensouilah, M.Abdaoui, Inclusion complex of N-nitroso, N-(2-chloroethyl), N', N'-dibenzylsulfamid with β-Cyclodextrin: Fluorescence and molecular modeling, C. R. Chimie 15 (2012) 1022-1036.

[44] a) P. Hobza, Z. Havlas, Blue-shifting hydrogen bonds, Chem. Rev. 100 (2000) 4253-4264**;** b) P. Hobza, V. Spirko, HL. Selzle, EW. Schlag, Anti-hydrogen bond in the benzene dimer and other carbon proton donor complexes, (1998) J. Phys. Chem. A. 102 (1998) 2501–2504.

[45] A.E. Reed, L.A. Curtiss, F. Weinhold, Intermolecular interactions from a natural bond orbital, donor-acceptor view point, Chem. Rev. 88 (1988) 899-926.

Highlights

The Highlights of research are as follows:

1- The new CTC complex formed between (S, S)-bis-N,N-sulfonyl bis-L-phenylalanine dimethylester and DDQ was synthesized.

2- The molar ratio method and Benesi-Hildebrand methods were applied to the determination of stoichiometric ratio and association constant (K).

3- The CTC was theoretically investigated using DFT:CAM/B3LYP and TD-DFT methods.

4- The NBO methodology provides a qualitative picture of the charge-transfer process between the acceptor and donor partners.