This item is the archived peer-reviewed author-version of:

Spectroscopic investigations and molecular docking study of (2E)-1-(4-Chlorophenyl)-3-[4-(propan-2-yl)phenyl]prop-2-en-1-one using quantum chemical calculations

Reference:

Parveen Shana, Al-Alshaikh Monirah A., Panicker C. Yohannan, El-Emam Ali A., Saliyan Vinutha V., Narayana B., Sarojini B.K., Van Alsenoy Christian.- Spectroscopic investigations and molecular docking study of (2E)-1-(4-Chlorophenyl)-3-[4-(propan-2-yl)phenyl]prop-2-en-1-one using quantum chemical calculations
Journal of molecular structure - ISSN 0022-2860 - 1120(2016), p. 317-326
Full text (Publisher's DOI): <https://doi.org/10.1016/J.MOLSTRUC.2016.05.030>
To cite this reference: <http://hdl.handle.net/10067/1362480151162165141>

Accepted Manuscript

Spectroscopic investigations and molecular docking study of (2*E*)-1-(4-Chlorophenyl)-3-[4-(propan-2-yl)phenyl]prop-2-en-1-one using quantum chemical calculations

Shana Parveen, Monirah A. Al-Alshaikh, C. Yohannan Panicker, Ali A. El-Emam, Vinutha V. Salian, B. Narayana, B.K. Sarojini, C. van Alsenoy

PII: S0022-2860(16)30476-8

DOI: [10.1016/j.molstruc.2016.05.030](https://doi.org/10.1016/j.molstruc.2016.05.030)

Reference: MOLSTR 22544

To appear in: *Journal of Molecular Structure*

Received Date: 27 October 2015

Revised Date: 10 March 2016

Accepted Date: 10 May 2016

Please cite this article as: S. Parveen, M.A. Al-Alshaikh, C.Y. Panicker, A.A. El-Emam, V.V. Salian, B. Narayana, B.K. Sarojini, C. van Alsenoy, Spectroscopic investigations and molecular docking study of (2*E*)-1-(4-Chlorophenyl)-3-[4-(propan-2-yl)phenyl]prop-2-en-1-one using quantum chemical calculations, *Journal of Molecular Structure* (2016), doi: 10.1016/j.molstruc.2016.05.030.

This is a PDF file of an unedited manuscript that has been accepted for publication. As a service to our customers we are providing this early version of the manuscript. The manuscript will undergo copyediting, typesetting, and review of the resulting proof before it is published in its final form. Please note that during the production process errors may be discovered which could affect the content, and all legal disclaimers that apply to the journal pertain.

Graphical abstract

Title of the paper: Spectroscopic investigations and molecular docking study of (2*E*)-1-(4-Chlorophenyl)-3-[4-(propan-2-yl)phenyl]prop-2-en-1-one using quantum chemical calculations

Spectroscopic investigations and molecular docking study of (2*E*)-1-(4-Chlorophenyl)-3-[4-(propan-2-yl)phenyl]prop-2-en-1-one using quantum chemical calculations

Shana Parveen S^a, Monirah A.Al-Shaikh^b, C.Yohannan Panicker^{c*}, Ali A.El-Emam^d,
Vinutha V.Salian^e, B.Narayana^e, B.K.Sarojini^f, C.Van Alsenoy^g

^aDepartment of Physics, TKM College of Arts and Science, Kollam, Kerala, India

^bDepartment of Chemistry, College of Sciences, King Saud University, Riyadh 11451,
Saudi Arabia

^cDepartment of Physics, Fatima Mata National College, Kollam, Kerala, India

^dDepartment of Pharmaceutical Chemistry, College of Pharmacy, King Saud University,
Riyadh 11451, Saudi Arabia

^eDepartment of Studies in Chemistry, Mangalore University, Mangalagangothri,
Karnataka, India.

^fDepartment of Studies in Industrial Chemistry, Mangalore University,
Mangalagangothri, Karnataka, India.

^gDepartment of Chemistry, University of Antwerp, Groenenborgerlaan 171, B-2020
Antwerp, Belgium

*author for correspondence: email: cyphyp@rediffmail.com

Abstract

In this work, the vibrational spectral analysis was carried out using FT-IR and FT-Raman spectroscopy of (2*E*)-1-(4-Chlorophenyl)-3-[4-(propan-2-yl)phenyl]prop-2-en-1-one. The computations were performed at DFT level of theory to get the optimized geometry and vibrational wave numbers of the normal modes of the title compound using Gaussian09 software. The complete vibrational assignments of wave numbers were made

on the basis of potential energy distribution. The calculated HOMO and LUMO energies show chemical activity of the molecule. The stability of the molecule arising from hyperconjugative interaction and charge delocalization has been analyzed using NBO analysis. The hyperpolarizability values are reported and the first hyperpolarizability of the title compound is 83.85 times that of standard NLO material urea. From the MEP plot, the negative electrostatic potential regions are mainly localized over the carbonyl group, the phenyl rings and are possible sites for electrophilic attack. The positive regions are localized over all the hydrogen atoms and are possible sites for nucleophilic attack. The molecular docking results suggest that the compound might exhibit inhibitory activity against lymphocyte-specific kinase and may results in design of novel T-cell immunosuppressants.

Keywords: DFT; FT-IR; FT-Raman; hyperpolrizable; Molecular docking.

1. Introduction

Chalcones are an important class of natural compounds and have been widely applied as synthons in synthetic organic chemistry. The nonlinear optical properties of the different chalcone derivatives have been reported [1-4]. These, α,β -unsaturated ketones possess a wide variety of biological activities, including anti-leishmanial [5], anticancer [6, 7], anti-invasive [8], anti-tuberculosis [9], antimicrobial [10, 11], anti-malarial [12], antitumor [13, 14], anti-proliferative [15] and anti-oxidant activity [16]. Asiri et al. [17] reported the synthesis, molecular structure, spectral investigation on (E)-1-(4-bromophenyl)-3-(4-(dimethylamino)phenyl)prop-2-en-one. Parveen et al. [18] reported the vibrational and structural observations and molecular docking study on 1-{3-(4-chlorophenyl)-5-[4-(propan-2-yl)phenyl]-4,5-dihydro-1H-pyrazol-1-yl}-ethanone. The

synthesis and molecular structure of 2-bromo-N-(7-(diethylamino)-coumarin-3-yl)phenyl)propanamide is reported by Kulai and Mallet-Ladeira [19]. Solid state structural and theoretical investigations of a biologically active chalcone is reported in literature [20]. Demir et al. [21] reported the vibrational spectroscopic studies of 1-(2-nitrobenzoyl)-3,5-diphenyl-4,5-dihydro-1H-pyrazole with X-ray diffractions and DFT calculations. The crystal structures of some chalcone derivatives viz., a second polymorph of (2*E*)-1-(4-fluorophenyl)-3-(3,4,5-trimethoxyphenyl)prop-2-en-1-one, 2,3-dibromo-1,3-bis(4-fluorophenyl)propan-1-one, (2*E*)-1-(3,4-dichlorophenyl)-3-(2-hydroxyphenyl)prop-2-en-1-one [22-24], 3-(3,4-dimethoxyphenyl)-1-(4-fluorophenyl)prop-2-en-1-one, 2,3-dibromo-1-(4-ethoxyphenyl)-3-[4-(methylsulfanyl)phenyl]propan-1-one, 2-bromo-1-(4-methylphenyl)-3-[4-(methylsulfanyl)phenyl]prop-2-en-1-one, (2*E*)-1-(2,4-dichlorophenyl)-3-[4-(methylsulfanyl)phenyl]prop-2-en-1-one [25-28] and 2-bromo-1-chlorophenyl-3-(4-methoxyphenyl)prop-2-en-1-one [29] have been reported. Mary et al. [30, 31] reported the molecular conformational analysis, vibrational spectra, NBO analysis and first hyperpolarizability of (2*E*)-3-phenylprop-2-enoic anhydride and (2*E*)-3-(3-chlorophenyl)prop-2-enoic anhydride based on density functional theory calculations.

Chloro-substituted cinnamic acids have received attention in the field of tumor treatment and the chloro-substituted phenyl analogues, on the other hand, have been proven to perform as efficient as the respective parent cinnamic acid without producing the side effects observed by the parent compounds [32]. In the present work, IR and Raman spectra of the title compound are reported both experimentally and theoretically. Also NBO, HOMO-LUMO, molecular electrostatic potential, first and second

hyperpolarizability studies are reported. Due to the different potential biological activity of the title compound, molecular docking study is also reported.

2. Experimental details

The compound was prepared (scheme 1) following the literature method reported [33].

Re-crystallized from ethanol (M.P.: 343-345 K).

Reaction Scheme

The FT-IR spectrum (Fig.1) was recorded using KBr pellets on a DR/Jasco FT-IR 6300 spectrometer. The FT-Raman spectrum (Fig. 2) was obtained on a Bruker RFS 100/s, Germany. For excitation of the spectrum the emission of Nd:YAG laser was used, excitation wavelength 1064 nm, maximal power 150mW, measurement on solid sample. The deconvoluted experimental IR and Raman spectra are provided as Fig.S1 and Fig.S2 (supporting material).

3. Computational details

For meeting the requirements of both accuracy and computing economy, theoretical methods and basis sets should be considered. Density functional theory has been proven to be extremely useful in treating the electronic structure of the molecules. Gaussian09 program [34] was used to carry out DFT calculations with Becke's three-

parameter hybrid model and the Lee-Yang-Parr correlation functional (B3LYP) method. The basis set B3LYP/6-31++G(d) (6D, 7F), which is an effective level with a reasonable cost to study fairly large organic molecules, was utilized. As the DFT hybrid B3LYP functional tends to overestimate the frequencies of the fundamental modes; scaling factors have to be used for obtaining a considerably better agreement with experimental data. Thus, a scaling factor of 0.9613 has been uniformly applied to the B3LYP calculated wavenumbers [35]. The assignments of the calculated wave numbers are aided by the animation option of GAUSSVIEW program, which gives a visual presentation of the vibrational modes [36] and the potential energy distribution (PED) values were calculated with the help of GAR2PED software package [37]. The optimized geometrical parameters (Fig. 3) with XRD data are given in Table 1.

4. Results and discussion

4.1 IR and Raman spectra

The observed IR and Raman bands and calculated (scaled) wavenumbers and assignments are given in Table 2. The carbonyl stretching C=O vibration [38-40] is expected in the region $1750\text{-}1600\text{ cm}^{-1}$ and in the present case the C=O mode appears at 1660 cm^{-1} in the IR spectrum, 1659 cm^{-1} in the Raman spectrum and at 1656 cm^{-1} theoretically. The in-plane and out-of-plane C=O deformations are expected in the regions 625 ± 70 and $540 \pm 80\text{ cm}^{-1}$, respectively [38]. The C=O deformation bands are observed at 669 cm^{-1} in the IR spectrum, 648 cm^{-1} in the Raman spectrum and at $671, 656\text{ cm}^{-1}$ theoretically. Mary et al. [30] reported the C=O modes at $1768, 1701, 804\text{ cm}^{-1}$ in the IR spectrum, $1763, 1697, 779, 697\text{ cm}^{-1}$ in the Raman spectrum and at $1768, 1702, 799, 771, 691, 653\text{ cm}^{-1}$ theoretically.

According to Socrates [41] the C=C stretching is expected around 1600 cm^{-1} when conjugated with C=O group. For the title compound, the bands observed at 1578 cm^{-1} in the IR spectrum and at 1580 cm^{-1} theoretically are assigned as C=C stretching mode. Mary et al. [30] reported the C=C stretching mode at 1620 cm^{-1} in the IR spectrum, $1621, 1601\text{ cm}^{-1}$ in the Raman spectrum and at $1611, 1607\text{ cm}^{-1}$ theoretically.

The methyl stretching modes are expected in the region $2900\text{-}3000\text{ cm}^{-1}$ [38]. The bands observed at $2975, 2929\text{ cm}^{-1}$ in the IR spectrum, $2972, 2930\text{ cm}^{-1}$ the Raman spectrum and in the range $2921\text{-}2993\text{ cm}^{-1}$ theoretically are assigned as these modes for the title compound. For the title compound, the methyl deformation modes are observed at $1462, 1362\text{ cm}^{-1}$ in the IR spectrum, 1459 cm^{-1} in the Raman spectrum and in the range $1470\text{-}1365\text{ cm}^{-1}$ theoretically as expected [38]. The first methyl rocking vibration [38] has been observed at $1190 \pm 45\text{ cm}^{-1}$ and the second methyl rock [38] absorb at $950 \pm 30\text{ cm}^{-1}$. These modes calculated (DFT) at $1136, 1040, 931, 904\text{ cm}^{-1}$ were assigned as rocking modes of the methyl group. These modes are observed at $1035, 898\text{ cm}^{-1}$ in the Raman spectrum.

For simple organic chlorine compounds, C-Cl absorptions are in the region $750\text{-}700\text{ cm}^{-1}$. Sundaraganesan et al. [42] reported C-Cl stretching at 704 (IR), 705 (Raman), and 715 cm^{-1} (DFT) and the deformation bands at 250 and 160 cm^{-1} . Renjith et al. [43] reported the C-Cl stretching modes in the range $609\text{-}947\text{ cm}^{-1}$. For the title compound, the band at 706 cm^{-1} (DFT) is assigned as C-Cl stretching modes. The deformation bands of C-Cl are also identified. This is in agreement with the literature data [44]. Mary et al. [45] reported the CCl stretching mode at 671 cm^{-1} theoretically.

In the following discussion, the para substituted phenyl ring with chlorine is designated as PhI and the other para-substituted phenyl ring as PhII. The C-H stretching modes occurs above 3000 cm^{-1} and is typically exhibited as a multiplicity of weak to moderate bands, compared with the aliphatic C-H stretch [46]. For the title compound, CH stretching vibrations of the phenyl rings are assigned in the range $3103\text{-}3081\text{ cm}^{-1}$ for PhI and $3075\text{-}3052\text{ cm}^{-1}$ for PhII theoretically. The phenyl CH stretching modes are observed at $3083, 3053\text{ cm}^{-1}$ in the IR spectrum and at 3057 cm^{-1} in the Raman spectrum.

The DFT calculations give the phenyl ring stretching modes in the range $1572\text{-}1289\text{ cm}^{-1}$ for PhI and in the range $1599\text{-}1272\text{ cm}^{-1}$ for PhII as expected [38]. The bands observed at $1603, 1488, 1403, 1382, 1292\text{ cm}^{-1}$ in the IR spectrum and at $1600, 1568, 1525\text{ cm}^{-1}$ in the Raman spectrum are assigned as the phenyl ring stretching modes. The ring breathing mode of the 1,4-disubstituted benzenes with entirely different substituent [47] has been reported in the interval $700\text{-}880\text{ cm}^{-1}$. For the title compound, the ring breathing modes are assigned at $720, 734\text{ cm}^{-1}$ in the IR spectrum, 734 cm^{-1} in the Raman spectrum and at $736, 717\text{ cm}^{-1}$ theoretically.

The in-plane CH deformation bands of the phenyl ring are expected above 1000 cm^{-1} [38] and in the present case, the bands at $1281, 1172, 1155, 1105, 1090, 1059\text{ cm}^{-1}$ (IR), $1282, 1092, 1058\text{ cm}^{-1}$ in Raman spectrum and in the range $1276\text{-}1064\text{ cm}^{-1}$ for PhI and $994\text{-}1279\text{ cm}^{-1}$ for PhII (DFT) are assigned as the in-plane CH deformation modes.

The CH out-of-plane deformations of the phenyl ring [38] are observed between 1000 and 700 cm^{-1} . The bands observed at $954, 830, 812\text{ cm}^{-1}$ in IR spectrum and in the range $957\text{-}801$ (DFT) for PhI and $943\text{-}811\text{ cm}^{-1}$ (DFT) are assigned as the CH out-of-plane deformations of the phenyl rings. Most of the modes are not pure but contains a

significant contribution from other modes also. In order to investigate the performance of vibrational wavenumbers of the title compound, the root mean square value between the calculated and observed wavenumbers were calculated and the RMS errors are 3.76 for IR and 4.98 for Raman modes.

4.2 Geometrical parameters

The aromatic ring of the title compound is somewhat irregular and the spread of C-C bond distance is (DFT/XRD) 1.3918-1.4053/1.3596-1.4026 Å in PhI and 1.3917-1.4091/1.3606-1.4015 Å in PhII, which is similar to the spread reported by Bhagyasree et al. [48]. For the title compound, the C=O and C=C bond lengths (DFT/XRD) are 1.2323/1.2275 Å and 1.3518/1.3207 Å, respectively. For the title compound, the CCl bond length (DFT/XRD) is 1.7558/1.7435 Å, while Mary et al. [49] reported the CCl bond length as 1.7581 Å (DFT).

The bond lengths of the title compound (DFT/XRD), C₆-C₈ = 1.4610/1.4696, C₄-C₃ = 1.4810/1.4855, C₃-C₂₈ = 1.5033/1.4746, C₁₃-C₁₈ = 1.5219/1.5105, C₁₈-C₂₀ = 1.5419/1.5256 and C₁₈-C₂₄ = 1.5417/1.5357 Å which clearly shows the typical single bond character and the elongation is due to the presence of adjacent groups as reported in literature [49].

At C₂₈ position, the bond angles, C₃₆-C₂₈-C₃ is increased by 3.6° and C₂₉-C₂₈-C₃ is reduced by 2.1°, from 120°, which reveals the interaction between carbonyl group and H₃₀. At C₃ position, the bond angles (DFT/XRD) are C₄-C₃-C₂₈ = 119.0/116.9, C₄-C₃-O₂ = 121.6/122.0 and C₂₈-C₃-O₂ = 119.5/121.0° and this asymmetry in bond angles reveal the interaction between C=O and C=C bonds. Similarly at C₈ position, the bond angles

(DFT/XRD) $C_9-C_8-C_{16} = 117.5/118.5$, $C_9-C_8-C_6 = 123.7/121.8$ and $C_{16}-C_8-C_6 = 118.8/119.7^\circ$ and this asymmetry is due to the presence of the adjacent $C=C$ group.

Due to the high electronegativity of chlorine atom, the bond angle (DFT/XRD) $C_{31}-C_{33}-C_{34}$ increased by $1.1/1.5^\circ$, from 120° as reported in literature [49]. The methyl groups are tilted from the phenyl ring PhII, as is evident from the torsion angles (DFT/XRD) $C_9-C_{11}-C_{13}-C_{18} = -179.9/-179.9$, $C_{11}-C_{13}-C_{18}-C_{20} = -117.0/-115.4$, $C_{11}-C_{13}-C_{18}-C_{24} = 117.7/121.0$, $C_{16}-C_{14}-C_{13}-C_{18} = 179.9/179.3$, $C_{14}-C_{13}-C_{18}-C_{20} = 62.9/64.3$ and $C_{14}-C_{13}-C_{18}-C_{24} = -62.3/-59.3^\circ$. Also the carbonyl group is tilted from the phenyl ring PhI which is evident from the torsion angles (DFT/XRD) $C_{34}-C_{36}-C_{28}-C_3 = -178.6/-175.0$, $C_{36}-C_{28}-C_3-C_4 = -16.4/-23.5$, $C_{31}-C_{29}-C_{28}-C_3 = 179.3/177.7$ and $C_{29}-C_{28}-C_3-C_4 = 165.1/159.6^\circ$.

4.3 Frontier molecular orbitals

Knowledge of the highest occupied molecular orbital (HOMO) and lowest unoccupied molecular orbital (LUMO) and their properties such as their energy is very useful to gauge the chemical reactivity of the molecule. The ability of the molecule to donate an electron is associated with the HOMO and the characteristic of the LUMO is associated with the molecule's electron affinity. The HOMO and LUMO energies are very useful for physicists and chemists and are very important terms in quantum chemistry [50]. The pictorial representation of the HOMO and the LUMO is shown in Fig.4. The HOMO lies at -8.181eV and whereas the LUMO is located at -6.061 eV and HOMO is delocalized over the phenyl ring PhI and the carbonyl group while LUMO is delocalized over the entire molecule. This shows that an eventual charge transfer occurs within the molecule, and that the frontier orbital energy gap is 2.12 eV . The lower the

energy gap the more easily are the electrons excited from the ground to the excited state. By using the HOMO and LUMO energy values, the global chemical reactivity descriptors such as hardness, chemical potential, electro-negativity and electrophilicity index as well as local reactivity can be defined [51]. Pauling introduced the concept of electro-negativity as the power of an atom in a molecule to attract electrons to it. Hardness (η), chemical potential (μ) and electro-negativity (χ) are defined using Koopman's theorem as $\eta = (I-A)/2 = 1.06$, $\mu = -(I+A)/2 = -7.121$ and $\chi = (I+A)/2 = 7.121$, where A and I are the ionization potential and electron affinity of the molecule. $I = -E_{\text{HOMO}} = 8.181$ eV and $A = -E_{\text{LUMO}} = 6.061$ eV. One can also relate the stability of the molecule to hardness, which means that the molecule with a lower energy gap shows higher reactivity. Parr *et al.* [52] have defined a descriptor to quantify the global electrophilic power of the molecule as the electrophilicity index, $\omega = \mu^2/2\eta = 23.92$. The usefulness of this new reactivity quantity has been demonstrated recently in understanding the toxicity of various pollutants in terms of their reactivity and site selectivity [53].

4.4 Nonlinear optical studies

Nonlinear optics deals with the interaction of applied electromagnetic fields in various materials to generate new electromagnetic fields, altered in wavenumber, phase, or other physical properties [54]. Quantum chemical calculations have been shown to be useful in the description of the relationship between the electronic structure of systems and its NLO response [55]. The computational approach allows the determination of molecular NLO properties as an inexpensive way to design molecules by analyzing their potential before synthesis and to determine high order hyperpolarizability tensors of the

molecules. The first order hyperpolarizability of the title compound is calculated and is found to be 10.90×10^{-30} esu. The calculated hyperpolarizability of the title compound is 83.85 times that of the standard NLO material urea (0.13×10^{-30} esu) [56]. The theoretical second order hyperpolarizability was calculated using the Gaussian09 software and is equal to -30.35×10^{-37} e.s.u. We conclude that the title compound and its derivatives are an attractive object for future studies of nonlinear optical properties.

4.5 Molecular Electrostatic Potential

Molecular electrostatic potential (MEP) at a point in space around a molecule gives information about the net electrostatic effect produced at that point by the total charge distribution over the molecule [57]. Moreover, the MEP surface helps to predict the reactivity of a wide variety of chemical systems in both electrophilic and nucleophilic reactions, the study of biological recognition processes and hydrogen bonding interactions [58]. It also provides visual understanding of the relative polarity of the molecule. The different values of the electrostatic potential at the surface are represented by different colors; red represents regions of most electro negative electrostatic potential, blue represents regions of most positive electrostatic potential and green represents regions of zero potential. The electrostatic potential increases in the order red < orange < yellow < green < blue [57]. To predict reactive sites for electrophilic and nucleophilic attack in the investigated molecule, the MEP surface is plotted for the title compound at DFT level [59]. Fig.5 shows the electrostatic potential contour map of the title compound. The negative electrostatic potential corresponds to an attraction of a proton by the aggregate electron density in the molecule (shades of red and yellow) and the positive electrostatic potential corresponds to the repulsion of a proton by the nuclei (shades of

blue). As can be seen from the Fig. 5, the negative electrostatic potential regions are mainly localized over the carbonyl group, the phenyl rings and are possible sites for electrophilic attack. The positive regions are localized over all the hydrogen atoms as possible sites for nucleophilic attack.

4.6 Natural Bond Orbital analysis

The natural bond orbitals (NBO) calculations were performed using NBO 3.1 program [60] as implemented in the Gaussian09 package at the DFT/B3LYP level and the possible intensive interaction are given in Table 3.

The important inter-molecular hyper-conjugative interactions are: C₄-C₆ from Cl₁ of $n_1(\text{Cl}_1) \rightarrow \sigma^*(\text{C}_4-\text{C}_6)$, C₄-C₆ from Cl₁ of $n_2(\text{Cl}_1) \rightarrow \sigma^*(\text{C}_4-\text{C}_6)$, C₃-C₂₈ from Cl₁ of $n_1(\text{Cl}_1) \rightarrow \sigma^*(\text{C}_3-\text{C}_{28})$, C₄-C₆ from O₂ of $n_1(\text{O}_2) \rightarrow \sigma^*(\text{C}_4-\text{C}_6)$ with electron densities, 0.01270, 0.01270, 0.06480, 0.01270 e and stabilization energies of 781.11, 423.83, 5426.1, 19.34 KJ/mol.

The NBO analysis also describes the bonding in terms of the natural hybrid orbital $n_3(\text{Cl}_1)$, which occupy a higher energy orbital (-0.42569 a.u.) with considerable p-character (100.00%) and low occupation number (1.92483) and $n_2(\text{O}_2)$, which occupy a higher energy orbital (-0.25981 a.u.) with considerable p-character (100.00%) and low occupation number (1.88747). The other orbitals are, $n_1(\text{Cl}_1)$ occupy a lower energy orbital (-0.93672 a.u.) with p-character (17.14%) and high occupation number (1.99293) and $n_1(\text{O}_2)$ occupy a lower energy orbital (-0.70170 a.u.) with p-character (41.12%) and high occupation number (1.97827).

Thus, a very close to pure p-type lone pair orbital participates in the electron donation to the $n_1(\text{Cl}_1) \rightarrow \sigma^*(\text{C}_4-\text{C}_6)$, $n_2(\text{Cl}_1) \rightarrow \sigma^*(\text{C}_4-\text{C}_6)$, $n_1(\text{Cl}_1) \rightarrow \sigma^*(\text{C}_3-\text{C}_{28})$, $n_1(\text{O}_2) \rightarrow \sigma^*(\text{C}_4-\text{C}_6)$ interactions in the compound. The results are tabulated in Table 4.

4.7 Molecular Docking studies

The lymphocyte-specific kinase (Lck) is a member of the Src family of non-receptor tyrosine kinases that plays an essential role for the selection and maturation of developing T-cell in the thymus and in mature T-cell function. Lck is considered an attractive cell-specific target for the design of novel T-cell immuno suppressants. Molecular docking simulations were performed on AutoDock-Vina software [61] and the 3D crystal structure of *Lck kinase* was obtained from Protein Data Bank (PDB ID: 1QPE) [62]. The protein was prepared for docking by removing the co-crystallized ligands, water molecules and co-factors. AutoDockTools (ADT) graphical user interface was used to calculate Kollman charges and to add polar hydrogens. Ligand was prepared for docking by minimizing its energy at B3LYP/6-31++G(d)(6D, 7F) level of theory. Charges were calculated by Geistenger method. Active site of the protein was defined so as to include residues of the active site within the grid size of $40\text{\AA} \times 40\text{\AA} \times 40\text{\AA}$. Docking protocol was tested by extracting co-crystallized inhibitor from the protein and then docking the same. Docking protocol which we employed predicted the same conformation as was present in the crystal structure with RMSD value well within the reliable range of $2\text{\AA}$. Amongst the docked conformations, one which binded at the active site with high affinity was visualized for detailed ligand-protein interactions in Discover Studio Visualizer 4.0 and Pymol software. The ligand binds at the catalytic site of substrate (Fig. 6) by weak non-covalent interactions most prominent of which are alkyl

and alkyl- π interactions. TYR264, TYR304 and ARG302 hold the aromatic rings by alkyl- π interactions (Fig.7). TYR304 forms a pi-pi stacking interaction with one of the phenyl rings. The inhibitor (2*E*)-1-(4-chlorophenyl)-3-[4-(propan-2-yl)phenyl]prop-2-en-1-one forms a stable complex with Lck. These preliminary results suggest that the compound might exhibit inhibitory activity against Lck. This may result in design of novel T-cell immunosuppressants. However biological tests need to be done so as to validate the computational predictions.

5. Conclusion

The vibrational spectroscopic studies of (2*E*)-1-(4-Chlorophenyl)-3-[4-(propan-2-yl)phenyl]prop-2-en-1-one were reported experimentally and theoretically. Potential energy distribution of normal modes of vibrations was done using GAR2PED program. MEP predicts the most reactive part in the molecule. The geometrical parameters obtained from theoretical calculations are in agreement with the XRD data. The calculated hyperpolarizability is high and the title compound and its derivatives are attractive object for future studies in nonlinear optics. For the title compound, HOMO is delocalized over the phenyl ring PhI and the carbonyl group while LUMO is delocalized over the entire molecule and this shows that an eventual charge transfer occurs within the molecule, and that the frontier orbital energy gap is 2.12 eV. The title compound binds at the catalytic site of substrate by weak non-covalent interactions most prominent of which are alkyl and alkyl- π interactions and forms a stable complex with Lck.

Acknowledgements

The authors would like to extend their sincere appreciation to the Deanship of Scientific Research at King Saud University for funding this work through the Research Group

Project No. PRG-1436-23. BN thanks UGC for assistance through BSR and the authors are thankful to University of Antwerp for access to the university's CalcUA Supercomputer Cluster.

References

- [1] B.K. Sarojini, B. Narayana, B.V. Ashalatha, J. Indira, K.G. Lobo, *J. Cryst. Growth* 295 (2006) 54-59.
- [2] S. Shettigar, G. Umesh, K. Chadrasekharan, B.K. Sarojini, B. Narayana, *Optical Materials* 30 (2008) 1297-1303.
- [3] P. Poornesh, S. Shettigar, G. Umesh, K.B. Manjunatha, K.P. Kamath, B.K. Sarojini, B. Narayana, *Optical Materials* 31 (2009) 854–859.
- [4] J. Indira, P.P. Karat, B.K. Sarojini *J. Cryst. Growth* 242 (2002) 209-214.
- [5] S.F. Nielsen, S.B. Christensen, G. Cruciani, A. Kharazmi, T. Liljefors, *J. Med. Chem.* 41 (1998) 4819–4832.
- [6] C.W. Mai, M. Yaeghoobi, N. Abd-Rahman, Y.B. Kang, M.R. Pichika, *Eur. J. Med. Chem.* 77 (2014) 378-387.
- [7] M. Wan, L. Xu, L. Hua, A. Li, S. Li, W. Lu, Y. Pang, C. Cao, X. Liu, P. Jiao, *Bioorg. Chem.* 54 (2014) 38-43.
- [8] S. Mukherjee, V. Kumar, A.K. Prasad, H.G. Raj, M.E. Bracke, C.E. Olsen, S.C. Jain, V.S. Parmar, *Bioorg. Med. Chem.* 9 (2001) 337–345.
- [9] Y.M. Lin, Y. Zhou, M.T. Flavin, L.M. Zhou, W. Nie, F.C. Chen, *Bioorg. Med. Chem.* 10 (2002) 2795–2802.

- [10] S.N. Lopez, M.V. Castelli, S.A. Zacchino, J.N. Dominguez, G. Lobo, C.C. Jaime, J.C.G. Cortes, J.C. Ribas, C. Devia, M.R. Ana, D.E. Ricardo, *Bioorg. Med. Chem.* 9 (2001) 1999–2013.
- [11] Z.N. Siddiqui, T.N.M. Musthafa, A. Ahmad, A.U. Khan, *Bioorg. Med. Chem. Lett.* 21 (2011) 2860-2865.
- [12] A. Agarwal, K. Srivastava, S.K. Puri, P.M.S. Chauhan, *Bioorg. Med. Chem.* 13 (2005) 4645–4650.
- [13] B. Insuasty, A. Montoya, D. Becerra, J. Quiroga, R. Abonia, S. Robledo, I.D. Velez, Y. Upegui, M. Nogueras, J. Cobo, *Eur. J. Med. Chem.* 67 (2013) 252-262.
- [14] R. Abonia, D. Insausti, J. Castillo, B. Insausti, J. Quiroga, M. Nogueras, J. Cobo, *Eur. J. Med. Chem.* 57 (2012) 29-40.
- [15] V. Sharma, A. Chaudhary, S. Arora, A.K. Saxena, M.P.S. Ishar, *Eur. J. Med. Chem.* 69 (2013) 310-315.
- [16] S. Shenvi, K. Kumar, K.S. Hatti, K. Rijesh, L. Diwakar, *Eur. J. Med. Chem.* 62 (2013) 435-442.
- [17] A.M. Asiri, M. Karabacak, S. Sakthivel, A.O. Al-youbi, S. Muthu, S.A. Hameed, S. Renuga, T. Alagesan, *J. Mol. Struct.* 1103 (2016) 145-155.
- [18] S. Parveen, M.A. Al-Alshaikh, C.Y. Panicker, A.A. El-Emam, B. Narayana, V.V. Saliyan, B.K. Sarojini, C. Van Alsenoy, *J. Mol. Struct.* 1112 (2016) 136-146.
- [19] I. Kulai, S. Mallet-Ladeira, *J. Mol. Struct.* 1104 (2016) 14-18.
- [20] A. Abbas, H. Gokce, S. Bahceli, M. Bolte, M.M. Naseer, *J. Mol. Struct.* 1112 (2016) 124-135.
- [21] S. Demir, F. Tinmazy, N. Dege, I.O. Ilhan, *J. Mol. Struct.* 1108 (2016) 637-648.

- [22] J.P. Jasinski, R.J. Butcher, K. Veena, B. Narayana, H.S. Yathirajan, *Acta Cryst.* E65 (2009) o1965-o1966.
- [23] J.P. Jasinski, C.J. Guild, S. Samshuddin, B. Narayana, H.S. Yathirajan, *Acta Cryst.* E66 (2010) o2018-o2018.
- [24] J.P. Jasinski, J.A. Golen, P.S. Nayak, B. Narayana, H.S. Yathirajan, *Acta Cryst.* E68 (2012) o366-o366.
- [25] R.J. Butcher, H.S. Yathirajan, H.G. Anilkumar, B.K. Sarojini, B. Narayana, *Acta Cryst.* E62 (2006) o1633-o1635.
- [26] R.J. Butcher, H.S. Yathirajan, B.K. Sarojini, B. Narayana, A. Mithun, *Acta Cryst.* E62 (2006) o1629-o1630.
- [27] R.J. Butcher, H.S. Yathirajan, H.G. Anilkumar, B.K. Sarojini, B. Narayana, *Acta Cryst.* E62 (2006) o1659-o1661.
- [28] R.J. Butcher, H.S. Yathirajan, B. Narayana, A. Mithun, B.K. Sarojini, *Acta Cryst.* E63 (2007) o30-o32.
- [29] W.T.A. Horison, H.S. Yathirajan, B.K. Sarojini, B. Narayana, K.K. Vijay Raj, *Acta Cryst.* E62 (2006) o1578-o1579.
- [30] Y.S. Mary, K. Raju, C.Y. Panicker, A.A. Al-Saadi, T. Thiemann, C. Van Alsenoy, *Spectrochim. Acta* 128 (2014) 638-646.
- [31] Y.S. Mary, K. Raju, C.Y. Panicker, A.A. Al-Saadi, T. Thiemann, *Spectrochim. Acta* 131 (2014) 471-483.
- [32] F.M. Sun, J.S. Wang, T.W. Traxler, *Chemosphere* 40 (2000) 1417-1425.

- [33] B. Narayana, V.V. Salián, B.K. Sarojini, J.P. Jasinski, *Acta Cryst.* E70 (2014) o855-o855.
- [34] Gaussian 09, Revision C.01, M.J. Frisch, G.W. Trucks, H.B. Schlegel, G.E. Scuseria, M.A. Robb, J.R. Cheeseman, G. Scalmani, V. Barone, B. Mennucci, G.A. Petersson, H. Nakatsuji, M. Caricato, X. Li, H. P. Hratchian, A.F. Izmaylov, J. Bloino, G. Zheng, J.L. Sonnenberg, M. Hada, M. Ehara, K. Toyota, R. Fukuda, J. Hasegawa, M. Ishida, T. Nakajima, Y. Honda, O. Kitao, H. Nakai, T. Vreven, J.A. Montgomery, Jr., J.E. Peralta, F. Ogliaro, M. Bearpark, J.J. Heyd, E. Brothers, K.N. Kudin, V.N. Staroverov, T. Keith, R. Kobayashi, J. Normand, K. Raghavachari, A. Rendell, J.C. Burant, S.S. Iyengar, J. Tomasi, M. Cossi, N. Rega, J.M. Millam, M. Klene, J.E. Knox, J.B. Cross, V. Bakken, C. Adamo, J. Jaramillo, R. Gomperts, R.E. Stratmann, O. Yazyev, A.J. Austin, R. Cammi, C. Pomelli, J.W. Ochterski, R.L. Martin, K. Morokuma, V.G. Zakrzewski, G.A. Voth, P. Salvador, J.J. Dannenberg, S. Dapprich, A.D. Daniels, O. Farkas, J.B. Foresman, J.V. Ortiz, J. Cioslowski, D.J. Fox, Gaussian, Inc., Wallingford CT, 2010.
- [35] J.B. Foresman, in: E. Frisch (Ed.), *Exploring Chemistry with Electronic Structure Methods: A Guide to Using Gaussian*, Pittsburg, PA, 1996.
- [36] R. Dennington, T. Keith, J. Millam, *Gaussview*, Version 5, Semichem. Inc., Shawnee Missions, KS, 2009.
- [37] J.M.L. Martin, C. Van Alsenoy, *GAR2PED*, A Program to Obtain A Potential Energy Distribution from a Gaussian Archive Record, University of Antwerp, Belgium, 2007.

- [38] N.P.G. Roeges, A guide to the complete interpretation of IR spectra of Organic Compounds, Wiley, New York 1994.
- [39] N.B. Colthup, L.H. Daly, S.E. Wiberly, Introduction to IR and Raman spectroscopy, Academic Press, New York 1990.
- [40] R.M. Silverstein, F.X. Webster, Spectrometric Identification of Organic Compounds, sixth ed., John Wiley Asia, 2003.
- [41] G. Socrates, Infrared Characteristic Group Frequencies, John Wiley and Sons, New York 1981.
- [42] N. Sundaraganesan, C. Meganathan, B.D. Joshua, P. Mani, A. Jayaprakash, Spectrochim. Acta 71 (2008) 1134-1139.
- [43] R. Renjith, Y.S. Mary, C.Y. Panicker, H.T. Varghese, M.P. Parys, C.V. Alsenoy, T.K. Manojkumar, Spectrochim. Acta 124 (2014) 480-491.
- [44] W.O. George, P.S. McIntyre, Infrared Spectroscopy (1st edn), John Wiley and sons, Chichester, 1987.
- [45] Y.S. Mary, K. Raju, I. Yildiz, O. Temiz-Arpaci, H.I.S. Nogueira, C.M. Granadeiro, C. Van Alsenoy, Spectrochim. Acta 96 (2012) 617-625.
- [46] J. Coates in: R.A. Meyers, (Ed.) Interpretation of Infrared Spectra, A Practical approach, John Wiley and Sons Inc. Chichester 2000.
- [47] G. Varsanyi, Assignments of Vibrational Spectra of Seven Hundred Benzene Derivatives, Wiley, New York 1974.
- [48] J.B. Bhagyasree, H.T. Varghese, C.Y. Panicker, J. Samuel, C. Van Alsenoy, K. Bolelli, I. Yildiz, E. Aki, Spectrochim. Acta 102 (2013) 99-113.

- [49] Y.S. Mary, K. Raju, C.Y. Panicker, A.A. Al-Saadi, T. Thiemann, *Spectrochim. Acta* 131 (2014) 471-483.
- [50] K. Fukui, *Science* 218 (1982) 474-754.
- [51] R.G. Parr, P.K. Chattaraj, *J. Am. Chem. Soc.* 113 (1991) 1854-1855.
- [52] R.G. Parr, L. Szentpaly, S. Liu, *J. Am. Chem. Soc.* 121 (1999) 1922-1924.
- [53] R. Parthasarathi, J. Padmanabhan, V. Subramanian, B. Maiti, P. Chattaraj, *Curr. Sci.* 86 (2004) 535-542.
- [54] Y.R Shen, *The Principles of Nonlinear Optics*, Wiley, New York 1984.
- [55] D.M. Burland, R.D. Miller, C.A. Walsh, *Chem. Rev.* 94 (1994) 31-75.
- [56] M. Adant, L. Dupuis, L. Bredas, *Int. J. Quantum Chem.* 56 (2004) 497-507.
- [57] P. Thul, V.P. Gupta, V.J. Ram, P. Tandon, *Spectrochim. Acta* 75 (2010) 251-260.
- [58] P. Politzer, J.S. Murray, in: D.L. Beveridge, R. Lavery (Eds.) *Theoretical Biochemistry and Molecular Biophysics, A comprehensive Survey, protein*, Vol. 2, Adenine Press, Schenectady, New York 1991.
- [59] A.D. Becke, *J. Chem. Phys.* 98 (1993) 5648-5682.
- [60] E.D. Glendening, A.E. Reed, J.E. Carpenter, F. Weinhold, NBO Version 3.1, Theoretical Chemistry Institute and Department of Chemistry, University of Wisconsin, Madison, 1988.
- [61] O. Trott, A. J. Olson, *J. Comput. Chem.* 31 (2010) 455-461.
- [62] X. Zhu, J.L. Kim, J.R. Newcomb, P.E. Rose, D.R. Stover, L.M. Toledo, H. Zhao, K.A. Morgenstern, *Structure Fold. Des.* 7 (1999) 651-661.

Figure Captions

Fig.1 FT-IR spectrum of (2*E*)-1-(4-chlorophenyl)-3-[4-(propan-2-yl)phenyl]prop-2-en-1-one

Fig.2 FT-Raman spectrum of (2*E*)-1-(4-chlorophenyl)-3-[4-(propan-2-yl)phenyl]prop-2-en-1-one

Fig.3 Optimized geometry of (2*E*)-1-(4-chlorophenyl)-3-[4-(propan-2-yl)phenyl]prop-2-en-1-one

Fig.4 HOMO, LUMO plots of (2*E*)-1-(4-chlorophenyl)-3-[4-(propan-2-yl)phenyl]prop-2-en-1-one

Fig.5 MEP plot of (2*E*)-1-(4-chlorophenyl)-3-[4-(propan-2-yl)phenyl]prop-2-en-1-one

Fig.6 The title compound, (2*E*)-1-(4-chlorophenyl)-3-[4-(propan-2-yl)phenyl]prop-2-en-1-one binds at the active site of Lck

Fig.7 Detailed interactions of (2*E*)-1-(4-chlorophenyl)-3-[4-(propan-2-yl)phenyl]prop-2-en-1-one with the inhibitor residues, dotted lines represent the interactions.

Scheme- synthesis pathway of the title compound

Table1

Optimized geometrical parameters of (2E)-1-(4-Chlorophenyl)-3-[4-(propan-2-yl)phenyl]prop-2-en-1-one

Bond lengths (Å) (DFT/XRD)

C33-C11	1.7558/1.7435	C3-O2	1.2323/1.2275
C3-C4	1.4810/1.4855	C3-C28	1.5037/1.4746
C4-H5	1.0850/0.9500	C4-C6	1.3518/1.3207
C6-H7	1.0896/0.9500	C6-C8	1.4610/1.4696
C8-C9	1.4086/1.3966	C8-C16	1.4091/1.3656
C9-H10	1.0865/0.9500	C9-C11	1.3917/1.3756
C11-H12	1.0882/0.9500	C11-C13	1.4054/1.3826
C13-C14	1.4038/1.4015	C13-C18	1.5219/1.5105
C14-H15	1.0874/0.9500	C14-C16	1.3927/1.3606
C16-H17	1.0878/0.9500	C18-H19	1.0988/1.0000
C18-C20	1.5419/1.5256	C18-C24	1.5417/1.5357
C20-H21	1.0969/0.9800	C20-H22	1.0969/0.9800
C20-H23	1.0959/0.9800	C24-H25	1.0959/0.9800
C24-H26	1.0969/0.9800	C24-H27	1.0968/0.9800
C28-C29	1.4053/1.3955	C28-C36	1.4042/1.4026
C29-H30	1.0854/0.9500	C29-C31	1.3918/1.3686
C31-H32	1.0853/0.9500	C31-C33	1.3976/1.3866
C33-C34	1.3949/1.3596	C34-H35	1.0852/0.9500
C34-C36	1.3958/1.3787	C36-H37	1.0851/0.9500

Bond angles (°) (DFT/XRD)

O2-C3-C4	121.6/122.0	O2-C3-C28	119.5/121.0
C4-C3-C28	119.0/116.9	C3-C4-H5	118.5/119.9
C3-C4-C6	120.5/120.2	H5-C4-C6	120.9/119.9
C4-C6-H7	116.2/116.4	C4-C6-C8	128.0/127.3
H7-C6-C8	115.8/116.4	C6-C8-C9	123.7/121.8
C6-C8-C16	118.8/119.7	C9-C8-C16	117.5/118.5
C8-C9-H10	120.1/119.9	C8-C9-C11	120.9/120.3

H10-C9-C11	119.1/119.9	C9-C11-H12	119.2/119.4
C9-C11-C13	121.6/121.2	H12-C11-C13	119.2/119.4
C11-C13-C14	117.6/117.6	C11-C13-C18	120.7/121.2
C14-C13-C18	121.7/121.2	C13-C14-H15	120.0/119.6
C13-C14-C16	121.1/120.8	H15-C14-C16	119.0/119.6
C8-C16-C14	121.4/121.6	C8-C16-H17	119.0/119.2
C14-C16-H17	119.6/119.2	C13-C18-H19	107.0/107.9
C13-C18-C20	111.9/112.1	C13-C18-C24	111.8/110.4
H19-C18-C20	107.4/107.9	H19-C18-C24	107.4/107.9
C20-C18-C24	111.0/110.4	C18-C20-H21	111.3/109.5
C18-C20-H22	110.4/109.5	C18-C20-C23	111.3/110.1
H21-C20-H22	107.7/109.5	H21-C20-H23	107.8/109.5
H22-C20-H23	108.2/109.5	C18-C24-H25	111.3/109.5
C18-C24-H26	110.4/109.5	C18-C24-H27	111.3/109.5
H25-C24-H26	108.2/109.5	H25-C24-H27	107.8/109.5
H26-C24-H27	107.7/109.5	C3-C28-C29	117.9/120.4
C3-C28-C36	123.6/122.6	C29-C28-C36	118.5/117.0
C28-C29-H30	118.4/119.4	C28-C29-C31	121.2/121.2
H30-C29-C31	120.4/119.4	C29-C31-H32	120.8/120.2
C29-C31-C33	119.1/119.6	H32-C31-C33	120.1/120.2
C11-C33-C31	119.5/119.9	C11-C33-C34	119.4/118.6
C31-C33-C34	121.1/121.5	C33-C34-H35	120.2/120.7
C33-C34-C36	119.1/118.5	H35-C34-C36	120.7/120.7
C28-C36-C34	121.0/122.2	C28-C36-H37	120.8/118.9
C34-C36-H37	118.2/118.9		
<u>Dihedral angles (°) (DFT/XRD)</u>			
O2-C3-C4-C6	-6.4/-13.2	C28-C3-C4-C6	174.4/162.3
O2-C3-C28-C29	-14.1/-25.1	O2-C3-C28-C36	164.4/152.1
C4-C3-C28-C29	165.1/159.6	C4-C3-C28-C36	-16.4/-23.5
C3-C4-C6-C8	179.1/176.1	C4-C6-C8-C9	-2.8/-16.9
C4-C6-C8-C16	177.3/165.7	C6-C8-C9-C11	179.9/178.8

C16-C8-C9-C11	-0.2/-1.3	C6-C8-C16-C14	-179.9/-179.9
C9-C8-C16-C14	0.2/2.1	C8-C9-C11-C13	-0.0/0.2
C9-C11-C13-C14	0.2/0.1	C9-C11-C13-C18	-179.9/-179.8
C11-C13-C14-C16	-0.1/.9	C18-C13-C14-C16	179.9/179.3
C11-C13-C18-C20	-117.0/-115.4	C11-C13-C18-C24	117.7/121.0
C14-C13-C18-C20	62.9/64.3	C14-C13-C18-C24	-62.3/-59.3
C13-C14-C16-C8	-0.1/-2.2	C3-C28-C29-C31	179.3/ 177.7
C36-C28-C29-C31	0.7/0.6	C3-C28-C36-C34	-178.6/-175.9
C29-C28-C36-C34	-0.1/1.2	C28-C29-C31-C33	-0.7/-1.7
C29-C31-C33-C11	-179.8/-179.3	C29-C31-C33-C34	0.0/1.2
C11-C33-C34-C36	-179.5/-179.1	C31-C33-C34-C36	0.6/0.6
<u>C33-C34-C36-C28</u>	<u>-0.6/-1.7</u>		

Table 2

Calculated (scaled) wavenumbers, observed IR, Raman bands and assignments

B3LYP/6-31++G(d)(6D,7F)			IR	Raman	Assignments ^a
$\nu(\text{cm}^{-1})$	IRI	RA	$\nu(\text{cm}^{-1})$	$\nu(\text{cm}^{-1})$	-
3103	3.16	262.12	-	-	$\nu\text{CHI}(96)$
3101	13.66	29.96	-	-	$\nu\text{CHI}(87)$, $\nu\text{CH}(12)$
3092	4.57	23.94	-	-	$\nu\text{CHI}(22)$, $\nu\text{CH}(61)$
3090	1.48	72.34	-	-	$\nu\text{CHI}(97)$
3081	11.20	70.62	3083	-	$\nu\text{CHI}(61)$, $\nu\text{CHII}(16)$, $\nu\text{CH}(19)$
3075	0.91	48.78	-	-	$\nu\text{CHII}(63)$, $\nu\text{CH}(21)$
3071	25.26	114.71	-	-	$\nu\text{CHII}(95)$
3055	7.27	83.88	-	3057	$\nu\text{CHII}(91)$
3052	20.19	61.62	3053	-	$\nu\text{CHII}(96)$
3048	1.39	26.95	3035	-	$\nu\text{CH}(91)$
2993	36.01	92.40	-	-	$\nu\text{CH}_3(92)$
2991	22.26	32.24	-	-	$\nu\text{CH}_3(96)$
2987	94.58	332.00	-	-	$\nu\text{CH}_3(95)$
2981	0.06	13.72	2975	2972	$\nu\text{CH}_3(99)$
2925	49.27	390.00	2929	2930	$\nu\text{CH}_3(99)$
2921	30.13	8.94	-	-	$\nu\text{CH}_3(100)$
2912	18.02	78.12	2908	2910	$\nu\text{CH}(95)$
1656	157.58	64.27	1660	1659	$\nu\text{C}=\text{O}(61)$, $\nu\text{C}=\text{C}(18)$
1599	45.61	89.80	1603	1600	$\nu\text{PhII}(58)$, $\nu\text{PhI}(23)$
1580	657.43	3628.00	1578	-	$\nu\text{C}=\text{C}(48)$, $\nu\text{PhI}(12)$
1572	99.16	3814.60	-	1568	$\nu\text{PhI}(64)$, $\nu\text{PhII}(10)$
1548	11.59	312.92	-	-	$\nu\text{PhI}(62)$, $\nu\text{PhII}(11)$
1544	66.66	566.26	-	1525	$\nu\text{PhII}(57)$, $\nu\text{PhI}(20)$
1495	23.70	79.51	1488	-	$\delta\text{CHII}(20)$, $\nu\text{PhII}(52)$
1471	15.81	93.09	-	-	$\delta\text{CHI}(55)$, $\nu\text{PhI}(26)$
1470	7.61	2.77	-	-	$\delta\text{CH}_3(74)$

1465	11.78	21.34	1462	1459	$\delta\text{CH}_3(88)$
1454	3.59	3.82	-	-	$\delta\text{CH}_3(88)$
1451	0.02	12.62	-	-	$\delta\text{CH}_3(90)$
1407	34.74	59.16	1403	-	$\nu\text{PhII}(44)$, $\delta\text{CHII}(15)$, $\delta\text{CH}(10)$
1385	5.33	11.46	-	-	$\delta\text{CH}_3(93)$
1381	18.36	89.61	1382	-	$\nu\text{PhI}(64)$, $\delta\text{CHI}(21)$
1365	5.00	0.21	1362	-	$\delta\text{CH}_3(93)$
1342	4.65	8.27	1344	-	$\delta\text{CH}(48)$, $\delta\text{CHII}(18)$, $\nu\text{PhII}(17)$
1321	186.18	48.03	1324	-	$\delta\text{CH}(30)$, $\delta\text{CHII}(13)$
1312	9.03	351.29	-	1314	$\delta\text{CH}(49)$, $\nu\text{CC}(15)$
1302	1.98	13.28	-	1300	$\delta\text{CH}(77)$
1289	5.74	15.02	1292	-	$\nu\text{PhI}(88)$
1279	98.22	123.56	1281	1282	$\nu\text{CC}(13)$, $\delta\text{CHII}(50)$, $\delta\text{CH}(10)$
1276	2.96	5.57	-	-	$\delta\text{CHI}(65)$
1272	2.57	116.07	-	-	$\nu\text{PhII}(53)$
1199	14.45	210.97	-	-	$\delta\text{CH}(23)$, $\delta\text{PhII}(19)$, $\nu\text{CC}(40)$
1193	64.81	25.52	-	-	$\delta\text{PhII}(13)$, $\nu\text{CC}(46)$, $\nu\text{PhII}(13)$
1186	159.77	40.27	1185	1185	$\nu\text{CC}(47)$, $\delta\text{CH}(11)$
1171	16.29	536.14	1172	-	$\delta\text{CHII}(59)$
1162	84.96	31.59	1155	-	$\delta\text{CHI}(65)$
1136	5.06	13.78	-	-	$\delta\text{CH}_3(44)$, $\nu\text{PhII}(14)$
1101	4.70	3.05	1105	-	$\delta\text{CHII}(47)$, $\nu\text{PhII}(25)$
1094	9.92	4.26	1090	1092	$\delta\text{CHI}(53)$, $\nu\text{PhI}(30)$
1082	0.73	12.04	-	-	$\nu\text{CC}(50)$, $\delta\text{CH}_3(28)$
1064	119.04	80.25	1059	1058	$\nu\text{CCl}(15)$, $\delta\text{CHI}(55)$
1040	15.11	28.03	-	1035	$\delta\text{CH}_3(47)$, $\nu\text{PhII}(15)$,

					$\delta\text{CH}(12)$
1010	129.28	253.74	1010	1010	$\nu\text{CC}(47)$, $\nu\text{PhI}(18)$
994	4.49	4.19	-	-	$\delta\text{CHII}(55)$, $\nu\text{PhII}(11)$
988	32.88	5.23	-	986	$\gamma\text{CH}(43)$, $\tau\text{C}=\text{C}(24)$, $\delta\text{PhI}(12)$
986	128.42	39.08	984	986	$\delta\text{PhI}(58)$
957	0.30	2.39	954	-	$\gamma\text{CHI}(85)$
943	0.19	0.80	-	-	$\gamma\text{CHII}(87)$
936	1.52	0.61	-	-	$\gamma\text{CHII}(77)$, $\tau\text{PhII}(16)$
931	0.59	2.37	-	-	$\gamma\text{CHI}(62)$
931	0.32	5.57	-	-	$\gamma\text{CHI}(11)$, $\delta\text{CH}_3(52)$, $\nu\text{CC}(10)$
904	0.48	1.11	-	898	$\delta\text{CH}_3(76)$, $\delta\text{CC}(15)$
873	6.67	21.34	875	874	$\delta\text{CC}(10)$, $\gamma\text{CH}(43)$, $\delta\text{C}=\text{C}(12)$, $\delta\text{C}=\text{O}(10)$
866	1.83	12.60	-	-	$\nu\text{CC}(66)$, $\delta\text{CH}_3(13)$
858	0.39	14.19	-	-	$\gamma\text{CH}(49)$, $\gamma\text{C}=\text{O}(11)$
828	3.37	3.36	830	-	$\gamma\text{CHI}(45)$, $\gamma\text{CHII}(27)$
814	0.82	1.06	-	-	$\gamma\text{CHII}(90)$
811	45.70	1.11	812	-	$\gamma\text{CHI}(24)$, $\gamma\text{CHII}(57)$
801	41.64	0.88	-	-	$\gamma\text{CHI}(69)$
790	26.17	16.21	788	-	$\delta\text{PhII}(14)$, $\nu\text{CC}(16)$, $\delta\text{PhI}(10)$, $\nu\text{PhII}(14)$
736	13.52	3.49	734	734	$\nu\text{PhII}(40)$, $\tau\text{PhI}(10)$, $\gamma\text{C}=\text{O}(10)$, $\gamma\text{CC}(16)$
717	8.97	34.75	720	-	$\nu\text{PhI}(49)$, $\nu\text{CCl}(12)$
706	0.49	7.42	-	-	$\tau\text{PhI}(22)$, $\tau\text{PhII}(20)$, $\nu\text{CCl}(43)$
671	11.65	2.35	669	-	$\nu\text{CC}(19)$, $\delta\text{C}=\text{O}(32)$, $\delta\text{PhI}(12)$
656	6.89	0.48	-	648	$\tau\text{PhI}(33)$, $\gamma\text{C}=\text{O}(36)$

629	1.39	19.86	632	626	$\delta\text{PhII}(78)$
618	2.42	4.50	-	-	$\delta\text{PhI}(84)$
550	6.25	6.57	-	555	$\delta\text{PhII}(25)$, $\delta\text{CC}(35)$, $\delta\text{C}=\text{C}(10)$
534	26.88	1.41	538	-	$\tau\text{PhII}(33)$, $\tau\text{CC}(39)$
516	17.92	13.12	514	-	$\delta\text{CC}(25)$, $\delta\text{C}=\text{O}(12)$
488	16.81	18.52	490	492	$\delta\text{CCl}(18)$, $\delta\text{CC}(28)$, $\delta\text{C}=\text{C}(11)$
465	9.33	0.16	466	-	$\tau\text{PhI}(42)$, $\gamma\text{CCl}(30)$, $\gamma\text{CC}(16)$
446	3.58	1.62	-	-	$\delta\text{CC}(42)$, $\delta\text{PhII}(11)$
404	0.46	0.20	-	-	$\tau\text{PhI}(27)$, $\tau\text{PhII}(43)$
401	0.36	0.37	-	-	$\tau\text{PhI}(56)$, $\tau\text{PhII}(25)$
393	0.10	0.66	-	-	$\tau\text{PhII}(50)$, $\gamma\text{CC}(12)$
372	12.54	9.20	-	375	$\delta\text{CC}(28)$, $\delta\text{PhI}(10)$
318	3.10	1.41	-	319	$\delta\text{CC}(40)$, $\delta\text{CCl}(17)$, $\delta\text{C}=\text{O}(10)$
304	0.90	0.70	-	-	$\delta\text{CC}(24)$, $\delta\text{CCl}(26)$
270	0.24	3.31	-	-	$\gamma\text{CC}(18)$, $\gamma\text{CCl}(13)$
257	0.52	0.23	-	-	$\tau\text{CH}_3(38)$, $\delta\text{CC}(12)$, $\tau\text{PhII}(11)$
251	0.94	2.19	-	-	$\tau\text{PhII}(23)$, $\delta\text{CC}(13)$, $\gamma\text{CC}(14)$
241	1.27	0.85	-	-	$\tau\text{CH}_3(38)$, $\delta\text{CCl}(11)$, $\delta\text{CC}(11)$
218	0.83	0.15	-	-	$\tau\text{CH}_3(77)$
205	2.55	0.46	-	-	$\delta\text{CC}(41)$, $\tau\text{CH}_3(28)$
162	0.32	2.06	-	158	$\delta\text{PhII}(11)$, $\delta\text{CC}(17)$
143	0.32	1.79	-	-	$\delta\text{CC}(27)$, $\tau\text{CC}(22)$
129	1.06	2.00	-	-	$\delta\text{CC}(16)$, $\gamma\text{CC}(34)$
102	0.16	3.35	-	98	$\tau\text{CC}(24)$, $\tau\text{PhI}(13)$,

					$\delta\text{CC}(18)$, $\tau\text{C}=\text{C}(13)$
77	2.89	0.65	-	75	$\tau\text{CC}(19)$, $\tau\text{PhI}(17)$, $\tau\text{C}=\text{O}(16)$, $\gamma\text{CC}(13)$
55	0.14	1.38	-	-	$\tau\text{CC}(33)$, $\tau\text{PhII}(22)$
41	0.01	2.86	-	-	$\delta\text{CC}(12)$, $\gamma\text{CC}(10)$, $\tau\text{CC}(64)$
35	0.02	1.87	-	-	$\delta\text{C}=\text{C}(22)$, $\delta\text{CC}(37)$
25	0.04	3.71	-	-	$\tau\text{C}=\text{O}(58)$, $\delta\text{CC}(14)$
17	0.04	0.55	-	-	$\tau\text{CC}(67)$

^a ν -stretching; δ -in-plane deformation; γ -out-of-plane deformation; τ -torsion; PhI-phenyl ring with chlorine; PhII-phenyl ring with methyl; potential energy distribution (%) is given in brackets in the assignment column; IR_I-IR intensity; R_A-Raman activity

Table 3

Second order perturbation theory analysis of Fock matrix in NBO basis corresponding to the Intra-molecular bonds of the title compound

Donor(i)	Type	ED/e	Acceptor(j)	Type	Ed/e	E(2) ^a	E(j)-E(i) ^b	F(i,j) ^c
C3-C4	σ	1.98059	C4-C6	σ^*	0.01270	79.08	0.47	0.173
-	-	-	C13-C18	σ^*	0.02784	10.97	0.83	0.085
C3-C28	σ	1.97841	C3-C28	σ^*	0.06480	4380.41	0.39	1.174
-	-	-	C4-C6	σ^*	0.01270	728.79	1.32	0.876
-	-	-	C6-C8	σ^*	0.02184	4199.40	0.40	1.153
C4-C6	σ	1.98166	C3-C4	σ^*	0.05666	1.75	1.19	0.041
-	-	-	C4-C6	σ^*	0.01270	10.44	0.61	0.071
C6-C8	σ	1.97776	C4-C6	σ^*	0.01270	19.26	0.57	0.094
-	-	-	C13-C18	σ^*	0.02784	6.08	0.93	0.067
C13-C18	σ	1.97492	C9-C11	σ^*	0.01273	2.26	1.04	0.043
-	-	-	C11-C13	σ^*	0.02131	1.56	1.18	0.038
C31-C33	σ	1.98208	C4-C6	σ^*	0.01270	15.80	0.61	0.088
-	-	-	C33-C34	σ^*	0.02688	3.29	1.15	0.055
C33-C34	π	1.66857	C4-C6	σ^*	0.01270	21.34	0.62	0.102
-	-	-	C31-C33	σ^*	0.02737	2.87	1.27	0.054
LP C11	σ	1.99293	C4-C6	σ^*	0.01270	2.16	0.81	0.037
-	-	-	C31-C33	σ^*	0.02737	1.66	1.46	0.044
LP C11	π	1.97261	C4-C6	σ^*	0.01270	423.83	0.36	0.350
-	-	-	C13-C18	σ^*	0.02784	41.45	0.72	0.154
-	-	-	C33-C34	π^*	0.38470	40.93	0.40	0.126
LP C11	n	1.92483	C3-C28	σ^*	0.06480	5426.1	0.37	1.266
-	-	-	C4-C6	σ^*	0.01270	781.11	1.30	0.913
-	-	-	C6-C8	σ^*	0.02184	5342.80	0.38	1.288
LP O2	σ	1.97827	C3-C4	σ^*	0.05666	1.66	1.15	0.039
-	-	-	C4-C6	σ^*	0.01270	19.34	0.57	0.094

^aE(2) means energy of hyper-conjugative interactions (stabilization energy in kJ/mol)

^bEnergy difference (a.u.) between donor and acceptor i and j NBO orbitals

^cF(i,j) is the Fock matrix elements (a.u.) between i and j NBO orbitals

Table 3

NBO results showing the formation of Lewis and non-Lewis orbitals

Bond(A-B)	ED/e ^a	EDA%	EDB%	NBO	s%	p%
σ C3-C4	1.98059	48.88	51.12	0.6992(sp ^{1.81})C	35.51	64.49
-	-0.59863	-	-	+0.7150(sp ^{2.14})C	31.84	68.16
σ C3-C28	1.97841	47.46	52.54	0.6889(sp ^{1.91})C	34.34	65.66
-	-1.44360	-	-	+0.7248(sp ^{2.21})C	31.15	68.85
σ C4-C6	1.98166	50.31	49.69	0.7093(sp ^{1.64})C	37.90	62.10
-	-0.73790	-	-	+0.7049(sp ^{1.66})C	37.51	62.49
σ C6-C8	1.97776	48.42	51.58	0.6958(sp ^{1.93})C	34.13	65.87
-	-0.69572	-	-	+0.7182(sp ^{2.05})C	32.73	67.27
σ C13-C18	1.97492	50.58	49.42	0.7112(sp ^{2.10})C	32.21	67.79
-	-0.62135	-	-	+0.7030(sp ^{2.82})C	26.18	73.82
σ C31-C33	1.98208	48.85	51.15	0.6989(sp ^{1.96})C	33.74	66.26
-	-0.73450	-	-	+0.7152(sp ^{1.59})C	38.59	61.41
π C33-C34	1.98191	51.43	48.57	0.7172(sp ^{1.00})C	0.00	100.0
-	-0.74298	-	-	+0.6969(sp ^{1.00})C	0.00	100.0
n1 Cl1	1.99293	-	-	sp ^{0.21}	82.86	17.14
-	-0.93672	-	-	-	-	-
n2 Cl1	1.97261	-	-	sp ^{1.00}	0.00	100.0
-	-0.48775	-	-	-	-	-
n3 Cl1	1.92483	-	-	sp ^{1.00}	0.00	100.0
-	-0.42569	-	-	-	-	-
n1 O2	1.97827	-	-	sp ^{0.70}	58.84	41.12
-	-0.70170	-	-	-	-	-
n2 O2	1.88747	-	-	sp ^{1.00}	0.00	100.0
-	-0.25981	-	-	-	-	-

^aED/e is expressed in a.u.

Fig.1 FT-IR spectrum of
(2*E*)-1-(4-chlorophenyl)-3-[4-(propan-2-yl)phenyl]prop-2-en-1-one

Fig.2 FT-Raman spectrum of
(2*E*)-1-(4-chlorophenyl)-3-[4-(propan-2-yl)phenyl]prop-2-en-1-one

**Fig.3 Optimized geometry of
(2E)-1-(4-chlorophenyl)-3-[4-(propan-2-yl)phenyl]prop-2-en-1-one**

**Fig.4 HOMO, LUMO plots of
(2E)-1-(4-chlorophenyl)-3-[4-(propan-2-yl)phenyl]prop-2-en-1-one**

**Fig.5 MEP plot of
(2*E*)-1-(4-chlorophenyl)-3-[4-(propan-2-
yl)phenyl]prop-2-en-1-one**

Fig.6 The title compound, (2*E*)-1-(4-chlorophenyl)-3-[4-(propan-2-yl)phenyl]prop-2-en-1-one binds at the active site of Lck

Fig.7 Detailed interactions of *(2E)*-1-(4-chlorophenyl)-3-[4-(propan-2-yl)phenyl]prop-2-en-1-one with the inhibitor residues, dotted lines represent the interactions.

Highlights

- The FT-IR and FT-Raman spectra were reported
- The vibrational wavenumbers were calculated by DFT method and discussed
- First and second hyperpolarizabilities were calculated to determine the NLO property
- Molecular docking studies show that the title compound exhibit inhibitory activity against lymphocyte-specific kinase.