Journal of Molecular Structure 1035 (2013) 157–164

Contents lists available at SciVerse ScienceDirect

Journal of Molecular Structure

journal homepage: www.elsevier.com/locate/molstruc

Spectral and theoretical studies on the molecular complexes of azacyclonol with new π-acceptors, alkoxysubstituted 1,4-benzoquinones

C. Balraj, A. Satheshkumar, K. Ganesh, Kuppanagounder P. Elango *

Department of Chemistry, Gandhigram Rural Institute (Deemed University), Gandhigram 624 302, India

HIGHLIGHTS

- Different new alkoxy substituted 1,4-benoquinones were employed as electron acceptors.
- The molecular complexes were characterized using various spectral techniques.
- Taft correlation indicated that both polar and steric effects of substituents govern reactivity.

ARTICLE INFO

Article history:
Received 2 July 2012
Received in revised form 12 September 2012
Accepted 12 September 2012
Available online 21 September 2012

Keywords:
Charge transfer
Benzoquinones
Azacyclonol
Taft correlation
Fluorescence

ABSTRACT

The molecular complexes of a series of new electron acceptors, 1,4-benzoquinones possessing variety of alkoxy substituents, with azacyclonol have been investigated using various spectral techniques such as UV–Vis, ^{1}H NMR, FT-IR, fluorescence and LC–MS. The stoichiometry of the complexes was determined by Job's continuous variation method and was found to be 1:1, in all the cases. The results of equilibrium, and kinetic studies were well supported by *ab initio* DFT calculations. Correlation of formation constants of the complexes with Taft's polar and steric constants indicated that both these factors play significant role in governing the reactivity. Also, the results indicated that an increase in electron releasing property of the alkoxy group makes these acceptors increasingly weaker while an increase in steric property of the substituent decreased the formation constant.

1. Introduction

Quinones are one of the most significant classes of organic compounds, as their applications ranges into various fields like biology [1,2], pharmaceutical [3], water management [4] and agriculture [5], etc. In many biological electron transfer processes quinones play an integral role [6,7]. It is established that the biological activity of these compounds is due to the redox chemistry of the quinone system [1,8]. The quinone ring accepts one or two electrons to form corresponding radical-anion ($Q^{\cdot-}$) and hydroquinone dianion (Q^{2-}). These species interact with crucial cellular molecules such as DNA, proteins and oxygen tuning their biological activity by accepting the electrons in the correct site [1,8,9].

The ability of the quinones to accept one or two electrons depends directly on their chemical structures [10]. It is known that the redox chemistry of these substances can be modified either by directly adding a substituent to the quinone ring or by attaching a substituted phenyl ring to the quinone system [11]. However, for some applications, fine tuning of the electron accepting properties are required. To achieve this, many attempts have been made to synthesize quinone systems with substituted phenyl rings directly attached to it and to study their redox chemistry. The biological activities of such systems have also been documented [12].

Over the years, a great deal of research has been carried out on the charge transfer complexes of quinones because of their wide applications ranging from chemistry, material science, medicine to biology [13–15]. In biological systems quinones exit in the form of substituted *p*-benzoquinones such as plastoquinones [16], Vitamin K [17], ubiquinones [2,18]. Also, these naturally occurring quinones possess variable number of methoxy groups. Though good amount of work, on the study of charge transfer (CT) complexes of number of quinones with variety of donors, has been carried out [19–22], reports related to quinones with systematic variation of substituents is rare in literature. Azacyclonol (chemically known as diphenyl(piperidin-4-yl)methanol) is an anti histamine drug that inhibits the action of histamine blocking it from attaching to the histamine receptors, or it may inhibit the enzymatic activity of histidine decarboxylase, catalyzing the transformation of histidine into histamine and are commonly used for the relief of allergies caused by intolerance of proteins [23,24].

* Corresponding author. Tel.: +91 451 2452371; fax: +91 451 2454466.
E-mail address: drkpelango@rediffmail.com (K.P. Elango).

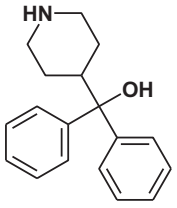
0022-2860/$ - see front matter © 2012 Elsevier B.V. All rights reserved.
http://dx.doi.org/10.1016/j.molstruc.2012.09.033

The main objective, therefore, of the present endeavor is to study the charge transfer complexes of azacyclonol drug with different 1,4-benzoquinones possessing variety of alkoxy groups. Though these chosen quinones are known to synthetic organic chemists as intermediates, to the best of our knowledge this is the first systematic investigation on the charge transfer complexes of these quinones as electron acceptors. In the frame of Density Functional Theory (DFT) we have also performed the complete optimization of the geometry for these quinones. An attempt has also been made to correlate Taft's polar (σ^*) and steric (E_s) substituent constants [25] with the formation constants of the CT complex formed between the quinones and the donor.

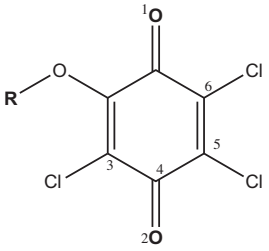
2. Experimental

2.1. Materials and measurements

The electron acceptors of alkoxy substituted 1,4-benzoquinones derivatives (MQ, EQ, IPQ, BQ) were prepared by reported method [26]. Spectroscopy grade solvents (Merck, India) were used as received. The electron donor drug azacyclonol was obtained as gift sample from a locally available pharmaceutical company and was used as received. The purity of the donor was ascertained using its m.p. (found 161 °C; Lit.160–163 °C). The structures of donor and the acceptors are shown below.



Azacyclonol



Acceptors

MQ (R= methyl); EQ (R= ethyl); IPQ (R= iso propyl); BQ (R= n-butyl)

Solutions for the spectroscopic measurements were prepared by dissolving accurately weighed amounts of donor (D) and acceptor (A) in appropriate volume of solvent immediately before running the spectra. The electronic absorption spectra were recorded on a JASCO (V630, Japan) double beam spectrophotometer using 1 cm matched quartz cells. The temperature of the cell holder was controlled with a water flow (±0.1 °C). FT-IR spectra were recorded in a JASCO (FT-IR 460 Plus, Japan) spectrometer. ^{1}H NMR spectra were recorded at Madurai Kamaraj University, Madurai in a Brucker NMR spectrometer (300 MHz, Switzerland).

2.2. Preparation and characterization of substituted quinones

An excess amount of sodium methoxide was added into a stirred solution of chlroanil in methanol at RT under N_2 atm. The reaction mixture was stirred for 12 h at 70 °C and was cooled to room temperature. Then the reaction mixture was added to 200 ml of water and stirred for 1 h at RT. The crude material formed was filtered through a filter paper, the residue was purified using column chromatography (Silica gel 60–120 by using 5–10% ethyl acetate petether mixture) and MQ was obtained as the major product. EQ was prepared using sodium ethoxide under identical conditions adopted for the preparation of MQ. For the preparation of IPQ and BQ, the corresponding alcohols along with 1 eqv. of Na_2CO_3 were used as the starting materials. The reaction mixture was stirred for 12 h at 90 °C, cooled to room temperature and 200 ml of water was added and stirred for 1 h at RT. The crude material was filtered through the filter paper, the solid residue was purified using column chromatography (see Scheme 1).

2.2.1. 3,5,6-Trichloro-2-methoxycyclohexa-2,5-diene-1,4-dione (MQ)

^{1}H NMR (DMSO-D^6, 300 MHz), δ(ppm) 4.19 (s, 3H); FT-IR (KBr, cm^{-1}): 1680 (C=O), 1668 (C=O), 1567 (C=C); UV–Vis in 1,2-dichloroethane (λ_{max}): 295 nm (π–π^*), log ε 4.24; Anal. Calcd. for $C_7H_3Cl_3O_3$: C, 34.82; H, 1.25; N, 0.0; found: C, 36.17; H, 1.74; N, 0.0; m.p. 172 °C.

2.2.2. 3,5,6-Trichloro-2-ethoxycyclohexa-2,5-diene-1,4-dione (EQ)

^{1}H NMR (DMSO-D^6, 300 MHz), δ(ppm) 1.39 (t, J = 6 Hz, 3H), 4.45–4.53 (m, 2H); FT-IR (KBr, cm^{-1}): 1676, 1608 (C=O); UV–Vis in 1,2-dichloroethane (λ_{max}): 293 nm (π–π^*), log ε 4.12; Anal. Calcd. for $C_8H_5Cl_3O_3$: C, 37.61; H, 1.97; N, 0.0; found: C, 36.87; H, 1.84; N, 0.0; m.p. 112 °C.

2.2.3. 3,5,6-Trichloro-2-isopropoxycyclohexa-2,5-diene-1,4-dione (IPQ)

^{1}H NMR (DMSO-D^6, 300 MHz), δ(ppm) 1.34 (d, J = 6 Hz, 6H), 4.98–5.10 (m, 1H); FT-IR (cm^{-1}): 1670, 1648 (C=O), UV–Vis in 1,2-Dichloroethane (λ_{max}): 293 nm (π–π^*), log ε 4.33; Anal. Calcd. for $C_9H_7Cl_3O_3$: C, 40.11; H, 2.62; N, 0.0; found: C, 40.81; H, 2.56; N, 0.0; m.p. 74 °C.

2.2.4. 2-Butoxy-3,5,6-trichlorocyclohexa-2,5-diene-1,4-dione (BQ)

^{1}H NMR (DMSO-D^6, 300 MHz), δ(ppm) 0.9 (t, J = 6 Hz, 3H), 1.35–1.48 (m, 2H), 1.63–1.74 (m, 2H), 4.45 (t, J = 6 Hz, 2H); FT-IR (cm^{-1}): 1672, 1649 (C=O), UV–Vis in 1,2-dichloroethane (λ_{max}): 293 nm (π–π^*), log ε 4.16; Anal. Calcd. for $C_{10}H_9Cl_3O_3$: C, 42.36; H, 3.20; N, 0.0; found: C, 42.14; H, 3.18; N, 0.0; m.p. 88 °C.

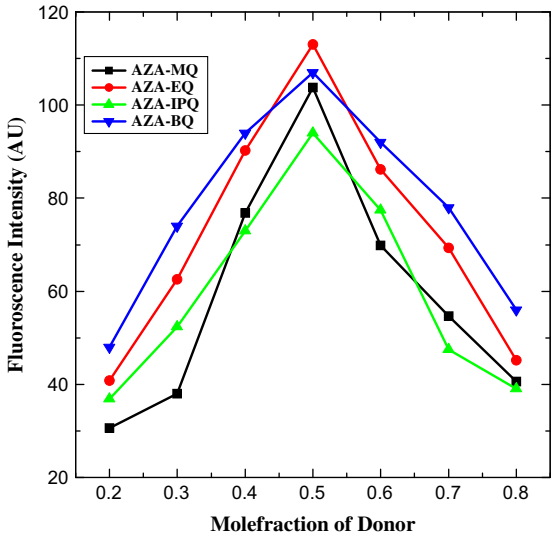


Fig. 1. Job's continuous variation plots for AZA–MQ, AZA–EQ, AZA–IPQ, and AZA–BQ in 1,2-dichloroethane at 298 K.

2.3. Kinetic procedure

The kinetics of the interaction of azacyclonol with the acceptors (MQ, EQ, IPQ and BQ) was followed at three different temperatures in 1,2-dichloroethane under pseudo-first-order conditions, keeping $[D] \gg [A]$. The increase in absorbance of the corresponding new peaks around at 564 nm for the all the systems with elapse of time was recorded. The pseudo-first-order rate constants (k_1) were calculated from the gradients of log (A_∞–A_t) against time plots, where A_∞ and A_t represent the absorbance at infinity and time t, respectively. The second order rate constants were calculated by dividing k_1 by $[D]$ [27,28].

3. Results and discussion

3.1. Stoichiometry of the interaction

The stochiometry of the CT complexes formed between AZA and the acceptors was determined by Job's continuous variation method using emission data [29]. In all the cases, symmetrical curves with maximum at 0.5 mol fraction indicated the formation of a 1:1 (D:A) CT complex (Fig. 1). The photometric titration measurements were also performed for the determination of the stoichiometry in these interactions. For that, the concentration of the donor in the reaction mixtures was kept constant while the concentrations of the acceptors were varied over a wide range. The results of the photometric curves (Fig. 2) also indicated that the stoichiometry of the interaction, in all the cases, was 1:1 (D:A) [30,31].

3.2. Electronic spectra and kinetics of the interaction

The electronic spectra of the acceptors (MQ, EQ, IPQ and BQ) exhibited a peak around 295 nm which is characteristic peak of π–π^* transition in quinone systems. The kinetics of the interaction of the donor (AZA) and the acceptors, under pseudo-first-order condition, i.e. $[D]/[A] > 100$ as a function of time were recorded. On mixing 1,2-dichloroethane solutions of AZA and EQ, there was an instantaneous formation of deep blue color with a low energy absorption maximum at 564 nm and also other absorption maximum appeared at 345 nm (Fig. 3). The intensity of these bands increased with elapse of time while that of the band at 295 nm decreased. Two clear isosbestic points were appeared at 308 and 276 nm. The interaction of MQ, IPQ and BQ (Figs. 4–6) exhibited

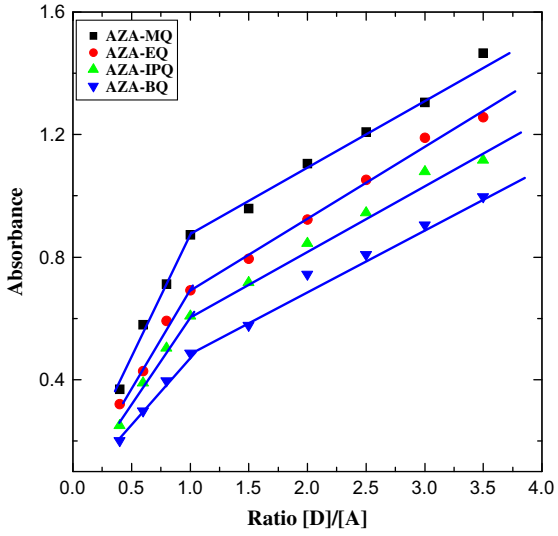


Fig. 2. Photometric titration plot for AZA–MQ, AZA–EQ, AZA–IPQ, AZA–BQ in 1,2-dichloroethane at 298 K.

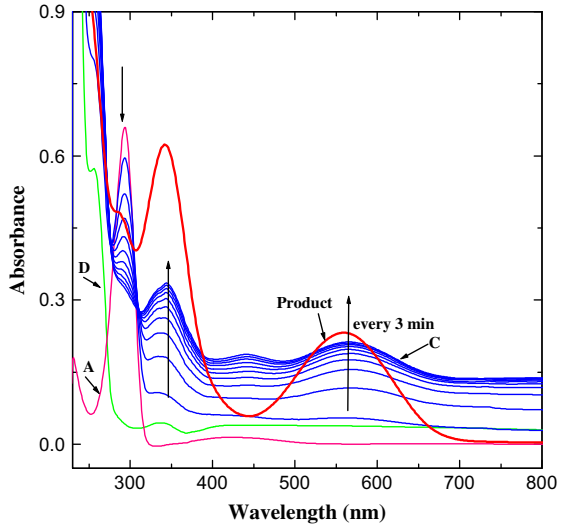


Fig. 3. Electronic spectra of AZA with EQ in 1,2-dichloroethane at 298 K.

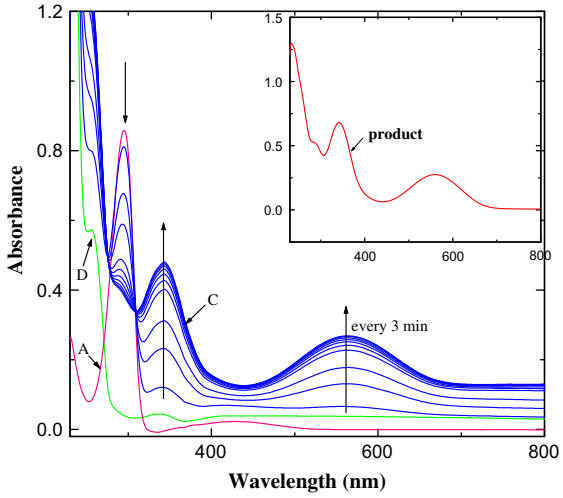


Fig. 4. Electronic spectra of AZA with MQ in 1,2-dichloroethane at 298 K.

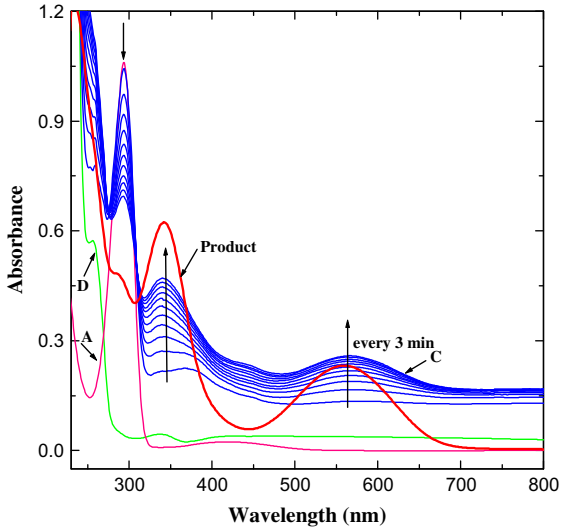


Fig. 5. Electronic spectra of AZA with IPQ in 1,2-dichloroethane at 298 K.

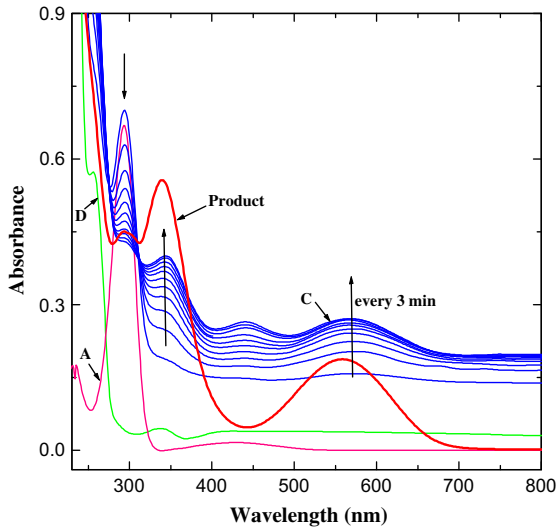


Fig. 6. Electronic spectra of AZA with BQ in 1,2-dichloroethane at 298 K.

similar electronic spectral behavior. These observed new low energy bands cannot be considered as the characteristic absorption bands of an outer complex because: the formation of outer complex may be an instantaneous process and the concentration of which may be very low to detect and also this may immediately be converted to the final product. This is well supported by the fact that the final product extracted, in all these cases, exhibited super imposable electronic spectrum.

The pseudo-first-order rate constants (k_1), for the formation of the products, as a function of [*D*] and [*A*] are collected in Table 1. It is evident from the results that the rate of the interaction is independent of initial concentration of *A* indicating first order dependence on [*A*]. The rate constant values increased with an increase in [*D*] and in all the cases, a plot of log k_1 versus log [*D*] is linear ($r > 0.95$) with a slope close to one, indicating first order dependence of rate on [*D*]. This was further supported by the constancy in k_2 values [27,28]. These observations indicated that the interaction of AZA with these acceptors proceed via the following plausible mechanism (Scheme 2).

The above mechanism leads to the following rate law

$$\text{Rate} = k[\text{CT complex}]$$

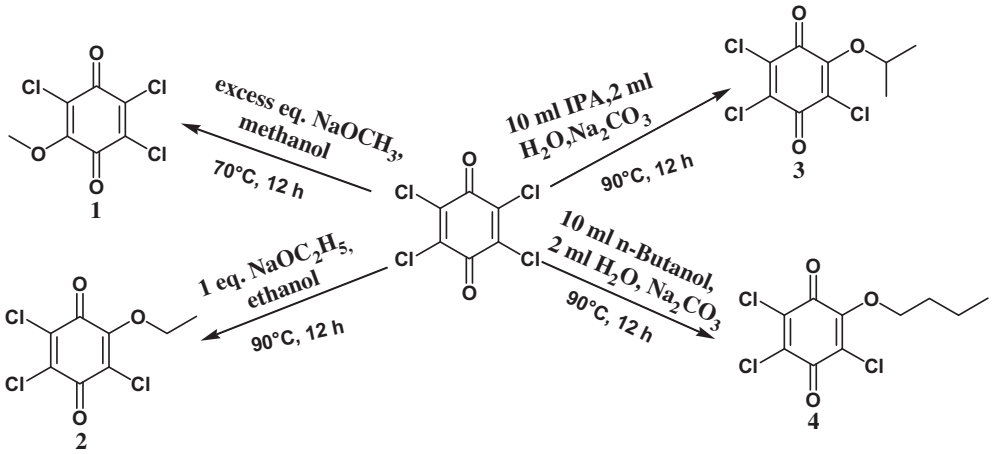
or

$$\text{Rate} = k_1[D][A]$$

where $k_1 = Kk$.

The rate constants as a function of temperature along with thermodynamic parameters are collected in Table 2. It is evident from the results that the enthalpy of activation, which is a measure of strength of the interaction between the donor and the acceptor in a molecular complex [32], follows the order AZA–MQ > AZA–EQ > AZA–BQ > AZA–IPQ.

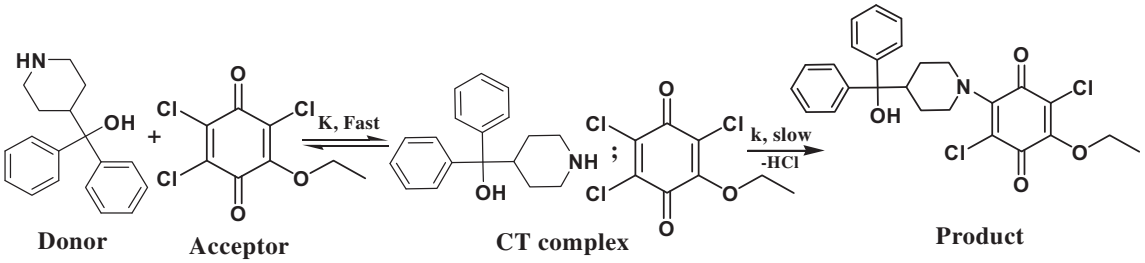
An attempt was also made to characterize the charge transfer complexes formed in these reactions. For that the absorbance of the new low energy bands were measured using constant acceptor concentration and varying concentrations of the donor, but always [*D*] ≫ [*A*] [29,33]. The formation constants (*K*) and molar extinction coefficients (ε) of the CT complexes were determined spectrophotometrically using the Scott equation [34]. The values of *K* and ε determined are given in Table 3. The observed high values of *K*



Scheme 1. Preparation method for MQ, EQ, IPQ, BQ.

Table 1
Effect of concentration of the donor and the acceptors on the rate of the interaction at 298 K.

[*D*] (10^{-4} M)	[*A*] (10^{-5} M)	k_1 (10^{-4} s^{-1})				k_2 (s^1 mol^{-1} dm^3)			
		AZA–MQ	AZA–EQ	AZA–BQ	AZA–IPQ	AZA–MQ	AZA–EQ	AZA–BQ	AZA–IPQ
4	5	14.6	13.3	11.8	9.6	3.6	3.3	2.9	2.4
6	5	21.2	18.9	16.8	14.6	3.5	3.2	2.8	2.4
8	5	28.7	25.7	22.4	19.7	3.6	3.2	2.8	2.5
10	5	35.8	31.9	28.1	24.7	3.6	3.2	2.8	2.5
10	5	35.9	31.1	28.2	24.2				
10	4	34.8	31.4	28.4	24.9				
10	3	35.2	31.8	28.7	24.1				
10	2	35.7	32.2	28.2	24.6				



Scheme 2. Interaction of AZA with EQ.

Table 2
Kinetic and thermodynamic parameters for the interaction of the donor with the acceptors in 1,2-dichloroethane.

System	λ (nm)	k_1 (10^{-4} s^{-1})			$\Delta H^{\#}$	$-\Delta S^{\#}$	$\Delta G^{\#}$
		298	305	313 K			
AZA–MQ	564	35.8	39.6	42.5	6	289	92
AZA–EQ	564	31.9	37.2	39.7	9	282	93
AZA–BQ	570	28.1	33.2	37.2	12	272	93
AZA–IPQ	570	24.7	30.2	34.6	14	264	94

$\Delta H^{\#}$ kJ mol^{-1}; $\Delta S^{\#}$ J K^{-1} mol^{-1}; $\Delta G^{\#}$ kJ mol^{-1}.

suggested that the formed complexes are of a strong type [35] and the linearity of the Scott plots ($r > 0.97$) further supports this result.

3.3. Characterization of the interaction product

In all the cases, the final product was obtained by stirring equimolar 1,2-dichloroethane solutions of the donor and the acceptor at room temperature for 24 h. The solid obtained, after evaporation of the solvent, was purified using column chromatography (Silica gel 60–120 by using 5–10% ethyl acetate/petether mixture). The products were characterized using analytical (CHN) and spectral (^{1}H NMR, FT-IR, LC–MS) techniques. The results obtained are:

3.3.1. AZA–MQ product: [2,5-dichloro-3-(4-(hydroxydiphenylmethyl) piperidin-1-yl)-6-methoxycyclohexa-2,5-diene-1,4-dione]

^{1}H NMR (DMSO-D^6, 300 MHz), δ(ppm) 1.24 (d, J = 3 Hz, 2H), 1.39 (d, J = 6 Hz, 2H), 2.90 (t, J = 9 Hz, 1H), 3.28 (t, J = 12 Hz, 2H), 3.76 (d, J = 12 Hz, 2H), 4.08 (s, 3H), 5.41 (s, 1H), 7.15 (t, J = 6 Hz, 2H), 7.30 (t, J = 9 Hz, 4H), 7.56 (d, J = 9 Hz, 4H); FT-IR (KBr, cm^{-1}): 3377 (O—H), 1677 (C=O), 1644 (C=O); LCMS: Calcd. for $C_{25}H_{23}Cl_2NO_4$: 472.36; found: 474.1. Anal. Calcd. for $C_{25}H_{23}Cl_2NO_4$: C, 63.57; H, 4.91; N, 2.97: found: C, 63.38; H, 4.87; N, 2.89.

3.3.2. AZA–EQ product [2,5-dichloro-3-ethoxy-6-(4-(hydroxydiphenylmethyl)piperidin-1-yl)cyclohexa-2,5-diene-1,4-dione]

^{1}H NMR (DMSO-D^6, 300 MHZ), δ(ppm) 1.30 (d, J = 9 Hz, 2H), 1.36 (d, J = 12 Hz, 3H), 1.64 (t, J = 9 Hz, 2H), 2.90 (t, J = 12 Hz, 1H), 3.19–3.28 (m, 2H), 3.76 (d, J = 12 Hz, 2H), 4.37–4.44 (m, 2H), 5.41 (s, 1H), 7.15 (t, J = 6 Hz, 2H), 7.30 (t, J = 9 Hz, 4H), 7.55 (d, J = 6 Hz, 4H); FT-IR (KBr, cm^{-1}): 3425 (O—H), 1670, 1644 (C=O); LCMS: Calcd. for $C_{26}H_{25}Cl_2NO_4$: 485.12; found: 486.2.

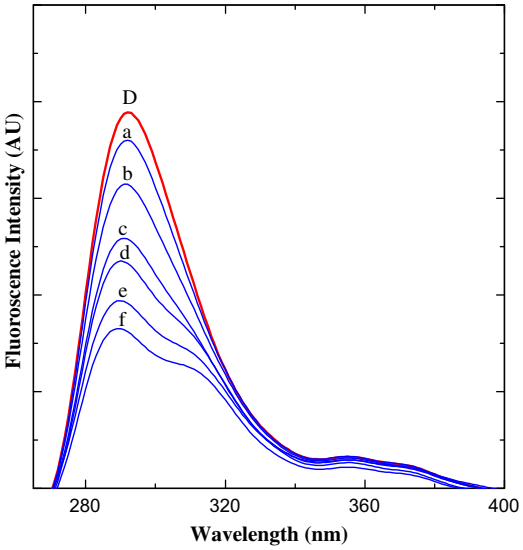


Fig. 7. Fluorescence spectra for AZA–EQ system in 1,2-dichloroethane at fixed concentrations of [D] = {8 × 10^{-4} M (curve d)} and variable concentration of [A](×10^{-5}) = {1 (curve a), 2 (curve b), 3 (curve c), 4 (curve d), 5 (curve e), 6 (curve f)}M at 298 K.

3.3.3. AZA–IPQ product [2,5-dichloro-3-(4-(hydroxydiphenylmethyl) piperidin-1-yl)-6-isopropoxycyclohexa-2,5-diene-1,4-dione]

^{1}H NMR (DMSO-D^6, 300 MHz), δ(ppm) 1.28 (s, 6H), 1.37 (s, 2H),1.57–1.68 (m, 2H), 2.90 (t, J = 12 Hz, 1H), 3.20–3.29 (m, 2H), 3.77 (d, J = 12 Hz, 2H), 4.89–4.99 (m,1H), 5.41 (s, 1H), 7.16 (t, J = 9 Hz, 2H), 7.30 (t, J = 6 Hz, 4H), 7.56 (d, J = 9 Hz, 4H); FT-IR (KBr, cm^{-1}): 3380 (O—H), 1678, 1642 (C=O); LCMS: Calcd. for $C_{27}H_{27}Cl_2NO_4$: 500.4; found: 499.6.

3.3.4. AZA–BQ product [2-butoxy-3,6-dichloro-5-(4-(hydroxydiphenylmethyl)piperidin-1-yl)cyclohexa-2,5-diene-1,4-dione]

^{1}H NMR (DMSO-D^6, 300 MHz), δ(ppm) 1.33–1.39 (m, 4H), 1.43 (t, J = 6 Hz, 3H), 1.65 (t, J = 9 Hz, 4H), 2.80–2.90 (m,1H), 3.28 (t, J = 12 Hz, 2H), 3.76 (d, J = 12 Hz, 2H), 4.39 (t, J = 6 Hz, 2H), 5.41 (s, 1H), 7.15 (t, J = 6 Hz, 2H), 7.30 (t, J = 9 Hz, 4H), 7.56 (d, J = 9 Hz,

Table 3
Formation constant and extinction coefficient of all the systems carried out in 1,2-dichloroethane at 298 K.

Systems	Formation constant **K** (dm^3 mol^{-1}) (*absorption method*)	Extinction coefficient **log** ε (dm^3 mol^{-1} cm^{-1}) (*absorption method*)	Association constant $\mathbf{K_f}$ (mol l^{-1}) (*emission method*)
AZA–MQ	1602	4.64	9.17 × 10^4
AZA–EQ	1362	4.59	8.94 × 10^4
AZA–BQ	1023	4.56	8.43 × 10^4
AZA–IPQ	684	4.57	8.06 × 10^4

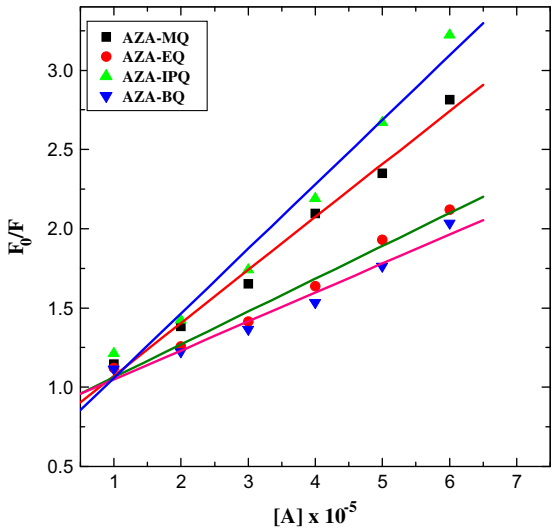


Fig. 8. Stern–Volmer plots for the fluorescence quenching of AZA with the acceptors in 1,2-dichloroethane at 298 K.

4H); FT-IR (KBr, cm^{-1}): 3425 (O—H), 1670, 1644 (C=O); LCMS: Calcd. for $C_{28}H_{29}Cl_2NO_4$: 514.44; found: 515.3.

3.4. Fluorescence study

One of the most important binding forces that produce favorable binding of a drug to its target is the CT interaction. The nature and magnitude of drug interaction significantly influences the biological activity of the drug. In the present study an attempt was made to investigate the mode of CT interaction between AZA with these acceptors using fluorescence spectroscopy. The fluorescence spectra were recorded in 1,2-dichloroethane at room temperature in the range of 230–730 nm upon excitation at 254 nm for all the systems. It is observed that these acceptors quenched the fluorescence of AZA through CT complexation. The experimental results indicated that the quenching efficiency increased with an increase in the concentration of the acceptors at a fixed concentration of the drug (Fig. 7 and Fig. 9S-11S). For all the systems, the CT interaction between the quencher and the fluorophore has been observed at 292 nm. The fraction of the acceptor bound to the drug (θ) was determined using the following equation [36].

$$\theta = (F_0 - F)/F_0 \quad (1)$$

where F and F_0 denote the fluorescence intensities of the drug in a solution with a given concentration of the acceptor and without the acceptor, respectively. From the values of θ the association constant, K_f, for the drug interaction with the acceptors was computed using the method described in the literature [37]. It has been shown that for equivalent and independent binding sites:

$$1/(1-\theta)K_f = [A_T]/\theta - n[D_T] \quad (2)$$

where n is the number of binding sites, $[A_T]$ is the total acceptor concentration and $[D_T]$ is the total drug concentration. The plot of $1/(1-\theta)$ versus $[A_T]/\theta$ was found to be linear ($r > 0.97$), for all the systems, indicating that under the experimental conditions all the binding sites are equivalent and independent. The values of K_f obtained from the plots for AZA–MQ, AZA–EQ, AZA–BQ and AZA–IPQ systems were found to be 9.17×10^4, 8.94×10^4, 8.43×10^4 and 8.06×10^4 mol l^{-1}, respectively. Parallel to the observation made under the electronic spectral studies, as enumerated earlier, the strength of the complex formation between the partners is in the order AZA–MQ > AZA–EQ > AZA–BQ > AZA–IPQ. The standard Gibbs energy change ΔG° was calculated from the K_f using the relation $\Delta G^\circ = -2.303\ RT \log_{10} K_f$. The ΔG° values for AZA–MQ, AZA–EQ, AZA–IPQ and AZA–BQ systems were found to be −28.31, −28.25, −28.10 and −27.99 kJ, respectively, which indicated that the interactions between the drug and the acceptors are spontaneous [38].

Fluorescence quenching can occur by different mechanisms viz. static or dynamic or both. Stern–Volmer equation (Eq. (3)) is useful in understanding the mechanism of fluorescence quenching.

$$F_0/F = 1 + K_{SV}[Q] \quad (3)$$

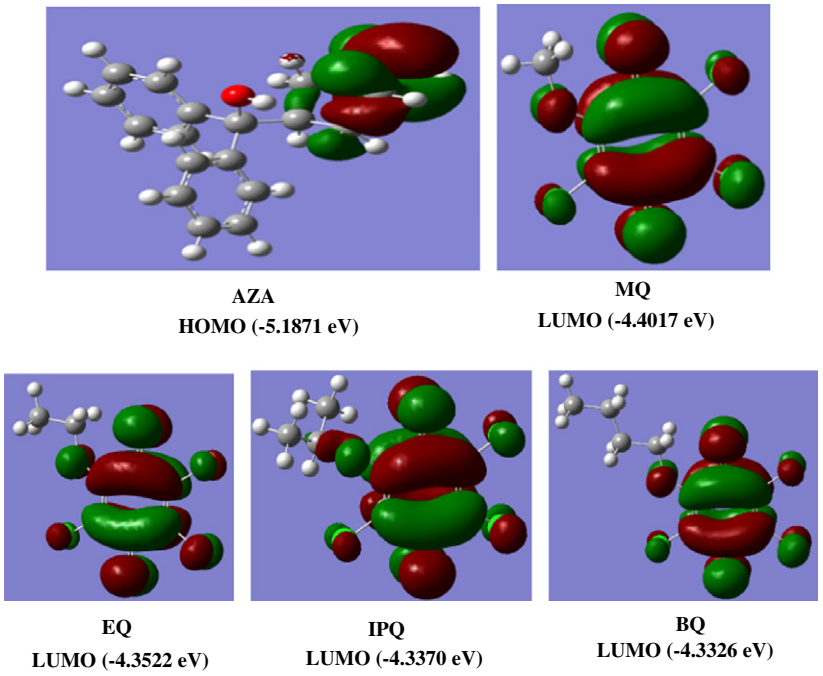


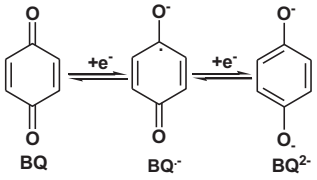
Fig. 9. The optimized structure for AZA with HOMO and acceptors with LUMO.

where F_0 is emission intensity in the absence of quencher (Q), F is emission intensity at quencher concentration [Q] and K_{SV} is the Stern–Volmer constant. In the present study, the linear Stern–Volmer relationship observed suggested that either static or dynamic quenching is dominant in all the systems (Fig. 8) [39,40]. The fluorimetric results indicated that the CT interaction between AZA and these acceptors is spontaneous and an increase in the strength of such interaction decreases the fluorescence intensity of AZA.

3.5. Theoretical calculations

To understand the foregoing experimental observations on the CT complex formed between AZA and the acceptors, we have performed the optimization of AZA, MQ, EQ, IPQ and BQ using Density Functional Theory with the Backle3LYP hybrid functional, by using a basis set of 6-31G. Computations have been performed using the Gaussian 03 Revision D.01 program package [41]. The optimized geometry of the donor along with HOMO and the acceptors along with LUMO are depicted in Fig. 9.

As spelt in the introduction section, quinone moiety accepts one electron or two electrons to form the corresponding radical-anion ($BQ^{\cdot-}$) and hydroquinone radical dianion (BQ^{2-}). The electron accepting capacity and several physicochemical/biological properties of a given quinone depends largely on the substituent present in it.



The optimized geometry of the acceptors indicated that the LUMO resides on the carbonyl group of the quinones and in the donor the HOMO resides on the NH moiety of the molecule (Fig. 9). The energies of the frontier orbitals of the donor and the acceptors along with the energy corresponds to the CT transition, ΔE(=$LUMO_{acceptor} - HOMO_{AZA}$) [42–44], for all the systems are shown in Fig. 10. It is evident from the figure that the ΔE depends on the nature of the substituent present in the quinone.

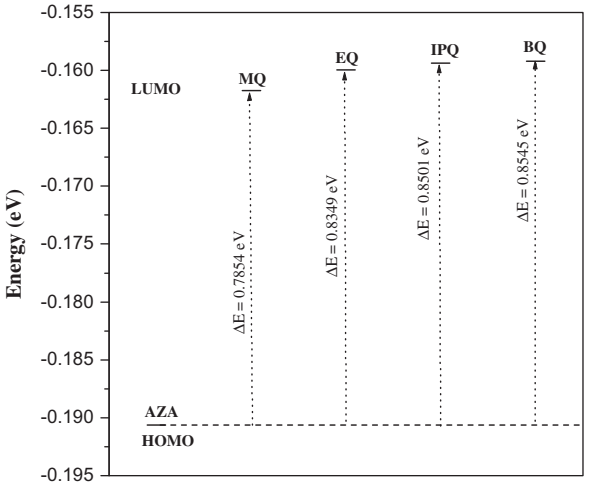


Fig. 10. Relationship between energies of $HOMO_{AZA}$ and $LUMO_{Acceptor}$.

3.6. Correlation analysis

A preliminary attempt has been made to correlate the results (i.e. formation constants) with Taft's polar and steric constants [25]. The results of the correlation analysis are shown below:

$$K = 4830\sigma^* + 1675 \quad (4)$$

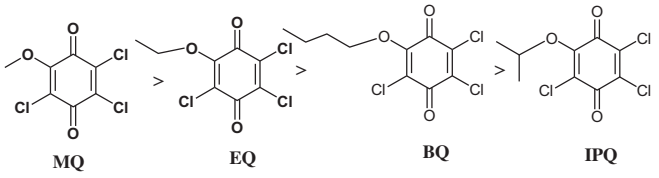
(r = 0.96; n = 4)

$$K = -1671E_s + 1556 \quad (5)$$

(r = 0.97; n = 4).

The good correlations obtained, between the formation constants of the CT complexes and Taft's constants, indicated that both polar and steric effects of the substituents play significant role in governing the reactivity of the quinones. The positive correlation observed between K and σ^* (Eq. (4)) indicated that with an increase in electron releasing power of the alkoxy substituent, makes the quinone increasingly a weaker acceptor. While the negative correlation found between K and E_s (Eq. (5)) suggested that an increase in steric nature of the substituent would makes the approach of the quinone towards the donor (to form the CT complex) relatively more difficult and consequently decreased the formation constant of the CT complex. Hence, isopropoxy substituted quinone is the weakest among the chosen acceptors as i-Pr group is the strongest electron releasing and also possesses the highest steric effect among these substituents.

The above observations indicated that the strength of the acceptor decrease in the order of the structures of the quinones:



4. Conclusions

The charge transfer interaction of 1,4-benzoquinones possessing variety of alkoxy substituents with azacyclonol, for the first time, has been investigated. Various spectral techniques have been employed to characterize the final product of these interactions. In all the cases, the stoichiometry of the CT interaction was found to be 1:1. The trends in the rate constants and formation constants showed that the strength of the complex formation is in the order of AZA–MQ > AZA–EQ > AZA–BQ > AZA–IPQ. The observed equilibrium, kinetic and fluorescence study of these acceptors were found to be well supported by theoretical calculations. Correlation of formation constants of the CT complexes with Taft's substitution constant indicated that both polar and steric effects of the substitutents play significant role in governing the reactivity.

Acknowledgements

The authors thank the University Grants Commission, New Delhi for its financial assistance to carry out this research work. One of the authors (C.B.) is thankful to the UGC, New Delhi for the award of UGC-BSR Fellowship in Sciences for Meritorious Students.

Appendix A. Supplementary material

Supplementary data associated with this article can be found, in the online version, at http://dx.doi.org/10.1016/j.molstruc.2012.09.033.

Reference

[1] R.A. Morton (Ed.), Biochemistry of Quinones, Academic Press, New York, 1965.
[2] K. Bradley, M. Briman, A. Satr, G. Gruner, Nano lett. 4 (2004) 253–256.
[3] S.T. Ulu, Spectrochim. Acta A 72 (2009) 1038–1042.
[4] M. Aeschbacher, S.H. Brunner, R.P. Schwarzenbach, M. Sander, Environ. Sci. Technol. 46 (2012) 4916–4925.
[5] J.N.C. Lopez, A.W. Johnson, J.F. Grove, M.S. Bulhoes, Cienc. Cult. (Sao Paulo) 29 (1977) 1145–1149.
[6] H. Sies, L. Packer (Eds.), Methods in Enzymology, vol. 378 and 382, Elsevier Academic Press, San Diego, London, 2004.
[7] C.A. Wraight, Front. Biosci. 9 (2004) 309–337.
[8] X.Q. Zhu, C.H. Wang, J. Org. Chem. 75 (2010) 5037–5047.
[9] H. Ishikita, G. Morra, E.W. Knapp, Biochemistry 42 (2003) 3882–3892.
[10] P. Zuman, Substituents Effects in Organic Polarography, Plenum Press, New York, 1967.
[11] N. Macias-Ruvalcaba, G. Cuevas, I. Gonzalez, M. Aguilar-Martinez, J. Org. Chem. 67 (2002) 3673–3681.
[12] M. Aguilar-Martinez, G. Cuevas, M. Jimenes-Estrada, I. Gonzalez, B. Lotina-Hennsen, N. Macias- Ruvalcuba, J. Org. Chem. 64 (1999) 3684–3694.
[13] S.d. Bella, I.L. Fragala, M.A. Ratner, T.J. Marks, J. Am. Chem. Soc. 115 (1993) 682–686.
[14] R.A.J. Smith, G.F. Kelso, A.M. James, M.P. Murphy, Methods Enzymol. 382 (2004) 45–67.
[15] G. Burnstock, Curr. Top. Med. Chem. 4 (2004) 793–803.
[16] d.W. Krogmann, E. Olivero, W. duane, J. Biol. Chem. 237 (1962) 3292–3295.
[17] V.V. Klimov, E. Dolan, E.R. Shaw, B. Ke, Proc. Natl. Acad. Sci. U.S.A. 77 (1980) 7227–7231.
[18] W. Ma, H. Zhou, Y.L. Ying, D.W. Li, G.R. Chen, Y.T. Long, H.Y. Chen, Tetrahedron 67 (2011) 5990–6000.
[19] A. Mostafa, H.S. Bazzi, Spectrochim. Acta A 79 (2011) 1613–1620.
[20] S.Y. AlQaradawi, A. Mostafa, H.S. Bazzi, J. Mol. Struct. 1011 (2012) 172–180.
[21] M. Pandeeswaran, K.P. Elango, Spectrochim. Acta A 75 (2010) 1462–1469.
[22] M.S. Refat, S.A. El-Korashy, I.M. El-Deen, S.M. El-Sayed, J. Mol. Struct. 980 (2010) 124–136.
[23] S.H. Sicherer, Understanding and Managing Your Child's Food Allergy, The Johns Hopkins University Press, Baltimore, 2006.
[24] J. Fischer, C. Robin Ganellin (Eds.), Analogue-based Drug Discovery II, Wiley-VCH, Weinheim, 2010.
[25] J. Shorter, Correlation Analysis of Organic Reactivity, Research Studies Press, New York, 1982.
[26] R. Huot, P. Brassard, *Can. J. Chem.* 52 (1974) 838–842.
[27] M. Pandeeswaran, E.H. El-Mossalamy, K.P. Elango, Int. J. Chem. Kinet. 41 (2009) 789–799.
[28] K. Ganesh, C. Balraj, K.P. Elango, Spectrochim. Acta A 79 (2011) 1621–1629.
[29] C. Balraj, K. Ganesh, K.P. Elango, J. Mol. Struct. 998 (2011) 110–118.
[30] C.A.T. Laia, S.M.B. Costa, D. Phillips, A.W. Parker, Photochem. Photobiol. Sci. 2 (2003) 555–562.
[31] M. Gaber, S.S. Al-Shihry, Spectrochim. Acta A 62 (2005) 526–531.
[32] M. Pandeeswaran, K.P. Elango, Spectrochim. Acta A 72 (2009) 789–795.
[33] M.S. Refat, J. Mol. Struct. 985 (2011) 380–390.
[34] R.L. Scott, *Recl. Trav. Chim. Pays-Bas Belg.* 75 (1956) 787–789.
[35] C. Balraj, K. Ganesh, K.P. Elango, Spectrochim. Acta A 79 (2011) 1137–1144.
[36] G. Weber, L.B. Young, J. Biol. Chem. 239 (1964) 1415–1423.
[37] K. Ganesh, C. Balraj, A. Satheshkumar, K.P. Elango, Spectrochim. Acta A 92 (2012) 46–55.
[38] B.P. Kamat, J. Seetharamappa, J. Photosci. 11 (2004) 29–33.
[39] J.S. Park, J.N. Wilson, K.I. Hardcastle, U.H.F. Burnz, M. Srinivasarao, *J. Am. Chem. Soc.* 128 (2006) 7714–7715.
[40] Q. Zhou, T.M. Swager, J. Am. Chem. Soc. 117 (1995) 12593–12602.
[41] M.J. Frisch, G.W. Trucks, H.B. Schlegel, G.E. Scuseria, M.A. Robb, J.R. Cheeseman, J.A.J. Montgomery, T. Vreven, K.N. Kudin, J.C. Burant, J.M. Millam, S.S. Iyengar, J. Tomasi, V. Barone, B. Mennucci, M. Cossi, G. Scalmani, N. Rega, G.A. Petersson, H. Nakatsuji, M. Hada, M. Ehara, K. Toyota, R. Fukuda, J. Hasegawa, M. Ishida, T. Nakajima, Y. Honda, O. Kitao, H. Nakai, M. Klene, X. Li, J. E. Knox, H.P. Hratchian, J.B. Cross, C. Adamo, J. Jaramillo, R. Gomperts, R.E. Stratmann, O. Yazyev, A.J. Austin, R. Cammi, C. Pomelli, J.W. Ochterski, P.Y. Ayala, K. Morokuma, G.A. Voth, P. Salvador, J.J. Dannenberg, V.G. Zakrzewski, S. Dapprich, A.D. Daniels, M.C. Strain, O. Farkas, D.K. Malick, A.D. Rabuck, K. Raghavachari, J.B. Foresman, J.V. Ortiz, Q. Cui, A.G. Baboul, S. Clifford, J. Cioslowski, B.B. Stefanov, G. Liu, A. Liashenko, P. Piskorz, I. Komaromi, R.L. Martin, D.J. Fox, T. Keith, M.A. Al-Laham, C.Y. Peng, A. Nanayakkara, M. Challacombe, P.M. W. Gill, B. Johnson, W. Chen, M.W. Wong, C. Gonzalez, J.A. Pople, Gaussian 03W Revision D.01, Gaussian, Inc., Wallingford CT, 2004.
[42] V.A. Nikitina, R.R. Nazmutdinov, G.A. Tsirlina, J. Phys. Chem. B 115 (2011) 668–677.
[43] M.S. Liao, Y. Lu, V.D. Parker, S. Scheiner, J. Phys. Chem. A 10 (2003) 8939–8948.
[44] D. Sun, S.V. Rosokha, J.K. Kochi, J. Phys. Chem. B 111 (2007) 6655–6666.