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Successful Application of TD-DFT in Transient Absorption Spectra Assignment

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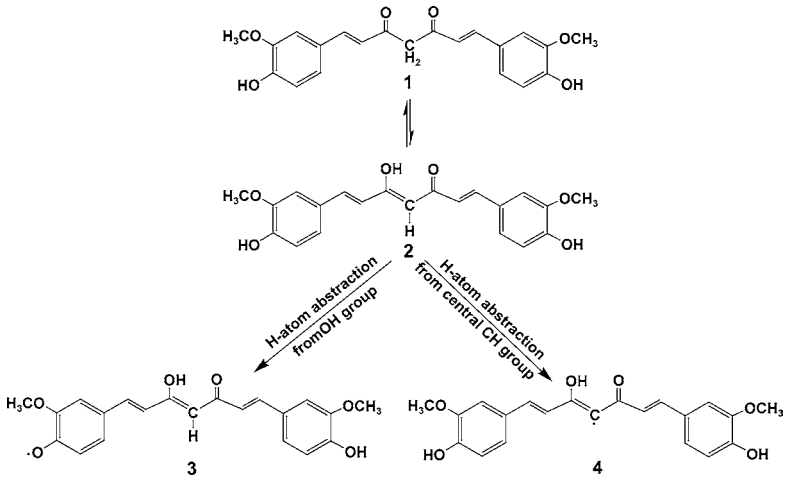
ABSTRACT



Despite the wide application of time-resolved spectra technology in investigating various chemical and biological processes, it is still a great challenge to give an unambiguous spectra assignment for observed transient species, e.g., the curcumin-derived radicals. Here we report that time-dependent density functional theory with the B3LYP functional and an appropriate basis set can give reliable absorption spectra for carbon- and oxygen-centered radicals derived from curcumin, which indicates the potential of theoretical methods in helping assign transient spectra.

Time-resolved spectra technology is an invaluable tool for investigating chemical and biological reaction mechanisms,[1,2] in which the assignment of transient absorption spectra is a key event. However, the transient spectra assignment usually depends on subjective speculations, and thus different observers may give distinct, even contradictory, conclusions. For example, there has been much debate on the transient absorption spectra assignments of curcumin radicals.[3,4] Considering the successful use of time-dependent density functional theory (TD-DFT) in calculating the electronic excitation spectra of closed-shell and open-shell molecules,[5−10]

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we attempted to explore the possibility of assigning the absorption spectra of transient species, e.g., curcumin radicals, by means of TD-DFT calculation.

Curcumin [1,7-bis(4-hydroxy-3-methoxyphenyl)-1,6-heptadiene-3,5-dione] is a yellow-orange dye derived from the rhizome of *Curcuma longa* (Figure 1, **1** and **2**), which has

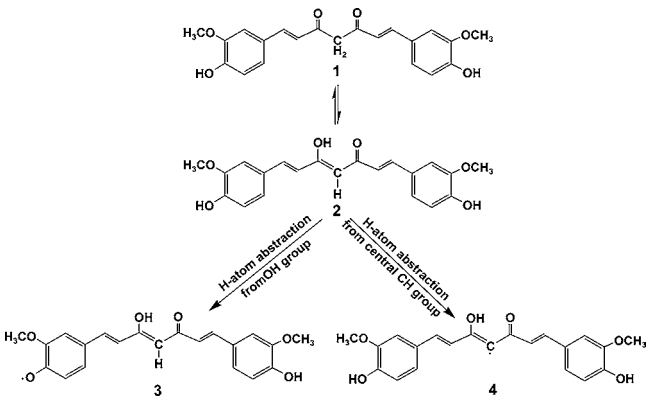

Figure 1. Structures of curcumin-related compounds.

attracted considerable attention due to its various biological activities, including antioxidant activity and anticancer activity, etc.[11−13] Therefore, much effort has been devoted to investigating the radical-scavenging mechanisms of curcumin.[3,4,14−16] On the basis of distinct assignments of the same transient absorption spectrum, contradictory opinions have been proposed to explain the radical-attacking sites in curcumin. Khopde et al. took the transient absorption at 490 nm as evidence of phenoxy radicals, and therefore attributed the H-atom-donating site to the phenolic OH group (Figure 1, **3**).[3] This is supported not just by a further experimental finding that synthesized nonphenolic curcuminoids have no antioxidant activity[14] but also by theoretical calculations that H-atom abstraction from OH group is much easier than that from CH group.[15,17] In contrast, Jovanovic and co-workers proposed an alternative radical-scavenging mechanism of curcumin by attributing the transient peak at 490 nm to a carbon-centered radical, which suggests that the H-atom abstraction occurs from the central CH group (Figure 1, **4**).[4] In addition, a weak absorption band at ∼750 nm was assigned to the phenoxy radical by Jovanovic et al.[4] Therefore, it is still a challenge to reach a consensus on the radical-scavenging mechanisms of curcumin.

In this paper, TD-DFT was employed to calculate the spectra of curcumin and derived radicals. The calculation procedures are as follows. Initial structures for the curcumin-related compounds were fully optimized by the hybrid B3LYP functional. Using these structures as starting points, we calculated the absorption wavelengths and oscillator strengths by TD-DFT formalism with various basis sets.[18] For the parent molecules, 6-31G(d) and 6-31G(d,p) basis sets were employed. For the carbon-centered radical of curcumin, five different Gaussian basis sets, 6-31G, 6-31+G, 6-31G-(d), 6-31+G(d), and 6-31G(d,p), were used to explore the basis-set dependence of the calculation. The solvent (acetonitrile) effect was also taken into consideration by employing the self-consistent reaction field (SCRF) method with polarized continuum model (PCM).[19−21] All calculations were performed with the Gaussian 03 package of programs.[22]

As shown in Figure 1, curcumin is unique for possessing two isomers, the β-diketone form (**1**) and the enol form (**2**). The absorption wavelengths and oscillator strengths for the five lowest singlet excitations of both isomers were calculated and are listed in Table 1. Of particular interest is that the calculated absorption maximum (419 nm) of the enol form is very close to the experimental value for curcumin (417 nm in benzene and 419 nm in chloroform),[23,24] which provides solid evidence to support the previous conclusion that curcumin exists in the enol form in solution.[14] At the same time, the good agreement between the theoretical and experimental data for the absorption spectra justifies the present calculation method. In addition, as shown in Table 1, the absorption maximum of the enol form (419 nm) gets red shifted in comparison with that of the β-diketone form (373 nm). According to the calculated results, the structure of the enol form is planar and allows resonance within the two feruloyl chomophores. As a consequence, it exhibits an intense absorption peak in the visible region. On the contrary, the structure of the β-diketone form is twisted. Hence, the

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Table 1. Absorption Wavelengths and Oscillator Strengths of Curcumin-Related Compounds Calculated with Various Basis Sets

1[a]	^1E (eV)	3.21	3.30	3.42	3.51	3.77
6-31G(d)	λ (nm)	387	375	362	353	329
	f	0.17	0.06	0.15	0.04	0.54
1[a]	^1E (eV)	3.19	3.33	3.37	3.50	3.79
6-31G(d,p)	λ (nm)	389	373	368	354	327
	f	0.15	0.24	0.04	0.00	0.50
2[a]	^1E (eV)	2.96	3.33	3.44	3.86	4.04
6-31G(d)	λ (nm)	419	372	361	321	307
	f	1.52	0.03	0.00	0.14	0.03
2[a]	^1E (eV)	2.96	3.33	3.46	3.85	4.04
6-31G(d,p)	λ (nm)	419 (417 or 419)[c]	372	358	322	307
	f	1.53	0.03	0.00	0.13	0.03
3[b]	^1E (eV)	1.57	1.60	1.87	2.14	2.24
6-31G(d)	λ (nm)	790	776	662	580	554
	f	0.00	0.13	0.01	0.05	0.06
3[b]	^1E (eV)	1.45	1.65	1.92	2.21	2.25
6-31+G(d)	λ (nm)	853	751 (750)[d]	646	562	550
	f	0.00	0.12	0.00	0.11	0.08
4[b]	^1E (eV)	1.53	1.77	2.11	2.55	2.59
6-31G	λ (nm)	812	701	588	487	479
	f	0.00	0.02	0.00	0.00	1.48
4[b]	^1E (eV)	1.43	1.73	2.09	2.39	2.52
6-31+G	λ (nm)	867	718	594	520	493
	f	0.00	0.02	0.00	0.00	1.57
4[b]	^1E (eV)	1.50	1.81	2.16	2.58	2.64
6-31G(d)	λ (nm)	826	685	575	481	470
	f	0.00	0.01	0.00	0.00	1.45
4[b]	^1E (eV)	1.43	1.76	2.12	2.43	2.55
6-31+G(d)	λ (nm)	869	703	584	511	488 (490)[d]
	f	0.00	0.01	0.00	0.00	1.53
4[b]	^1E (eV)	1.50	1.81	2.16	2.58	2.64
6-31G(d,p)	λ (nm)	828	685	575	481	471
	f	0.00	0.01	0.00	0.00	1.45
4[a]	^1E (eV)	1.54	1.81	2.17	2.70	2.74
6-31G	λ (nm)	807	684	572	460	452
	f	0.00	0.01	0.00	0.00	0.49
4[a]	^1E (eV)	1.44	1.79	2.14	2.51	2.71
6-31+G	λ (nm)	863	693	579	4.94	457
	f	0.00	0.01	0.00	0.00	0.90
4[a]	^1E (eV)	1.52	1.85	2.22	2.77	2.79
6-31G(d)	λ (nm)	814	669	558	448	444
	f	0.00	0.01	0.00	0.00	0.47
4[a]	^1E (eV)	1.44	1.83	2.19	2.59	2.76
6-31+G(d)	λ (nm)	859	678	565	479	450
	f	0.00	0.01	0.00	0.00	0.89
4[a]	^1E (eV)	1.52	1.86	2.23	2.77	2.79
6-31G(d,p)	λ (nm)	817	668	557	448	445
	f	0.00	0.01	0.00	0.00	0.46

[a] Calculated in the gas phase. [b]Calculated in acetonitrile. [c]Data in parentheses show the experimental absorption peak for the curcumin in benzene[23] or chloroform.[24] [d]Data in parentheses show the experimental absorption peak for the curcumin-derived radicals in acetonitrile[3,4]

absorption maximum shifts to the near-ultraviolet region and it is anticipated that the molecule will lose its color in the keto form.

The calculated results for the radicals formed by H-atom abstraction from the central CH and the phenolic OH group have been given in Table 1. According to the in-solvent data obtained with the 6-31+G(d) basis set, the carbon-centered radical exhibits a strong absorption peak (with a rather high oscillator strength of 1.54) at about 488 nm in acetonitrile solution, which is almost the same as the experimental absorption peak for the curcumin-derived radical (490 nm) observed by both groups.[3,4] The consistency between theoretical and experimental values provides direct evidence to support Jovanovic et al.'s assignment of the 490 nm peak to the carbon-centered radical.[4] Moreover, the theoretical absorption wavelengths at different basis sets (Table 1) indicate that the addition of diffuse functions brings significant improvement for the calculation of radical spectra, while the polarization functions have little influence, which is in contrast with the calculation on parent curcumin that even the 6-31G(d) basis set displays satisfactory performance. Furthermore, the solvent effect is also crucial to the theoretical treatment for radicals, because the neglect of the solvent effect leads to an error of 26−38 nm compared with the experimental data (Table 1).

In addition to the carbon-centered radical, we also calculated the absorption spectrum of oxygen-centered radical of curcumin by the TD-DFT method on B3LYP/6-31+G(d) and B3LYP/6-31G(d) basis sets. It can be seen from Table 1 that the oxygen-centered radical exhibits an absorption band at 751 nm, which also agrees well with Jovanovic et al.'s assignment that the absorption peak of 750 nm is due to the phenoxy radical of curcumin. Moreover, as shown in Table 1, the large difference between oscillator strengths of a carbon-centered radical (1.54) and a phenoxy radical (0.12) provides clues for quantitatively estimating the concentration of both radicals.

Thus, it is clear that the H-atom abstraction from the central CH group indeed occurs in acetonitrile solution. But why is the central CH group of synthesized nonphenolic curcuminoids inert as a radical scavenger in styrene/chlorobenzene solution?[14] We think the solvent effect and the initial radicals must be considered to reconcile the contradiction. In hydrogen-accepting solvents, e.g., acetonitrile, an intermolecular hydrogen bond (IHB) can form between the phenolic hydroxyl and the solvent molecule (Figure 2), and the steric effect will hamper the H-atom-donating process from the phenolic group.[25] Accordingly, the H-atom abstraction from the central CH group will be

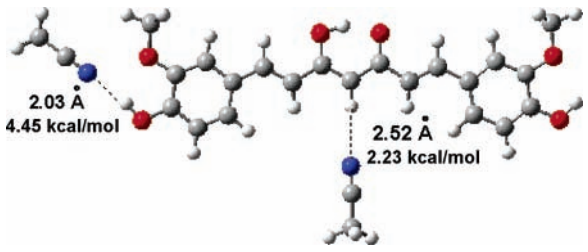

Figure 2. B3LYP/6-31G(d)-calculated intermolecular hydrogen bond lengths and energies between curcumin and an acetonitrile molecule.

preferred in hydrogen-accepting solvents.[26] However, as there is no IHB between curcumin and nonpolar solvent molecules, the H-atom abstraction from the phenolic OH group is still predominant. On the other hand, the radical employed in Barclay et al.'s experiment,[14] $ROO^{\bullet}$, cannot abstract an H-atom from the CH group but can only abstract an H-atom from the phenolic OH, because the O−H bond dissociation enthalpy (BDE) of ROOH (∼88 kcal/mol)[27] is higher than that of phenolic OH of curcumin (∼80 kcal/mol)[15,17] but much lower than the C−H BDE of central CH group (∼116 kcal/mol).[15] As a consequence, it is understandable why synthesized nonphenolic curcuminoids had no antioxidant activity in styrene/chlorobenzene solvents.[14]

In conclusion, TD-DFT with the B3LYP functional and an appropriate basis set can give reliable absorption spectra of transient species, including carbon- and oxygen-centered radicals. Considering the previous successful TD-DFT studies on carbon-centered radicals[28] and nitrogen-centered radicals,[29] we believe that the combination of time-resolved-spectra technology and TD-DFT calculation will provide a very potent methodology for investigating transient chemical and biological processes.

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Supporting Information Available: Selected molecular geometries calculated at different basis sets. This material is available free of charge via the Internet at http://pubs.acs.org.

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