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Ultrafast quenching of the excited S_2 state of benzopyranthione by acetonitrile

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Abstract

Femtosecond and nanosecond transient absorption and picosecond time-correlated single photon counting techniques have been used to study the mechanism and dynamics of the efficient quenching of an aromatic thioketone, 4H-1-benzopyrane-4-thione (BPT) in the S_2 state, by acetonitrile. The results suggest the involvement of two aborted processes in the quenching mechanism: exciplex formation and hydrogen abstraction. The occurrence of the latter process is supported by the observation of a clear isotope effect on going from acetonitrile to deuterated acetonitrile.

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1. Introduction

Aromatic thioketones show many interesting and unusual spectral and photophysical properties including direct $S_0 \rightarrow T_1$ absorption, well-resolved $S_0 \rightarrow S_1$, $S_0 \rightarrow S_2$ and $S_0 \rightarrow S_3$ absorption bands, thermally activated S_1 -fluorescence, and efficient fluorescence from the S_2 state and phosphorescence from the T_1 state in solution at room temperature [1–3]. The long S_2 state lifetime of thioketones ($\tau_{S_2} = 10^{-9}$ – 10^{-11} s), due to a large $\Delta E(S_2 - S_1)$ energy gap, is responsible for the S_2 -state fluorescence, whereas emission from the S_1 state (radiative rate constant of about 10^5 s⁻¹) is insignificant due to an ultrafast intersystem crossing process to the T_1 state ($\tau_{S_1} \approx 10^{-12}$ s) [4]. The S_2 state is known to be extremely reactive in solution because of efficient intermolecular quenching by most solvents including acetonitrile, but except perfluorohydrocarbons (PF) in which the S_2 state decay is exclusively intramolecular [1,3,5–8]. Recently, we have reported an analysis of the quenching mechanism of the S_2 state of 4H-1-benzopyrane-4-thi-

one (BPT) by hydrocarbons using femtosecond transient absorption spectroscopy [9]. We have demonstrated the involvement of the hydrocarbon C–H bonds in the quenching process. Two possible quenching mechanisms have been proposed: efficient H-atom abstraction followed by ultrafast back hydrogen transfer, or ‘aborted hydrogen abstraction’. In the latter case, the progress along the reaction path was assumed to deactivate the S_2 state to the S_1 state through a conical intersection between the S_2 and S_1 energy surfaces.

The quenching of the S_2 state of thioketones by acetonitrile has been investigated only for xanthione (XT) from picosecond emission (time-correlated single photon counting) and femtosecond transient absorption measurements [5,7]. The formation of a S_2 state solute–solvent exciplex has been suggested as the intermolecular interaction responsible for the XT S_2 state quenching process. A very weak transient absorption signal, observed after subtraction of the S_2 and T_1 absorption bands, has been tentatively attributed to this exciplex [7]. The purpose of the present work is to extend this study to the case of BPT and determine whether the formation of such an exciplex can be confirmed or not. Moreover, the isotope effect induced by deuteration of

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the acetonitrile solvent on the quenching rate constant, not investigated for XT, will be examined carefully for BPT. In order to provide kinetic information on the BPT S_2 state, we used the picosecond time-correlated single photon counting fluorescence technique. Femtosecond transient absorption spectroscopy allowed us to characterise also the non-emissive short lived species. These ultrafast experiments were complemented with nanosecond transient absorption and phosphorescence data as well as steady-state absorption and fluorescence measurements.

2. Experimental

We have used identical experimental conditions and the same femtosecond transient absorption apparatus as described previously [9]. The picosecond time-correlated single-photon counting system and data fitting procedures have also been characterised elsewhere [10]. In both techniques the pump wavelength was set at 403 nm, which corresponds to the low energy edge of the BPT $S_0 \rightarrow S_2$ absorption band. The S_2 state was thus populated with no significant vibrational excitation. The molecular rotational diffusion effects were eliminated, since experiments were performed at the magic angle configuration.

In the UV–visible nanosecond transient absorption experiments, 8 ns (FWHM), 355 nm pulses generated at a repetition rate of 0.5 Hz by a Q-switched Nd:YAG laser (*Continuum Surelite II*) were used as pump excitation. The probing light source was a 150 W xenon arc lamp (*Applied Photophysics*), used in the pulsed mode with a 1 Hz repetition rate. The transmitted light was dispersed by a monochromator (6 nm spectral resolution) and detected by a photomultiplier (*R928 Hamamatsu*) coupled to a digital oscilloscope (*Tektronix TDS 680 C*). The dialog between the PC and the oscilloscope, AOD calculations, data fitting and time-control of TTL signals to trigger the laser, the lamp pulser and the shutters, via an input output card (*PCI-MIO-16XE-10*), were ensured by a home-made program written in *LabView 4.1* environment. Phosphorescence measurements were realised by using the same experimental setup in which the lamp was switched off. Nanosecond transient absorption and emission experiments were performed on 4 ml solution samples contained in a quartz cell (1 cm \times 1 cm section). All solutions were deaerated for about 15 min prior to each experiment with a helium gas flow passing through a hot copper column to remove traces of O_2 . A sample absorbance of about 1 at the laser excitation wavelength (355 nm) was generally used, which corresponds to a BPT concentration of approximately 1×10^{-4} M.

All measurements were performed at room temperature (20 °C). BPT was synthesised and purified

according to procedures described elsewhere [11,12]. Acetonitrile and deuterated acetonitrile (spectroscopic grade) were purchased from Aldrich and used as received.

3. Results

3.1. Steady-state measurements

Previous steady-state spectroscopic measurements on BPT have shown the absorption and S_2 -state fluorescence in various PF and in *n*-hexane [8,9]. Similar spectral properties are found in the present work in acetonitrile. The $S_0 \rightarrow S_2$ transition leads to a strong absorption band maximising at 371 nm ($\epsilon = 17,900$ M $^{-1}$ cm $^{-1}$). For concentrations of BPT up to 10^{-3} M, no perceptible changes in the absorption and emission spectra are noted, indicating the absence of any aggregation of BPT molecules. Thus, time-resolved measurements performed using concentrations between 10^{-5} – 10^{-3} M are not affected by dimer formation. Since the energy difference between the vibrationally relaxed S_3 and S_2 states is about 7000 cm $^{-1}$, the choice of pump wavelengths at 355 or 403 nm ensures a selective excitation of BPT within the $S_0 \rightarrow S_2$ transition.

3.2. Time-resolved fluorescence measurements

Fig. 1 presents the kinetics of fluorescence of the S_2 state of BPT measured at 470 nm in acetonitrile and in acetonitrile- d_3 by using the picosecond time-correlated single counting method. Similar results were obtained, within the experimental error, at all emission wavelengths in the 450–530 nm range. The lifetime of the S_2 state in the hydrogenated and deuterated solvent was 14.9 ± 1 and 24.1 ± 1.3 ps, respectively. An isotope effect of about 1.6 was thus observed.

3.3. Nanosecond transient absorption and phosphorescence measurements

It is known that the lowest triplet T_1 state of thio-ketones is efficiently formed after excitation to the S_n state ($n \geq 2$), irrespective of the solvent used [1,11,13]. Thus before going into the details of the femtosecond transient absorption results of BPT, it is worth presenting the absorption and emission data obtained on the nanosecond/microsecond time scale. The transient absorption spectra and the corresponding kinetics recorded at 460 nm as well as the $T_1 \rightarrow S_0$ phosphorescence kinetics obtained at 630 nm are presented in Fig. 2a–c respectively. The absorption spectrum reveals two absorption bands at 290 and 470 nm and a negative signal at 370 nm, which all disappear with a single exponential decay kinetics having a characteristic time of

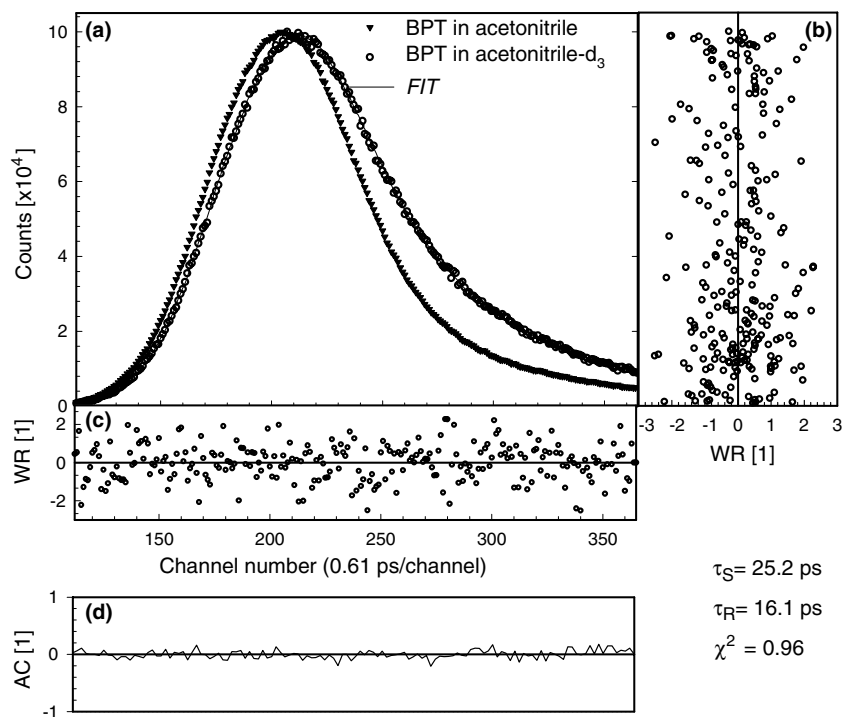


Fig. 1. (a) Experimental decay of fluorescence of BPT (3×10^{-4} M) in acetonitrile (\blacktriangledown) and acetonitrile- d_3 (\circ) monitored at 470 after 403 nm excitation (magic angle configuration), and best fit according to the data treatment procedure described in [10]. (b) and (c) Plots of the weighted residuals against intensity and time, respectively. (d) Autocorrelation function of the weighted residuals.

810 ± 40 ns. Isosbestic points are noted at 330 and 410 nm. The same time (803 ± 20 ns) is obtained for the phosphorescence decay kinetics. We can thus attribute the transient absorption bands in Fig. 2a to the triplet state spectrum. The negative band corresponds to the ground state depletion (GSD) signal induced by the pump pulse, because its shape is similar to that of the ground state absorption spectrum of BPT in acetonitrile. The GSD dynamics are related to the recovery of BPT in the ground state due to the $T_1 \rightarrow S_0$ transition. Note that the shape of the transient absorption spectrum of the BPT T_1 state is less structured in acetonitrile than in the hydrocarbon solvents [9]. This modification of the band shape is possibly due to a change in the electronic configuration of the lowest triplet state on going from polar solvents (π, π^*) to non-polar solvents (n, π^*) [14]. Weak maxima at 580, 630, and 680 nm are still observed (see Fig. 3b). An approximate value of the T_1 state extinction coefficient ϵ (470 nm) = 1600 ± 300 $M^{-1} cm^{-1}$ can be estimated from the ratio of the positive OD at 470 nm to the negative OD at 370 nm ($\epsilon_{S_0 \rightarrow S_2}$ at 370 nm = $17,900 M^{-1} cm^{-1}$). There is no indication of the formation of additional species such as exciplexes or radicals on this time-scale.

3.4. Femtosecond transient absorption measurements

Femtosecond transient absorption spectra recorded in the 430–740 nm spectral range within a time window

of 1 ps to 1.5 ns following 403 nm excitation of BPT in acetonitrile and acetonitrile- d_3 are shown in Fig. 3a. These spectra are similar to those previously obtained in hydrocarbon solvents [9] and can be directly assigned by analogy. The presence of only two species is observed, the singlet S_2 state (short time $S_2 \rightarrow S_n$ absorption at 620 nm and $S_2 \rightarrow S_0$ stimulated emission at 470 nm) and the triplet T_1 state (final absorption at 470 nm). The attribution of the latter is confirmed without ambiguity by comparison with the nanosecond $T_1(\pi, \pi^*) \rightarrow T_n$ transient absorption spectrum (see Fig. 3b).

It is worthwhile noting that in Fig. 3a the ratio $I_{\max}(S_2)/I_{\max}(T_1)$ of the S_2 absorption band intensity at 1 ps and T_1 state absorption band intensity at 100 ps is equal to 2. It is comparable to that found when using hydrocarbon solvents [9]. Assuming that almost all the BPT molecules in the S_2 state deactivate to the T_1 state, the extinction coefficients of the S_2 absorption band at 620 nm and T_1 absorption band at 470 nm follow the relation $\epsilon_{S_2}^{\max} \sim 2\epsilon_{T_1}^{\max}$. An approximate value of $\epsilon_{S_2}^{\max} = 3200 \pm 600 M^{-1} cm^{-1}$ is deduced. This value is close to that obtained in hydrocarbon solvents ($3600 M^{-1} cm^{-1}$), in agreement with the assumption of an almost 100% deactivation of the S_2 state to the T_1 state. Finally, the fact that the isosbestic point at 560 nm between the S_2 state absorption and stimulated emission bands (see Fig. 3a) is not perturbed by the superimposed T_1 absorption band suggests that the S_2 decay and T_1 appearance have comparable kinetics. As a matter of

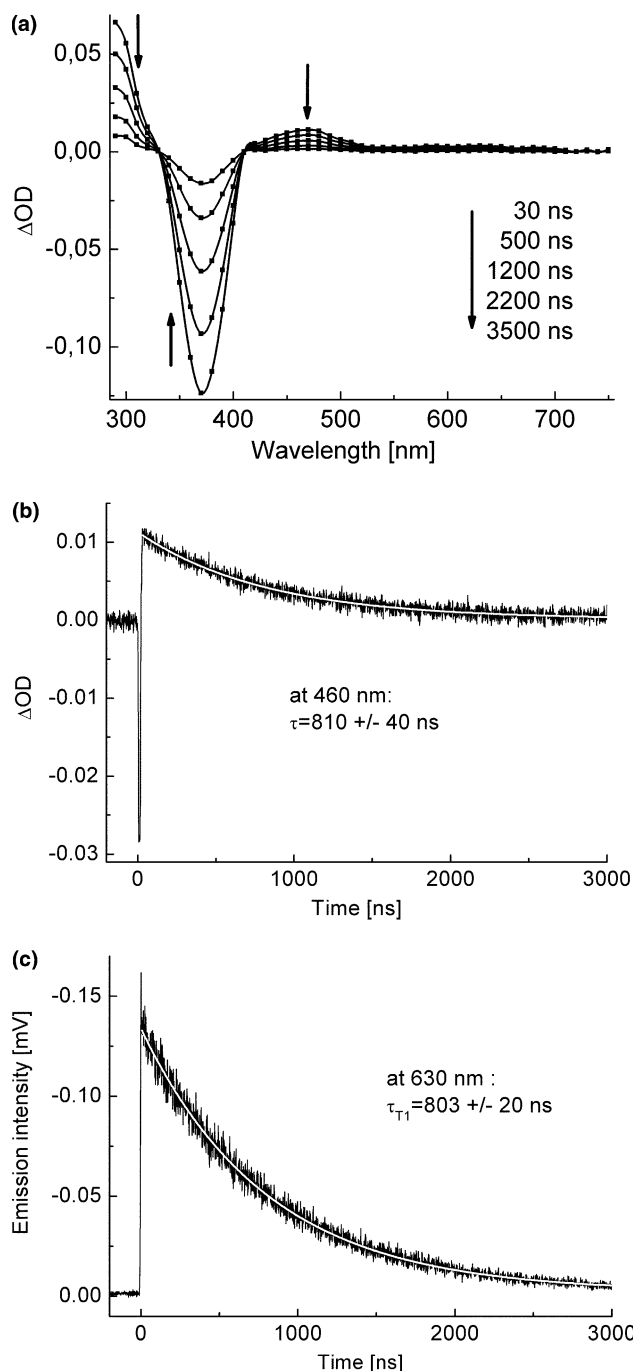


Fig. 2. Time-resolved absorption and phosphorescence measurements of BPT (5.7×10^{-5} M) in acetonitrile after excitation at 355 nm (pulse energy 0.8 mJ). (a) Transient absorption spectra within the 30–3500 ns time window (the phosphorescence emission contribution is subtracted). (b) Transient absorption decay recorded at 460 nm. (c) Phosphorescence emission decay recorded at 630 nm. The solid white lines are the best single exponential fits to the experimental data.

fact, the kinetics monitored every 10 nm in the whole 430–740 nm spectral range (some examples are shown in Fig. 3c) could be fitted to a single exponential function using the non-linear least square Levenberg–Marquardt algorithm with a single time-constant of 15.6 ± 1.0 ps.

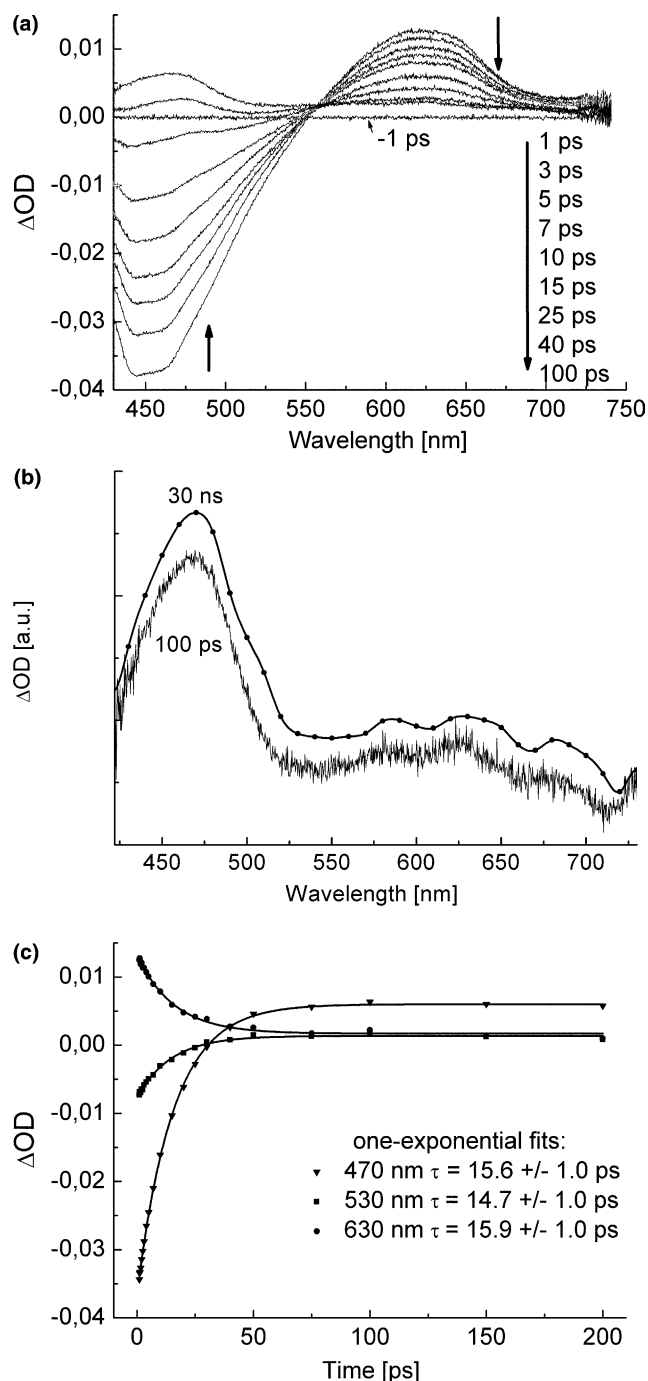


Fig. 3. (a) Transient absorption spectra recorded from 1 to 100 ps after photoexcitation of BPT (1×10^{-4} M) in acetonitrile at 403 nm. The -1 ps spectrum (the probe pulse is set 1 ps before the pump pulse) gives the background signal. (b) Comparison of the transient absorption spectra obtained for pump–probe delays of 100 ps (from data in a) and 30 ns (from data in Fig. 2a) after normalisation. (c) Time-dependence of the signal at 470 nm (∇), 530 nm (\blacksquare) and 630 nm (\bullet) in the 1–200 ps time range. The solid lines are the best single exponential fits to the experimental data.

This time is consistent with the 14.9 ps value found above for the S_2 state fluorescence decay. Similarly, a 25.8 ± 1.5 ps value is found in acetonitrile- d_3 , which can

be compared to the 24.1 ps one determined by time-resolved fluorescence. The transient absorption measurements provide not only a confirmation of the S_2 state lifetime τ_{S_2} , but also show that, similarly to what was observed for BPT in hydrocarbons [9], the rise of the triplet T_1 band parallels the decay of the singlet S_2 band. Therefore, if there exists any additional transient species intermediate between the S_2 and T_1 states, whichever their nature (S_1 state, exciplex, ...), they must have much shorter lifetime than the S_2 state and are not observed.

4. Discussion

In the absence of intermolecular quenching, in perfluorohydrocarbon solvents, the intramolecular radiationless deactivation path of S_2 BPT, $S_2 \rightarrow S_1 \rightarrow T_1$, has been well established [1,3,8]. The $S_1 \rightarrow T_1$ intersystem crossing step being much faster than the $S_2 \rightarrow S_1$ internal conversion, time-resolved spectroscopic data are characteristic of an apparently direct $S_2 \rightarrow T_1$ process and the S_1 state is not observed [9]. The shortening of the BPT S_2 state lifetime τ_{S_2} by about an order of magnitude on going from perfluorohydrocarbons (about 180 ps in perfluoro-*n*-hexane [8]) to acetonitrile demonstrates the existence of an efficient quenching process by acetonitrile. As previously observed in hydrocarbon solvents [9], the quenching process in acetonitrile leads, as in the absence of quenching, to an apparently direct formation of the T_1 state. Moreover, the yield of formation of T_1 , as estimated from the intensity ratio of the final T_1 absorption at 470 nm to the initial S_2 absorption at 620 nm, is comparable in acetonitrile and in perfluorohydrocarbons. These observations indicate that, as in the case of hydrocarbon solvents [9], the quenching reaction in acetonitrile provides an additional, intermolecular, route of radiationless deactivation of S_2 to S_1 . The generally low net photochemical consumption of thioketones ($\Phi_D < 10^{-3}$ [15]) supports this statement.

Quenching by acetonitrile is surprising because this solvent is usually considered as chemically inert towards excited molecules. At first we considered that the quenching process could be attributed to a singlet-singlet energy transfer from BPT in the S_2 state to acetonitrile. However, such a process would be highly endothermic and thus can be ruled out. Neither can the quenching of the S_2 state of thioketones be explained by a vibronic coupling between the S_2 and S_1 states involving high-energy solvent vibrational modes as attested by the results reported by Topp and co-workers [5]. Another mechanism based on a π -type interaction has been reported to explain the S_2 state quenching of aromatic thioketones by unsaturated solvent molecules such as acetonitrile or benzene [3,5]. For acetonitrile,

this interaction would involve the π -electrons density of the cyano group, leading to the formation of a S_2 state exciplex. This proposition has been recently supported by the observation of a xanthione (XT)-acetonitrile exciplex by femtosecond transient absorption [7]. Such an electronically induced quenching process is thus likely to contribute to the fast decay of S_2 BPT in acetonitrile.

However, for XT in benzene, almost no isotope effect on the quenching rate constant has been reported ($\tau_{S_2} = 11$ and 12 ps in benzene- h_6 and benzene- d_6 , respectively [5]), which is consistent with the pure exciplex formation quenching process that has been proposed. In contrast, the hydrogen abstraction induced quenching process occurring in hydrocarbon solvents has been characterised by a notable isotope effect [5,9], explained by the fact that the CH bond dynamics is involved in the reaction mechanism. The fact that quenching by hydrogen abstraction does not occur in benzene is consistent with the poor hydrogen atom donor character of this aromatic solvent (C–H bond energy of 465.3 ± 3.4 kJ/mol [16]). In this regard, the observation of an isotope effect for BPT in acetonitrile indicates that the exciplex formation mechanism alone cannot explain the quenching process. It suggests that, as in the case of hydrocarbon solvents, a hydrogen abstraction induced quenching process contributes to the BPT S_2 state quenching by acetonitrile. Although acetonitrile is generally not considered as a good hydrogen atom donor solvent despite a relatively weak C–H bond energy (392.9 ± 8.4 kJ/mol) compared to that of alkanes (≈ 400 –440 kJ/mol) [16], Nau and co-workers proposed an aborted hydrogen atom transfer quenching mechanism from acetonitrile to the S_1 state of azoalkanes to explain the observed 2.6 value of the H/D solvent isotope effect [17,18]. In conclusion, to take into account the two contradictory facts that, on one hand, the S_2 state of most of the thioketones is generally quenched by acetonitrile via an exciplex formation mechanism and that, on the other hand, a notable isotope effect exists in the case of BPT, we tentatively propose that both the exciplex formation and hydrogen abstraction routes are competing in the quenching of the BPT S_2 state by acetonitrile.

The formation of an S_2 state exciplex can be rationalised by the following interactions between the BPT S_2 state and acetonitrile molecules: (1) π – π interaction between the four π electrons from the nitrile group $N \equiv C$ and the two electrons (π^* and π) from the thio group $>C=S$ (and a possible additional involvement of the electrons of the benzo moiety), (2) charge-transfer between BPT in the S_2 state (donor) and acetonitrile (acceptor). Moreover, the exciplex can be stabilised by interactions with surrounding acetonitrile molecules due to dipole-dipole interactions (the dipole moments of acetonitrile and of BPT in the S_2 state are 3.5 D [19] and

~ 1.0 D [20], respectively) and dispersion interactions (attractive interaction between induced dipoles).

As already remarked, the fact that only the BPT S_2 and T_1 states are detected experimentally and that the T_1 -state appearance parallels the S_2 -state decay indicates that all intermediate species between these two states have very short lifetimes. In this regard, we suggest that the hydrogen abstraction reaction in acetonitrile is equivalent to the aborted process previously proposed in hydrocarbon solvents [9]. Similarly, we suppose that the formation of the exciplex between the BPT S_2 state and an acetonitrile molecule is not completed and that the S_2 state deactivation occurs through a conical intersection between the S_1 state and S_2 potential curves situated along reaction coordinate of establishment of the exciplex (see Fig. 4).

The S_2 state lifetime of BPT can be expressed as:

$$\tau_{S_2} = \frac{1}{k_{\text{Exciplex}} + k_H + k_{nr} + k_r}, \quad (1)$$

where k_{Exciplex} and k_H are the exciplex formation and hydrogen abstraction quenching rate constants respectively, and k_{nr} and k_r are the non-radiative and radiative rate constants (intramolecular processes) respectively. The radiative rate constant k_r is about $1.1 \times 10^8 \text{ s}^{-1}$ [1,3]. According to the Energy Gap Law, the k_{nr} value is about $1.5 \times 10^{10} \text{ s}^{-1}$ [8]. Note that a constant energy gap value of $\Delta E(S_2 - S_1) = 7150 \text{ cm}^{-1}$ has been found in acetonitrile and acetonitrile- d_3 by using steady-state measurements. A global quenching rate $k_{\text{Exciplex}} + k_H$ of $5.2 \times 10^{10} \text{ s}^{-1}$ in acetonitrile and $2.6 \times 10^{10} \text{ s}^{-1}$ in acetonitrile- d_3 is obtained by introducing the experimental τ_{S_2} lifetimes (14.9 ps in acetonitrile, 24.1 ps in acetonitrile- d_3), and the $(k_{nr} + k_r)$ value in Eq. (1). As a result,

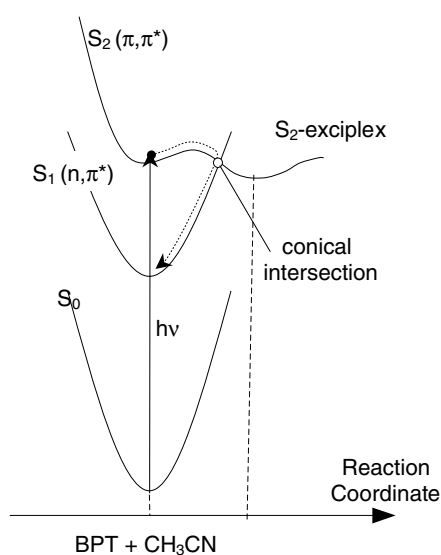
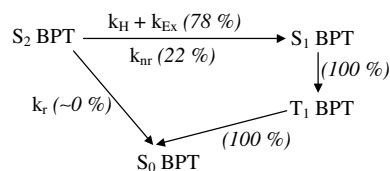


Fig. 4. Schematic potential energy surface diagram corresponding to the S_2 state quenching via the aborted formation of an exciplex with acetonitrile.



Scheme 1.

we deduce that 78% of the BPT S_2 state molecules are quenched by acetonitrile. Scheme 1 summarises the deactivation pathways of the BPT S_2 state in acetonitrile.

The deactivation of the S_2 state to S_1 is followed instantaneously by efficient population of the T_1 state due to the high rate of the intersystem crossing process ($\sim 2 \times 10^{12} \text{ s}^{-1}$) [4]. Then the T_1 state decays to yield back the ground state in about 800 ns (depending on thioetone concentration).

Since, for BPT, the solvent isotope effect has shown that aborted hydrogen abstraction is an important deactivation channel of the S_2 state, we intend to measure this effect for XT to complement and verify the previously reported interpretation [7] according to which the exciplex formation was the only S_2 state quenching process.

5. Conclusions

This paper presents transient absorption results providing information on the mechanism and dynamics of the quenching of an aromatic thioetone, 4H-1-benzopyrane-4-thione (BPT), in the S_2 state by acetonitrile. The results are interpreted with the help of time-correlated fluorescence measurements. As many as 78% of the S_2 state BPT molecules are found to be quenched by the interaction with acetonitrile. Two concomitant mechanisms have been tentatively proposed to account for the observed quenching: an aborted formation of a S_2 state exciplex and an aborted hydrogen-atom abstraction from acetonitrile. According to the fact that these mechanisms are different in nature, we can assume that they proceed via two reaction independent coordinates.

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References

- [1] A. Maciejewski, R.P. Steer, *Chem. Rev.* 93 (1993) 67.
- [2] V. Ramamurthy, R.P. Steer, *Acc. Chem. Res.* 21 (1988) 380.
- [3] A. Maciejewski, D.R. Demmer, D.R. James, A. Safarzadeh-Amari, R.E. Verrall, R.P. Steer, *J. Am. Chem. Soc.* 107 (1985) 2831.
- [4] D. Tittelbach-Helmrich, R.P. Steer, *Chem. Phys. Lett.* 262 (1996) 369.
- [5] C.J. Ho, A.L. Motyka, M.R. Topp, *Chem. Phys. Lett.* 158 (1989) 51.
- [6] A. Maciejewski, *J. Photochem. Photobiol. A* 50 (1990) 87.
- [7] M. Lorenc, A. Maciejewski, M. Ziolk, R. Naskrecki, J. Karolczak, J. Kubicki, B. Ciesielska, *Chem. Phys. Lett.* 346 (2001) 224.
- [8] J. Kubicki, A. Maciejewski, M. Milewski, T. Wrozowa, R.P. Steer, *Phys. Chem. Chem. Phys.* 4 (2002) 173.
- [9] G. Burdzinski, A. Maciejewski, G. Buntinx, O. Poizat, C. Lefumeux, *Chem. Phys. Lett.* 368 (2003) 745.
- [10] J. Karolczak, D. Komar, J. Kubicki, T. Wrozowa, K. Dobek, B. Ciesielska, A. Maciejewski, *Chem. Phys. Lett.* 344 (2001) 154.
- [11] A. Maciejewski, M. Szymanski, R.P. Steer, *J. Phys. Chem.* 92 (1988) 2485.
- [12] M. Milewski, W. Urjasz, A. Maciejewski, W. Augustyniak, *Pol. J. Chem.* 72 (1998) 2405.
- [13] C.V. Kumar, L. Qin, P.K. Das, *J. Chem. Soc. Faraday Trans. 2* (80) (1984) 783.
- [14] A. Maciejewski, M. Szymanski, R.P. Steer, *Chem. Phys. Lett.* 143 (1988) 559.
- [15] U. Brühlmann, J.R. Huber, *Chem. Phys. Lett.* 54 (1978) 606.
- [16] J.A. Kerr Jr, in: D.R. Lide (Ed.), *Handbook of Chemistry and Physics*, CRC Press LLC, Boca Raton, 1998, pp. 9–64.
- [17] W.M. Nau, G. Greiner, H. Rau, J. Wall, M. Olivucci, J.C. Scaiano, *J. Phys. Chem. A* 103 (1999) 1579.
- [18] W.M. Nau, W. Adam, J.C. Scaiano, *Chem. Phys. Lett.* 253 (1996) 92.
- [19] C. Laurence, P. Nicolet, T. Dalati, J.L.M. Abboud, R. Notario, *J. Phys. Chem.* 98 (1994) 5807.
- [20] H.K. Sinha, O.K. Abou-Zied, R.P. Steer, *Chem. Phys. Lett.* 201 (1993) 433.