Photochemical Reaction of Benzene-1,2,4,5-tetracarbonitrile with the Ketals of Cyclic and Bicyclic Ketones

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The radical cations of the ethylene ketals of some cyclic and bicyclic ketones are generated by single electron transfer to excited benzene-1,2,4,5-tetracarbonitrile (TCB). Their fragmentation yields 1,5- and 1,6-distonic radical cations, which add to $TCB^{-\bullet}$ to give [ω-[(2-hydroxyethoxy)carbonyl]alkyl]-benzenetricarbonitriles. The reduction of the radical center occurs only to a small extent, and is enhanced in the presence of dodecylmercaptan, in the case of hindered radicals. The reaction of the camphor ethylene ketal (both alkylation of TCB and reduction) occurs with total diastereoselectivity at the reacting radical center.

Knowledge of organic radical cations and their fragmentation has long been limited to study in the gas phase under low pressure. More recently, however, it has been demonstrated that such species are conveniently obtained in solution by photoinduced single electron transfer (PET), according to eq 1.[1] In this way, pairs of oppositely charged species are generated, and back electron transfer strongly limits the lifetime of the radical cations, which nevertheless display their chemistry, including fragmentation to give a neutral radical and a cation,[2-14] as is observed in the gas phase.

$$A^* + R\text{-}X \rightarrow A^{-\bullet} + R\text{-}X^{+\bullet} \quad (1)$$

$$R\text{-}X^{+\bullet} \rightarrow R^\bullet + X^+ \quad (2)$$

In the photochemical reactions reported to occur by this path, the products usually result either from the alkylation, by the radical, of the acceptor (a ketone,[8,14] an aromatic molecule)[9,11-13] or from the reduction of the radical.[7]

$$A^{-\bullet} + R^\bullet \rightarrow R\text{-}A^- \rightarrow \text{products} \quad (3)$$

$$R^\bullet + e^- \rightarrow R^- \rightarrow RH \quad (4)$$

This suggests that PET may offer a new method for the generation of organic radicals under mild conditions and thus open a new chapter in the rapidly developing field of organic synthesis via radicals.[15] However, the scope of the reported reactions is quite restricted. For example, the radicals generated in this way are limited to a few simple structures. In most cases, these are resonance-stabilized species, i.e. benzyl,[7,11a] allyl,[11b,13,14] and α-amino[4,5] radicals, although recently, some unstabilized alkyl radicals have been similarly generated and reacted.[11c,12b] In order to evaluate the synthetic potential of the method, several questions need to be answered, e.g. can this reaction be extended to more complex radicals; has the cation produced along with the radical any influence on the reaction; is there any possibility of asymmetric induction?

We recently found that irradiation of acetals and ketals in the presence of the strong acceptor 1,2,4,5-benzenetetracarbonitrile (TCB) induces electron transfer followed by carbon–carbon bond fragmentation of the substrate to yield an alkyl radical (which adds to the TCB radical anion) and a dioxy cation (which adds to a nucleophile).[16]

We reasoned that when applied to the ketals of cyclic ketones, this reaction would afford an interesting entry to new distonic radical cations,[17] where charge and spin sites are unambiguously defined and nondelocalized. If the reaction of these species is as expected, this experiment would offer (1) a method for the introduction on the

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(17) Distonic radical cations (formally arising from the ionization of a zwitterion or a diradical) may be key intermediates in the gas-phase reactions of ionized molecules (ref 18). However, such species have a role also under conditions nearer to preparative chemistry. Thus, addition of a photochemically generated aryl olefin radical cation to the neutral substrate generates a 1,4-distonic cation (ref 19). Likewise, fragmentation of cyclic radical cations, such as those of phenylcyclopropane (ref 20) and 2-methoxy-1-phenylcyclopentane but not 2-methoxy-1-phenylcyclohexane (ref 21), has been suggested to yield 1,3- or 1.5-distonic radical cations, respectively. All of these reactions are specific of aromatic derivatives and lead to extensively delocalized radical ions, contrary to the present case.

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Scheme 1

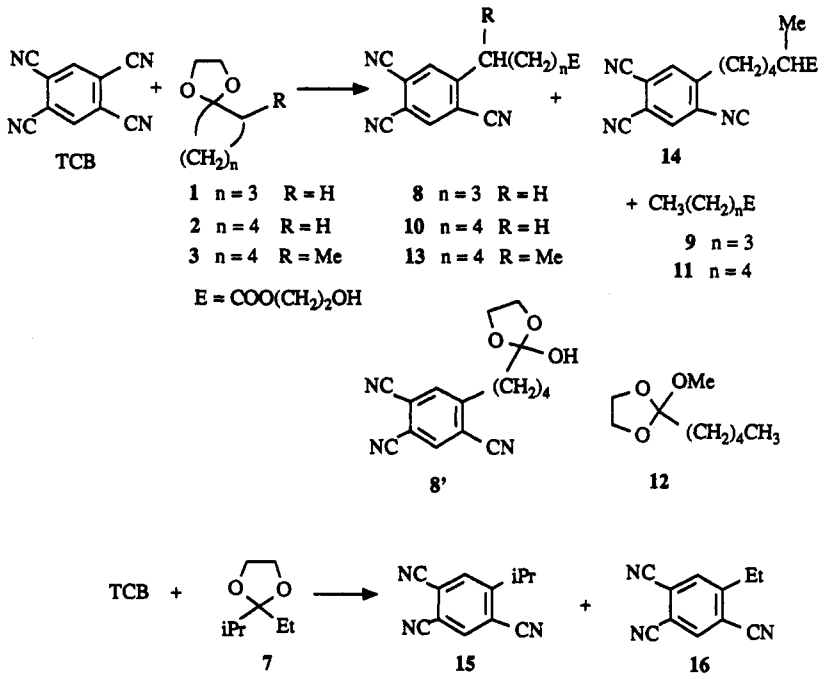


Table 1. Steady State Parameters for the Photochemical Reaction between TCB and Some 2,2-Dialkyl-1,3-dioxolanes in Acetonitrile

dioxolane	K_{sv}, M^{-1}	k_q, M^{-1} sec^{-1}	Φ_{-TCB}[a]
1	97	9×10^9	0.18
2	109	10.1×10^9	0.15
5	98	9×10^9	0.20
6	121	11.2×10^9	0.26
7	70.5	6.5×10^9	

[a] In the presence of 0.05 M dioxolane.

Table 2. Isolated Yield from the Irradiation of TCB in the Presence of 2,2-Dialkyl-1,3-dioxolanes in Acetonitrile

dioxolane	alkylbenzenetricarbonitriles (% yield on reacted TCB)
1	8 (81.6)
2	10 (69)
3	13 (82), 14 (14)
4	17 + 18 (60), 19 (12)
5	21 + 22 (60), 23 (11)
6	24 (82), 25 (10)
7	15 (80), 16 (11)

aromatic ring of a chain bearing the functional group arising from the cation rather than just a simple alkyl chain and (2) a model for judging whether the cation affects the radical reaction. Thus, we presently report the photochemical reactions between TCB and some ketals of cyclic and bicyclic ketones.

Results

We wished to explore the effect of the substrate structure both on the fragmentation of the radical cation and on the chemistry of the alkyl radical generated. Therefore, structures with various substituents at the planned radical and cationic centers (both as a part of a ring or of an open chain) were considered. Preliminary experiments showed that 2,2-dialkyldioxolanes underwent SET-induced dealkylation with a higher efficiency than 1,3-dioxanes and open-chain ketals. As a result, we chose for the present study the ethylene ketals of various cyclic and bicyclic ketones: cyclopentanone (1), cyclohexanone (2), 2-methylcyclohexanone (3), menthone (4), trisnorcamphor (5), and camphor (6). The ethylene ketal of an open-chain ketone (2-methyl-3-pentanone, 7) was also considered for the sake of comparison. All of them quenched the fluorescence of TCB (Table 1).

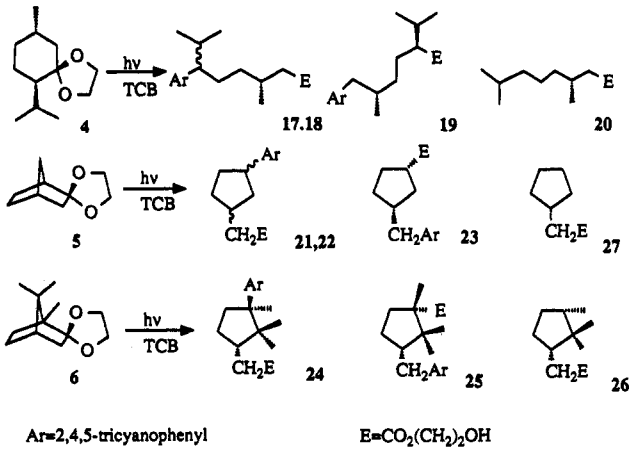
Preparative irradiations in acetonitrile were routinely complemented by experiments in the presence of a mercaptan, in order to test the possibility of reducing the intermediate radical.

Irradiation of 1 and TCB in acetonitrile (containing 0.1% water) followed by chromatographic separation gave 2-hydroxyethyl 5-(2,4,5-tricyanophenyl)pentanoate (8) along with a small amount of 2-hydroxyethyl pentanoate (9) (Table 2, Scheme 1). Spectroscopic examination of the raw photolysate before chromatography showed that orthoacids, e.g. 8', rather than the corresponding 2-hydroxyethyl esters, were present initially and rearranged during workup. This point was not further investigated. From the irradiation of TCB and 2, the corresponding hexanoates 10 and 11 were similarly obtained. No change in the product distribution was observed when the irradiation was carried out in the presence of *n*-dodecylmercaptan. On the other hand, when the reaction was performed in anhydrous MeCN containing 0.1% MeOH, orthoesters rather than orthoacids, or the hydroxyethyl esters arising from them, were obtained (e.g., 12 in the place of 11).

When the ketal (3) of an asymmetric ketone, for instance, that of 2-methylcyclohexanone, was used, the products resulting from both possible modes of C–C bond cleavage were obtained, with the alkylated nitrile resulting from the reaction with the secondary radical (13) predominating over its isomer 14 in a 6 to 1 ratio. The reaction with the acetal (7) of an open-chain ketone was also carried out, and the product 15 resulting from the alkylation by the secondary radical largely predominated over that resulting from the primary radical (16).

The study was extended to an optically active substrate, the ethylene ketal of (−)-menthone (4) (see Scheme 2). In this case, a satisfactory separation fo the alkylation products was not obtained. However, the spectra of the

Scheme 2



fraction containing the aromatic adducts clearly showed that three isomers had been formed, the main ones being the diastereoisomeric (tricyanophenyl)octanoates **17** and **18** (in ca. 1 to 1 ratio) and the minor one being the adduct **19**. Furthermore, a sizable amount of the optically active aliphatic ester **20** was isolated.

The reaction with the ketals of bicyclic ketones was carried out analogously. Irradiation of TCB in the presence of **5** gave three aromatic derivatives. Two of them were contained in the main chromatographic fraction and were the two diastereoisomeric (tricyanophenyl)-cyclopentaneacetates (**21**, **22**) resulting from attack by the secondary radical. The third one was the [(tricyanophenyl)methyl]cyclopentanecarboxylate **23**, resulting from attack by the primary radical.

Finally, the reaction with the ethylene ketal (**6**) of (±)-camphor gave only two aromatic products, which were separated. Although identification was not straightforward in this case due to the similar pattern of the spectra, selective heteronuclear decoupling NMR experiments (see Experimental Section) evidenced that they were not stereoisomers, but two different adducts arising from the two alternative cleavages of the radical cation, the phenylcyclopentaneacetate **24** (the main product) and the benzylcyclopentanecarboxylate **25** (the minor one), each of them as a single stereoisomer. The material balance was satisfactory and a small quantity of an aliphatic ester, the cyclopentaneacetate **26** (a single diastereoisomer), was also obtained. In every case the relative configuration of the asymmetric centers was established by NOE experiments (see Experimental Section).[22] The reaction was repeated with the acetal of (+)-camphor, and each one of the previously discussed products was obtained as a single enantiomer.

In the case of ketal **5**, the reaction in the presence of $C_{12}H_{25}SH$ gave a small amount of the aliphatic ester **27**, detected in traces in neat acetonitrile. In the case of **6**, this additive resulted primarily in the production of **26**, again as a single diastereoisomer (Table 3).

Table 3. Results from the Irradiations in the Presence of *n*-Dodecylmercaptan

	aliphatic esters (mmol)		TCB consumed (mmol)	
dioxolane	MeCN[a]	MeCN/RSH[b]	MeCN[a]	MeCN/RSH[b]
2	0.93	0.77	1.85	0.54
3	0.78	0.54	1.78	0.51
5	<0.1	0.80	2.45	0.93
6	0.21	3.15	3.23	0.21

[a] Irradiation for 22 min of a solution (0.05 M dioxolane and 0.005 M TCB) in MeCN. [b] Irradiation for 22 min of a solution (0.05 M dioxolane and 0.005 M TCB) in MeCN/0.025 M *n*-dodecylmercaptan.

Discussion

Fragmentation of the Radical Cations. The observation of fluorescence quenching and the negative calculated free energy change[23] support that the first step in these reactions is electron transfer from the acetals to singlet excited TCB. This is followed by fragmentation of the radical cation of the acetal. Preliminary data show that the quantum yield for TCB alkylation (and, by inference, the relative efficiency for the radical cation fragmentation, suggested to be the rate-determining step of the overall reaction) is larger with 2,2-dialkyl-1,3-dioxolanes than with open-chain ketals.

This is reasonably related to the better alignment between the half-filled n_O orbital and the σ_{C-C} bond involved in the cleavage, in the case of the rigid dioxolane ring. The presently reported ketals all cleave with an efficiency (Table 1) close to that measured for the ethylene ketals of open-chain ketones,[16] as one would expect, since the incorporation of the alkyl chains in a ring does not greatly affect the conformation. The limiting quantum yields for alkylation with these ketals are in the range 0.2 to 0.3, showing that radical cation cleavage competes efficiently with back electron transfer. Indeed, this is a relatively high value, taking into account that many photoinduced SET reactions have an efficiency of ca. 0.01, although this still represents the wastage of most of the absorbed energy. Preliminary experiments in the presence of salts showed that an increase in the medium polarity has only a modest effect on the alkylation yield.

There is no ambiguity about the mode of cleavage, since the positive charge is always generated at the dialkoxy-substituted center, as revealed by exclusive nucleophile addition at that position, and no product arising from a dialkoxy radical was detected. As noted in related cases,[16,21] this is due to the stabilization of the heteroatom-delocalized cation in solution. Furthermore, asymmetric ketals of both cyclic and acyclic ketones show a marked selectivity in the cleavage. Thus, there is, in every case, a marked preference for the cleavage of the more substituted radical, e.g. the ratio is ca. 6 to 1 or the competition between a secondary and a primary radical, both from **3** and from **7**, and is 8 to 1 for the tertiary vs primary radical in ketal **6**.

Reactions Observed. The fragmentation of the radical cations leads to 1,5- or 1,6-distonic radical cations, either open chain (from the spiro ketals **1**–**4** of monocyclic ketones) or with the radical center at a cyclic position, at least in one of the two possible fragmentations, from the spiro ketals **5** and **6** of bicyclic ketones. Each center independently undergoes the expected chemistry, that is

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(22) The structure of compound **24** has been confirmed by a single crystal structure determination (Bovio, B., Pavia, personal communication).
(23) SET from ketals to singlet excited TCB is calculated to be exothermic by ca. 0.2 to 0.4 eV by means of the Weller equation (ref 24).
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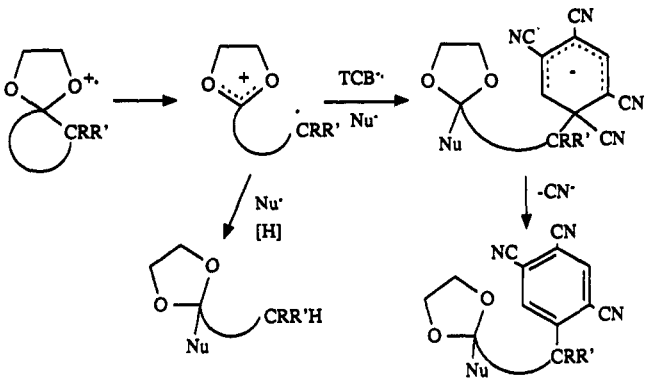
Scheme 3



addition of a nucleophile (water or methanol) to the cationic site and addition of the radical anion to the radicalic site (see Scheme 3).

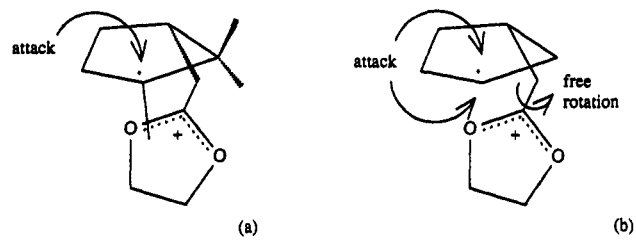
Addition to $TCB^{\bullet-}$ is the almost exclusive reaction involving the radicals. Competition by hydrogen abstraction takes place only to a small degree, except when the radical center is sterically hindered, as in the case of **4**, and particularly when it is both hindered and at a cyclic position, as in the case of **6**. The addition of a good hydrogen donor like dodecylmercaptan minimally affects the reaction in the cases of donors **1–3**, while the reduction of the radical center increases when this is hindered or cyclic, to the extent that with acetal **6** this becomes the main process.

Thus, the radical–radical anion combination leading to the anionic adduct (and from this to the end-product through cyanide loss) is a very fast process, as indeed it has been found to be in some related alkylations.[11c] It is possible that both radical cation fragmentation and radical–radical anion coupling take place, at least in part, before diffusion of the radical ions from the original pair.

Stereoselectivity in the Alkylation. The present results show that it is possible to generate complex alkyl radicals for the functionalization of aromatics through a photoinduced SET process. This raises the question of whether it is possible to induce some diastereoselectivity in the addition to the planar radical center. The results with the open-chain 1,6-distonic radical cation derived from the menthone ethylene ketal are negative, with formation of nearly equal amounts of the two possible diastereoisomers. This confirms that it is a free-radical addition, wherein no effect from an asymmetric center that is γ to the reacting center is expected.

On the other hand, the result with the rigid (cyclic) distonic radical ion formed from the camphor ketal shows complete diastereoselectivity in the radicalic addition. The new C–C bond is formed on the side opposite to the one that is cleaved. Several rationalizations for this result were considered and discarded. Coulombic attraction keeping the radical anion on the same side as the cationic center would lead to the opposite result. Likewise, induction by the other asymmetric center is unlikely, in view of the results with ketal **4**. The fact that in the case of **5**, attack onto the planar radical center proceeds with no selectivity, giving a 1:1 mixture of *cis* and *trans* 1,3-cyclopentanes, shows that the exclusive formation of **24** from **6** does not depend on steric approach control. A better explanation can be found in the hindrance exerted by the cationic center, since in the 1,5-distonic radical cation arising from **6**, the two methyl groups make rotation of the cationic site away from the radical site slower than the radical–radical anion addition (contrary to the case of the radical cation derived from **5**; see Scheme 4, compare formulae a and b). One may also consider that recent theoretical and experimental results show that some stabilization is associated with distonic radical cations.[18] This effect is probably less important in a polar solvent than in the gas phase, but, together with steric hindrance by the methyl groups, it may play a role in "freezing" the conformation of the radical cation.

Scheme 4



In keeping with the proposed rationalization, the selectivity with inversion also extends to the reduction of the radical site by the mercaptan, which apparently also takes place before the stabilized conformation **a** is lost (Scheme 4). This disfavors the alternative hypothesis that the reaction with the aromatic nitrile is a nucleophilic substitution of the radical anion onto the radical cation[25] (in which case one should also expect diastereoselectivity with ketal **5**).

Conclusion

Irradiation of TCB in the presence of the ketals of cyclic ketones gives ω-(alkoxycarbonyl)alkyl derivatives in good yield. This shows that PET-initiated alkylation of aromatics is a preparatively useful method, and reasonably complex molecules containing functional groups susceptible to further elaboration are obtained in this way. Essential features of the method are, besides its efficiency ($\Phi > 0.2$), the predictable regioselectivities both in the fragmentation of the radical cation (at least 6 to 1 in favor of the more-substituted radical) and in the attack on the aromatic ring (at the position of highest spin density in the radical anion). Furthermore, a special case of stereoselectivity has been found, which is based on the hindrance by the cationic center on the addition to the radical site. At the moment, a limitation of the method is the fact that the photochemical oxidant required to initiate the reaction becomes incorporated in the final product. However, the efficient reduction observed in the case of the camphor acetal in the presence of a mercaptan shows that in principle it is possible to manipulate the chemistry of the radical generated in this way. We plan to further develop these indications.

Experimental Section

General. ^1H and ^{13}C NMR spectra were recorded on a Bruker AC300 spectrometer in $CDCl_3$ solutions, and chemical shifts are reported in ppm downfield from TMS. $[\alpha]_D$ were measured in $CHCl_3$ solution. Elemental analyses were made using a Carlo Erba Model 1106 instrument. Fluorescence intensities were measured by means of an Aminco-Bowman MPF spectrofluorimeter. TCB was prepared and purified according to a previously reported method.[16] The acetals **1–7** were prepared from the

(25) Notice however that the nucleophilic cleavage of a one electron σ-bond occurs with inversion of configuration, as observed in the case of the radical cation of a phenylcyclopropane (ref 26).

corresponding carbonyl derivatives by azeotropic water elimination from the benzene–ethylene glycol solution in the presence of *p*-toluenesulfonic acid (TSA) and redistillation. In the case of camphor, in order to obtain a good yield of the corresponding ketal 6, triethyl orthoformate was added to the benzene–ethylene glycol solution.[27] Anhydrous acetonitrile was obtained by refluxing and fractional distillation from CaH_2.

All photochemical reactions were performed by using N_2-purged MeCN solution (80 mL subdivided in four quartz tubes) of TCB (100 mg, 0.56 mmol) containing the amount of ketal required for making the solution ca. 0.05 M and a multilamp reactor fitted with six 15-W phosphor-coated lamps (maximum of emission, 320 nm) for the irradiation. To avoid the formation of polyalkylated aromatic products, the irradiation was stopped at a <60% conversion of TCB. The reaction course was followed by TLC and VPC. Workup of the photolysates involved concentration in vacuo and chromatographic separation employing Merck 60 silica gel. The yields of the photoreactions are based on consumed TCB.

Photochemical Reaction between TCB and Ketal 1. A solution of TCB and ketal 1 (510 mg, 4 mmol) was irradiated for 2 h. The solvent was evaporated and the residue was bulb-to-bulb distilled under reduced pressure (50 mmHg) in order to isolate excess ketal and 2-hydroxyethyl pentanoate (9). The residue was then separated with flash chromatography eluting with cyclohexane–ethyl acetate mixture of increasing polarity. 2-Hydroxyethyl 5-(2,4,5-tricyanophenyl)pentanoate (8) (80 mg, 81.6%, oil) was isolated. NMR of the raw photolysate before chromatography showed the presence of the orthoacid (8′).

8: ^{1}H NMR δ 1.7 (m, 4H)), 2.3 (s, exch, 1H OH), 2.45 (t, J = 7 Hz, 2H), 3.0 (t, J = 7 Hz, 2H), 3.8 (m, 2H), 4.2 (m, 2H), 7.85 (s, 1H), 8.05 (s, 1H). Anal. Calcd for $C_{16}H_{18}N_3O_3$: C, 64.63; H, 5.09; N, 14.14. Found: C, 65.0; H, 4.85; N, 14.4.

8′: ^{1}H NMR δ 1.7 (m, 4H), 1.6 (s, exch, 1H, OH), 1.9 (t, J = 7 Hz, 2H), 2.95 (t, J = 7 Hz), 4.1 (AA′BB′ system, 4H), 7.75 (s, 1H), 8.0 (s, 1H).

Photochemical Reaction between TCB and Ketal 2. A solution of TCB and ketal 2 (560 mg, 4 mmol) was degassed and irradiated for 2 h; after workup, as for ketal 1, were isolated 2-hydroxyethyl 6-(2,4,5-tricyanophenyl)hexanoate (10) (60 mg, 69%, oil)[16] and 2-hydroxyethyl hexanoate (11) (oil, impure of ketal 2).[16] Irradiation of a solution of TCB and the ketal (concentration as above) in anhydrous MeCN containing 0.1% MeOH gave the orthoesters (12).[16]

Photochemical Reaction between TCB and Ketal 3. Irradiation of a solution of TCB and ketal 3 (560 mg, 3.6 mmol) for 1 h followed by workup and silica gel column chromatography (cyclohexane–EtOAc) gave 63 mg (82%, oil) of 2-hydroxyethyl 6-(2,4,5-tricyanophenyl)heptanoate (13) and 13 mg (14%, oil) of 2-hydroxyethyl 2-methyl-6-(2,4,5-tricyanophenyl)hexanoate (14). The formation of a small amount of 2-hydroxyethyl heptanoate was confirmed with GC-MS analysis of the photolysated solution.

13: ^{1}H NMR δ 1.37 (d, J = 7 Hz, 3H), 1.2–2.0 (m, 6H), 2.35 (t, J = 7 Hz, 2H), 3.3 (sextet, J = 7 Hz, 1H), 3.8 (m, 2H), 4.2 (m, 2H), 7.75 (s, 1H), 8.0 (s, 1H). Anal. Calcd for $C_{18}H_{19}N_3O_3$: C, 66.44; H, 5.89; N, 12.92. Found: C, 66.2; H, 5.95; N, 12.5.

14: ^{1}H NMR δ 1.19 (d, J = 7 Hz, 3H), 1.2–2.0 (m, 6H), 2.5 (sextet, J = 7 Hz, 1H), 2.96 (t, J = 7 Hz, 2H), 3.8 (m, 2H), 4.2 (m, 2H), 7.75 (s, 1H), 8.0 (s, 1H). Anal. Calcd for $C_{18}H_{19}N_3O_3$: C, 66.44; H, 5.89; N, 12.92. Found: C, 66.1; H, 5.9; N, 12.5.

Photochemical Reaction between TCB and Ketal 4. Irradiation of a solution of TCB and the ethylene ketal of (−)-menthone 4 (700 mg, 3.5 mmol) for 2 h followed by workup by using the general conditions gave after silica gel chromatography (cyclohexane–EtOAc) 40 mg (oil) of (3*R*)-2-hydroxyethyl 3,7-dimethyloctanoate (20) and 70 mg of an oily fraction analyzing for $C_{21}H_{25}N_3O_3$, which resulted to be a mixture of three different compounds. On the basis of the integral of proton NMR this mixture was attributed as follows: 55 mg (60%) of 2-hydroxyethyl 3,7-dimethyl-6-(2,4,5-tricyanophenyl)octanoate [mixture of the (3*R*,6*R*) and the (3*R*,6*S*) diastereoisomers 17 and 18 in the ratio 0.51 to 0.49], 15 mg (12%) of (2*S*,5*R*)-2-hydroxyethyl 5-methyl-2-(1-methylethyl)-6-(2,3,5-tricyanophenyl)hexanoate (19).

The assignments of ^{1}H and ^{13}C signals were supported by ^{13}C-DEPT, ^{1}H/^{1}H 2-D correlated spectra, as well as ^{1}H/^{13}C heterocorrelated 2D spectra.

17 and 18: Major isomer ^{1}H NMR δ 0.76 (d, J = 7 Hz, 3H), 0.9 (d, J = 7 Hz, 3H), 1.05 (d, J = 7 Hz, 3H), 0.9 (m) and 1.3 (m) (2H, CH_2-5), 1.65 (m) and 1.95 (m) (2H, CH_2-4), 1.9 (m, 1H, H-7), 1.95 (m, 1H, H-3), 2.2 (AB part of ABX system, 2H, CH_2-2), 2.85 (m, 1H, H-6), 3.75 (m, 2H), 4.1 (m, 2H), 7.85 (s, 1H), 8.1 (s, 1H); ^{13}C NMR δ 19.1 (CH_3), 20.2 (CH_3), 20.5 (CH_3), 29.6 (CH_2), 30.25 (CH), 33.6 (CH), 34.09 (CH_2), 41.2 (CH_2), 51.4 (CH), 60.6 (CH_2), 65.6 (CH_2), 113.5, 114.1, 114.8, 118.6, 118.7, 119.1, 132.8 (CH), 136.8 (CH), 155.4, 172.8 (COOR).

Minor isomer: ^{1}H NMR δ 0.7 (d, J = 7 Hz, 3H), 1.1 (d, J = 7 Hz, 3H), 0.9 (d, J = 7 Hz, 3H), 0.9 (m) and 1.3 (m) (2H, CH_2-5), 1.9 (m, 1H, H-7), 1.65 (m) and 1.95 (m) (2H, CH_2-4), 1.95 (m, 1H, H-3), 2.22 (AB part of ABX system, 2H, CH_2-2), 2.85 (m, 1H, H-6) 3.75 (m, 2H), 4.1 (m, 2H), 7.85 (s, 1H), 8.1 (m, 1H); ^{13}C NMR δ 19.7 (CH_3), 20.3 (CH_3), 20.6 (CH_3), 19.7 (CH_3), 29.3 (CH_2), 29.7 (CH), 33.6 (CH), 33.7 (CH_2), 40.7 (CH_2), 51.1 (CH), 60.6 (CH_2), 65.6 (CH_2), 113.9, 114.2, 114.8, 118.6, 118.7, 119.06, 132.7 (CH), 136.8 (CH), 155.4, 172.7 (COOR).

19: ^{1}H NMR δ 0.93 (d, J = 7 Hz, 6H), 0.95 (d, J = 7 Hz, 3H), 1 (m) and 1.2 (m) (2H), 1.65 (m) and 1.9 (m) (2H), 1.6 (m, $CHMe_2$) 1.95 (m, H-5), 2.15 (m, H-2), 2.7 (dd, J_{gem} = 13 Hz, J_{vic} = 8 Hz, 1H) and 3.3 (dd, J_{gem} = 13 Hz, J_{vic} = 6 Hz, 1H) (CH_2-6), 3.8 (m, 2H), 4.3 (m, 2H), 7.8 (s, 1H), 8.1 (s, 1H); ^{13}C NMR δ 19.03 (CH_3), 20 (CH_3), 20.2 (CH_3), 26.7 (CH_2), 30.5 (CH), 34.5 (CH_2), 35.1 (CH), 41.5 (CH_2), 52.5 (CH), 61.05 (CH_2), 65.5 (CH_2), 114.04, 114.1, 114.6, 116.8, 117.9, 135.2 (CH), 136.7 (CH), 151.4, 175.8 (C-1). Anal. Calcd for $C_{21}H_{25}N_3O_3$: C, 68.64; H, 6.86; N, 11.44. Found (mixture): C, 68.4; H, 6.9; N, 11.2.

20: ^{1}H NMR δ 0.83 (d, J = 7 Hz, 6H), 0.9 (d, J = 7 Hz, 3H), 1.05–1.3 (m, 6H), 1.48 (m, H-7), 1.9 (m, H-3), 1.95 (s, exch, 1H, OH), 2.1 (dd, J_{gem} = 15 Hz, J_{vic} = 8 Hz, 1H) and 2.3 (dd, J_{gem} = 15 Hz, J_{vic} = 6 Hz, 1H) (CH_2-2), 3.8 (m, 2H), 4.15 (m, 2H); $[\alpha]_D$ +0.13. Anal. Calcd for $C_{12}H_{24}O_3$: C, 66.63; H, 11.18. Found: C, 66.9; H, 11.0.

Photochemical Reaction between TCB and Ketal 5. Irradiation of a MeCN solution of TCB and the ethylene ketal of trisnorcamphor 5 (600 mg, 3.9 mmol) for 1 h followed by the general workup procedure and silica gel chromatography (cyclohexane–EtOAc) gave two fractions containing aromatic compounds. The faster eluting one (52 mg, oil, 60%) was a mixture of *trans*- and *cis*-2-hydroxyethyl 3-(2,4,5-tricyanophenyl)cyclopentaneacetate (21 and 22 in the ratio 0.53 to 0.46 as determined by the proton NMR spectrum), while the slower eluting one was of *cis* 2-hydroxyethyl 3-[(2,4,5-tricyanophenyl)methyl]cyclopentanecarboxylate (23) (5.5 mg, oil, 11%). A very small amount of 2-hydroxyethyl cyclopentaneacetate (27) was detected by VPC and confirmed by GC-MS analysis.

21 and 22: Major isomer ^{1}H NMR δ 1.3–2.7 (m, 9H), 3.66 (m, 1H, H-3), 3.85 (m, 2H), 4.25 (m, 2H), 7.88 (s, 1H), 8.02 (s, 1H); ^{13}C NMR δ 34.4 (CH_2), 35.9 (CH_2), 35.9 (CH), 39.2 (CH_2), 39.7 (CH_2), 42.8 (CH), 61.1 (CH_2), 66.0 (CH_2), 113.6, 114.1, 114.3, 114.7, 117.4, 119.6, 132.2 (CH), 137.1 (CH), 172.75 (COOR).

Minor isomer: ^{1}H NMR δ 1.3–2.7 (m, 9H), 3.58 (m, 1H, H-3), 3.85 (m, 2H), 4.25 (m, 2H), 7.9 (s, 1H), 8.02 (s, 1H); ^{13}C NMR δ 31.5 (CH_2), 32.8 (CH_2), 36.5 (CH), 39.4 (CH_2), 40.8 (CH_2), 44.0 (CH), 61.1 (CH_2), 66.0 (CH_2), 113.6, 114.1, 114.3, 114.7, 117.4, 119.6, 132.3 (CH), 137.0 (CH), 155.8, 172.7 (COOR). Anal. Calcd for $C_{18}H_{17}N_3O_3$: C, 66.86; H, 5.30; N, 13.00. Found: C, 66.5; H, 5.2; N, 12.7.

23: ^{1}H NMR δ 1.3–2.15 (m, 9H), 2.28 (m, 1H, H-3), 2.54 (m, 1H, H-1), 3.04 (AB system, 2H), 3.85 (m, 2H), 4.25 (m, 2H), 7.8 (s, 1H), 8.05 (s, 1H); ^{13}C NMR δ 26.8 (CH_2), 32.8 (CH_2), 34.7 (CH_2), 41.1 (CH_2), 42.2 (CH), 46.2 (CH), 61.1 (CH_2), 66.2 (CH_2), 113.5, 114.1, 114.6, 116.7, 117.7, 119.3, 134.8 (CH), 137.1 (CH), 151.6, 176.3 (COOR). Anal. Calcd for $C_{18}H_{17}N_3O_3$: C, 66.86; H, 5.30; N, 13.00. Found: C, 66.6; H, 5.1; N, 12.8.

Photochemical Reaction between TCB and the Ketal 6 of (±)-Camphor. Irradiation of a solution of TCB and the ethylene ketal 6 of (±)-camphor (700 mg, 3.6 mmol) for 2 h followed by the general workup gave after silica gel chromatography (cyclohexane–EtOAc), 105 mg (87%, mp 106 °C, EtOH) of *trans*-

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2-hydroxyethyl 2,2,3-trimethyl-3-(2,4,5-tricyanophenyl)cyclopentaneacetate (24) and 20 mg (10%) (mp 175 °C, EtOH) of *cis*-2-hydroxyethyl 1,2,2-trimethyl-3-(2,4,5-tricyanophenylmethyl)-cyclopentanecarboxylate (25). Moreover 8 mg (oil) of *cis*-2-hydroxyethyl 2,2,3-trimethylcyclopentaneacetate (26) were isolated.

NMR experiments with selective $^{13}C^{1}\{H\}$ decoupling showed that compounds 24 and 25 were not diastereoisomers: the carbonyl carbon in compound 25 was coupled with a methyl group, while in isomeric 24 no coupling was observed with any methyl groups. The assignments of the NMR signals were confirmed by ^{13}C-DEPT, $^{1}H/^{1}H$ correlated 2D spectra, and $^{1}H/^{13}C$ heterocorrelated 2D spectra.

24: ^{1}H NMR δ 0.80 (s, 3H Me-2), 0.97 (s, 3H, Me-2), 1.74 (s, 3H Me-3), 1.90 (m, 1H,H-1), 2.33 (AB part of an ABX system, 2H, CH_2-α), 1.65 (m) and 2.25 (m)(2H,CH_2-5), 2.03 (m) and 2.38 (m)(2H,CH_2-4), 3.85 (m, 2H), 4.20 (m, 2H), 7.80 (s, 1H), 8.05 (s, 1H); ^{13}C NMR δ 19.2 (CH_3), 23.0 (CH_3), 24.2 (CH_3), 28.9 (CH_2), 35.1 (CH_2), 38.8 (CH_2), 43.9 (CH), 48.9, 54.9, 61.0 (CH_2), 66.0 (CH_2), 113.4, 113.9, 114.4, 117.6, 117.8, 118.3, 134.6 (CH), 139.3 (CH), 157.8, 173.0 (COOR). The configuration was attributed on the basis of the following NOE experiments. Irradiation of the singlet at δ 0.8 caused a 5.8% enhancement of the signal at δ 1.9 (H-1) and a 6.4% enhancement of the A part of the AB signal at δ 2.33; irradiation of the singlet at δ 0.97 caused a 5.6% enhancement of the B part of the signal at δ 2.33 and a 2.6% enhancement of the δ 1.75 singlet; irradiation of the δ 1.74 singlet caused a 3.2% enhancement of the δ 0.94 singlet; this established that the methyl group in 3 was *trans* to the methyl at δ 0.8 which in turn was *cis* to the proton in 1; the other NOE effects observed were in accordance. Anal. Calcd for $C_{21}H_{23}N_3O_3$: C, 69.02; H, 6.34; N, 11.50. Found: C, 68.9; H, 6.3; N, 11.5.

25: ^{1}H NMR δ 0.87 (s, 3H, Me-2), 1.22 (s, 3H, Me-1), 1.25 (s, 3H, Me-2), 1.5 (m, 2H, CH_2-4), 1.95 (s, exch, 1H, OH), 2.05 (m, 1H, H-3), 2.35 (m) and 2.6 (m) (2H, CH_2-5), 2.67 (dd, J_{gem} = 13 Hz, J_{vic} = 11 Hz, 1H) and 3.1 (dd, J_{gem} = 13 Hz, J_{vic} = 3 Hz, 1H) (CH_2-α), 3.88 (m, 2H), 4.25 (m, 2H), 7.8 (s, 1H), 8.05 (s, 1H); ^{13}C NMR δ 19.5 (CH_3), 21.8 (CH_3), 22.1 (CH_3), 26.3 (CH_2), 32.0 (CH_2), 36.1 (CH_2), 46.1, 49.0 (CH), 55.7, 61.3 (CH_2), 66.1 (CH_2), 113.6, 114.1, 114.5, 117.8, 119.1, 134.9 (CH), 137.1 (CH), 152.3, 176.3 (COOR). For the sake of comparison, NOE experiments were made also in this case even if the configuration of chiral centers was expected to remain the same as in camphor. Irradiation of the singlet at δ 0.87 caused enhancements of 9% and, respectively, of 4.3% on the signals at δ 2.67 and 3.1; irradiation of the singlet at δ 1.22 caused enhancement of 10% on the signal at δ 2.05; irradiation of the singlet at δ 1.25 caused enhancements of 6.8 and 7.8%, respectively, on the signals at δ 3.1 and 2.05; moreover irradiation of the signals at δ 2.05 caused enhancements of 2.5% on the singlet at δ 1.25 and of 4% on the singlet at δ 1.22. This established that the methyl group at δ 1.22 (Me-1) was *cis* to the methyl at δ 1.25 which in turn was *cis* to the proton in 3; the other NOE effects observed were in accordance. Anal. Calcd for $C_{21}H_{23}N_3O_3$: C, 69.02; H, 6.34; N, 11.50. Found: C, 69.0; H, 6.3; N, 11.3.

26: ^{1}H NMR δ 0.54 (s, 3H, Me-2), 0.84 (d, J = 7 Hz, 3H, Me-3), 0.89 (s, 3H Me-2), 1.55 (m, 1H, H-3), 1.85 (m, 1H, H-1), 1.2 (m) and 1.78 (m) (2H), 1.8 (m) and 1.85 (m) (2H), 2.12 (dd, J_{gem} = 14, J_{vic} = 10 Hz, 1H) and 2.44 (dd, J_{gem} = 14 Hz, J_{vic} = 3 Hz, 1H) (CH_2-α), 3.8 (m, 2H), 4.2 (m 2H); ^{13}C NMR δ 13.9 (CH_3), 14.4 (CH_3), 25.3 (CH_3), 28.0 (CH_2), 29.8 (CH_2), 35.5 (CH_2), 44.6 (CH), 46.9 (CH), 61.3 (CH_2), 65.9 (CH_2), 174.4 (COOR). The configuration was attributed on the basis of the following NOE experiments: irradiation of the singlet at δ 0.54 caused enhancements of 4.6% and 6.8%, respectively, on the signals at δ 2.44 and 2.12 as well as a 0.9% enhancement of the doublet at δ 0.84; conversely, irradiation of the δ 0.84 doublet caused a 1.2% enhancement of the δ 0.54 singlet. Irradiation of the singlet at δ 0.89 enhanced the following signals δ 1.55 (5%), 1.85 (6.5%), 2.44 (7.8%). This established that H-1 and H-3 were both *cis* to the same methyl group; the other NOE effects observed were in accordance. Anal. Calcd for $C_{12}H_{22}O_3$: C, 67.25; H, 10.35. Found: C, 67.0; H, 10.4.

Photochemical Reaction between TCB and the Ketal 6 of (+)-Camphor. Irradiation of a solution of TCB and the ethylene ketal 6 of (+)-camphor (700 mg, 3.6 mmol) for 2 h followed by general workup gave, after silica gel chromatography (cyclohexane–EtOAc), 100 mg (85%) (mp 106 °C EtOH)($[\alpha]_D$ -12.8°) of (1*R*,3*R*)-*trans*-2-hydroxyethyl 1,2,2-trimethyl-3-(2,4,5-tricyanophenyl)cyclopentaneacetate (24), 18 mg (9%) (mp 175 °C, EtOH) ($[\alpha]_D$ +34.5°) of (1*R*,3*S*)-*cis*-2-hydroxyethyl 1,2,2-trimethyl-3-[(2,4,5-tricyanophenyl)methyl]cyclopentanecarboxylate (25) and 6 mg (oil)($[\alpha]_D$ +27.9°) of (1*R*,3*S*)-*cis*-2-hydroxyethyl 2,2,3-trimethylcyclopentaneacetate (26).

Photochemical Reaction between TCB and Ketal 7. Irradiation of a MeCN solution of TCB and the ethylene ketal 7 of 2-methyl-3-pentanone (500 mg, 3.5 mmol) for 1 h followed by general workup procedure gave, after silica gel chromatography (cyclohexane–EtOAc), 60 mg (80%) (mp 116–117 °C, EtOH) of 5-(2-methylethyl)-1,2,3-tricyanobenzene (15)[11c] and 12 mg (11%) of 5-ethyl-1,2,4-tricyanobenzene (16).

16: ^{1}H NMR δ 1.4 (t, J = 7 Hz, 3H), 3.05 (q, J = 7 Hz, 2H), 7.83 (s, 1H), 8.05 (s, 1H). Anal. Calcd for $C_{11}H_7N_3$: C, 72.91; H, 3.89; N, 23.19. Found: C, 73.0; H, 3.9; N, 23.0.

Photochemical Reaction in the Presence of *n*-Dodecylmercaptan. General. Exploratory tests were performed using 3 mL of a degassed MeCN solution (0.005 M in TCB and 0.05 M in the ketal). The concentration of *n*-dodecylmercaptan was changed from 0.01 to 0.2 M. The reaction course was followed by TLC in order to check the distribution of the aromatic adducts and by VPC to monitor the concentration of TCB and of 2-hydroxyethyl aliphatic esters. In general no change in the product distribution was observed but only a decrease in the rate of TCB consumption and of TCB alkylation. As regard to the formation of 2-hydroxyethyl aliphatic esters, it was enhanced in the case of ketal 5 and much more strongly with ketal 6.

Photochemical Reaction between TCB and the Ketal 6 of (+)-Camphor in the Presence of *n*-Dodecylmercaptan. Irradiation of a solution of TCB (17 mg, 0.1 mmol, in 20 mL of MeCN) and the ethylene ketal 6 of (+)-camphor (40 mg) and *n*-dodecylmercaptan (0.02 M) for 6 h followed by general workup gave, after silica gel chromatography (cyclohexane–EtOAc), 30 mg of *cis* 2-hydroxyethyl 2,2,3-trimethylcyclopentaneacetate (26) (70%, based on initial ketal concentration); 12 mg of TCB was recovered unchanged while only traces (<4 mg) of products 24 and 25 were obtained.

Quantum Yield Determination. Experiments for quantum yield determination were carried out in spectrophotometric cuvettes irradiated by means of a focalized Osram 150-W high-pressure mercury arc fitted with an interference filter centered at 313 nm. The TCB consumption was determined by VPC.

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