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A Meta Effect in Organic Photochemistry? The Case of S_N1 Reactions in Methoxyphenyl Derivatives

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Abstract: The photochemistry of isomeric methoxyphenyl chlorides and phosphates has been examined in different solvents (and in the presence of benzene) and found to involve the triplet state. With the chlorides, C−Cl bond homolysis occurs in cyclohexane and is superseded by heterolysis in polar media, while the phosphate group is detached (heterolytically) only in polar solvents. Under such conditions, the isomeric *triplet* methoxyphenyl cations are the first formed intermediates from both precursors, but intersystem crossing (isc) to the singlets can take place. Solvent addition (forming the acetanilide in MeCN, the ethers in alcohols, overall a S_N1 solvolysis) is a diagnostic reaction for the singlet cation, as reduction and trapping by benzene are for the corresponding triplet. Solvolysis is most important with the meta isomer, for which the singlet is calculated (UB3LYP/6-31g(d)) to be the ground state of the cation ($\Delta E = 4$ kcal/mol) and isc is efficient (k_{isc} ca. 1×10^8 s^{-1}), and occurs to some extent with the para isomer (isoenergetic spin states, k_{isc} ca. 1.7×10^6 s^{-1}). The triplet is the ground state with the ortho isomer, and in that case isc does not compete, although trapping by benzene is slow because of the hindering of C_1 by the substituent. The position of the substituent thus determines the energetic order of the cation spin states, in particular through the selective stabilization of the singlet by the *m*-methoxy group, a novel case of "meta effect".

Nucleophilic substitution reactions have had an important role in the development of organic photochemistry. In 1956 Havinga reported that the hydrolysis of nitrophenyl phosphates and sulfates, not occurring to a significant extent at room temperature, was much accelerated by (room) light and actually occurred smoothly by deliberate irradiation, in particular in the case of the meta isomers (see Scheme 1a).[1] The reaction was later characterized as a S_N2 (Ar*) process and it was demonstrated that the process mainly involved cleavage of the C−O bond under basic conditions or of the P−O bond in a neutral solution.[2,3] In 1963, Zimmerman reported a new example of the meta effect by electron-withdrawing groups in aryl trityl ethers and further that hydrolysis of benzyl acetates was accelerated by electron donor groups positioned meta to the site involved (Scheme 1b).[4] The latter author rationalized the observed effect on the basis of the calculated charge distribution in the excited states (by the Hückel method, but the result did not change when using CASSF computations, as in a new proposal)[5a,b] and found that the electron density was transmitted to and from the meta (and ortho) position, rather than to the para and ortho position as in the ground state. The phenomenon was termed the "meta effect".

Along with other typical thermal/photochemical dichotomies, such as the opposite stereochemistry in electrocyclic reactions, this was one of the key observations evidencing the different behavior of excited states versus ground states[5c−e] and gave impetus to the development of organic photochemistry and its rationalization in the following years. Subsequent studies have afforded further examples of this directing effect,[2] and rationalizations based on the charge distribution have again been found useful.[6] However, recognizing an effect of the excited-state structure on the rate of reaction requires that this term be disentangled from the many factors contributing to the overall photochemical reactivity (singlet or triplet reaction, competing radiative and nonradiative decays, reversibility of the reaction, identification of the step of the mechanism where the substituent exerts its effect), as shown, for example, for the photo-Claisen reaction of aryl allyl ethers by Pincock through a thorough study.[7] While one has to be aware of this difficulty, the didactic

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(1) Havinga, E.; de Jongh, R. O.; Dorst, W. *Recl. Trav. Chim. Pays-Bas* **1956**, *75*, 378.

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(3) de Jongh, R. O.; Havinga, E. *Recl. Trav. Chim. Pays-Bas* **1968**, *87*, 1318. de Jongh, R. O.; Havinga, E. *Recl. Trav. Chim. Pays-Bas* **1968**, *87*, 1327.

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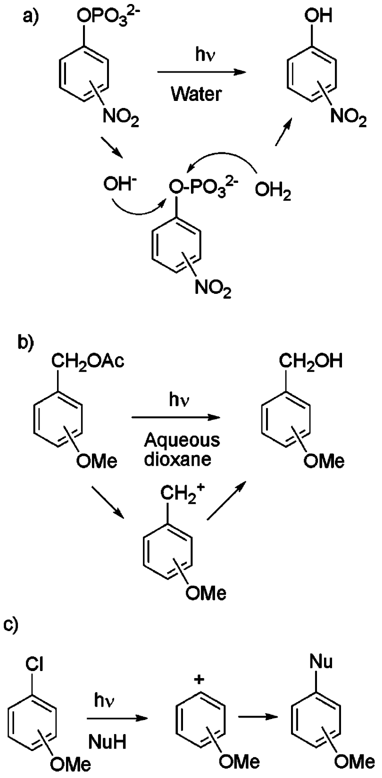
Scheme 1. S_N2 and S_N1 Paths in Photonucleophilic Substitution

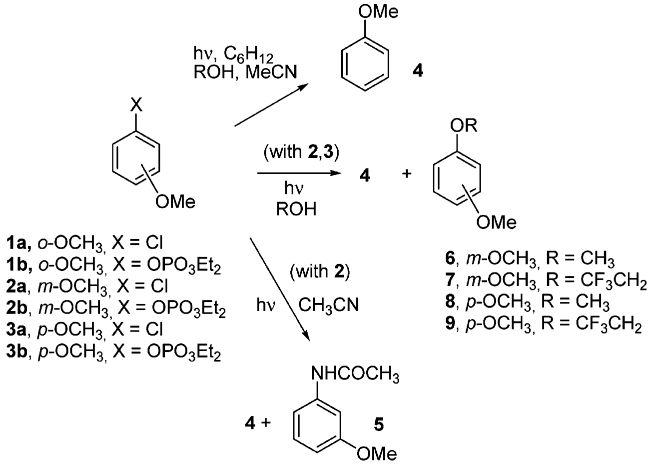


value of such simple rationalizations makes it desirable that more examples of directing effect are found.

Recalling that electron-donating meta substituents had been found to accelerate photosolvolyses at the benzylic position in the original study,[4] we wondered whether a donating group may direct the substitution at a phenylic position, obviously in a reaction the mechanism of which could be well understood. As an example, a donating group may favor photosubstitution via a S_N1 mechanism, in contrast to the favored S_N2 path with electron accepting substituents (see Scheme 1c). However, there are only a few examples of the former mechanism in the literature[2] and no indication about the directing effect of substituents on it. The photosolvolysis of isomeric chloroanisoles could be an obvious choice for investigating this point. The photochemistry of these compounds has been investigated, and reduction and substitution of the chloro atom have been observed. However, it has been concluded that the three isomers were best discussed separately, and there was no common mechanism.[8]

In contrast, it was recently shown that irradiation of 4-chloroaniline, -anisole, and -phenol in the presence of π nucleophiles supported that unimolecular heterolysis of the C−Cl bond occurred giving the corresponding phenyl cations.[9] These intermediates underwent electrophilic attack either to the solvent (resulting in overall solvolysis of the aryl chloride) or to the π-nucleophile (giving the respective arylated products). We reasoned that comparing the two reactions as well as the key photophysical parameters and the medium effect on them may offer a handle for understanding the mechanism and the possible existence of a directing effect by the substituent on some intermediate.

Scheme 2. Products from the Photolysis of Isomeric Methoxyphenyl Chlorides and Phosphates



Results

In the following, we report a study of the photochemistry of the three chloroanisoles (**1a**−**3a**) in various solvents, both neat and in the presence of benzene as a typical π trap for electrophiles. This was supplemented by a parallel study on the corresponding methoxyphenyl phosphates (**1b**−**3b**), since some phenyl phosphates bearing a methoxy or dialkylamino group in 4 (as well as the corresponding mesylates and triflate) had been shown to give the same trapping products as the chlorides.[10] Thus, comparison of the two series of aromatics with different (potential) nucleofugal groups may offer a test for the involvement of a common intermediate and reveal the effect of substituents both on the formation and on the reactivity of such intermediate, if any. The experimental work was complemented by DFT calculations as a support to the mechanistic proposal.

Photochemistry. The photochemistry of the above aromatics was investigated in a series of solvents, from nonpolar to highly polar. Irradiation at 254 nm of 2-chloroanisole (**1a**) gave only anisole (**4**) in all of the solvents tested, namely, cyclohexane, acetonitrile, methanol, and 2,2,2-trifluoroethanol (TFE) (see Scheme 2). The highest quantum yield of reaction measured was in cyclohexane (0.33), while the value in MeCN was 40 times smaller and intermediate values were observed in the alcohols (Table 1). Reduction to **4** was again the only photoprocess from 3-chloroanisole (**2a**) in cyclohexane, but this was not the case in the other solvents. Thus, in MeCN compound **4** was accompanied by *N*-(3-methoxyphenyl)-acetanilide (**5**), that is, a product resulting from chlorine substitution by the weakly nucleophilic N atom of the solvent (see Scheme 2). Similarly, in the alcohols the corresponding ethers **6** and **7** were formed; indeed, the ether was the main product in TFE. A similar course was followed in part with 4-chloroanisole (**3a**), with which reduced **4** was the only product in both cyclohexane and MeCN but was accompanied by the ethers **8** and **9** in the alcohols (in TFE also by 4-fluoroanisole, **10**), although in a lower proportion than with **2a**. With both **2a** and **3a**, the quantum yield strongly decreased from cyclohexane to MeCN and grew again in the alcohols.

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(9) Fagnoni, M.; Albini, A. *Acc. Chem. Res.* **2005**, *39*, 713.
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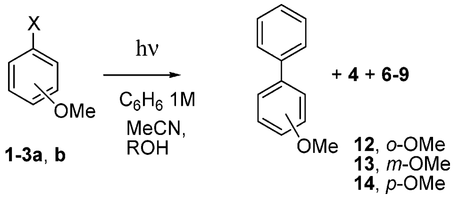
Table 1. Quantum Yield of Reaction and Product Formation for the Photochemical Reaction of *o*-, *m*-, and *p*-chloroanisole (**1a**−**3a**) and Methoxyphenyl Diethyl Phosphates (**1b**−**3b**) in Various Solvents

	Products formed and quantum yields from the photolysis of anisoles **1-3**		
solvent	**1a**	**2a**	**3a**
C_6H_{12}	**4**, 0.33	**4**, 0.28	**4**, 0.13
MeCN	**4**, 0.008	**4**, 0.01; **5**, 0.01	**4**, 0.003
MeOH	**4**, 0.08	**4**, 0.12; **6**, 0.08	**4**, 0.08; **8**, 0.02
CF_3CH_2OH	**4**, 0.012	**4**, 0.05; **7**, 0.08	**4**, 0.03; **9**, 0.02; **10**, 0.02
solvent	**1b**	**2b**	**3b**
C_6H_{12}	**4**, 0.013	**4**, 0.011	**4**, 0.0012
MeCN	**4**, 0.012	**4**, 0.009	**4**, 0.0017
MeOH	**4**, 0.036	**4**, 0.026	**4**, 0.10; **8**, 0.06
CF_3CH_2OH	**4**, 0.028[a]	**4**, 0.008, **7**, 0.056	**4**, 0.09: **9**, 0.06; **10**, 0.13

[a] A further portion of **1b** reacted to give 2-methoxyphenol **11** (about $^2/_3$ of **4**) via thermal hydrolysis, as checked by blank experiments.

Scheme 3. Products from the Photolysis of Isomeric Methoxyphenyl Chlorides and Phosphates in the Presence of Benzene



Examination of the three methoxyphenyl phosphates showed that the product distribution was similar, with **1b** giving only **4**, and **2b** and **3b** giving also the ethers **6**−**9** in the alcohols (as well as the fluoride **10** from **3b** in TFE). Differently from the previous series, however, the quantum yield remained low (some percent) along the sequence of solvents, though regularly increasing with polarity. This trend was more dramatic with **3b**, where it increased by a factor of >200 from 0.0012 (cyclohexane) to 0.28 (TFE). In TFE a certain amount of 2-methoxyphenol (**11**) was formed from **1b**, but this was due to thermal solvolysis of the phosphate ester moiety.

Preparative irradiations were performed also under acetone sensitization (by using "310 nm" phosphor-coated lamps in the presence of 0.9 M acetone, which absorbed most of the light under these conditions) and were found to give the same product distribution.

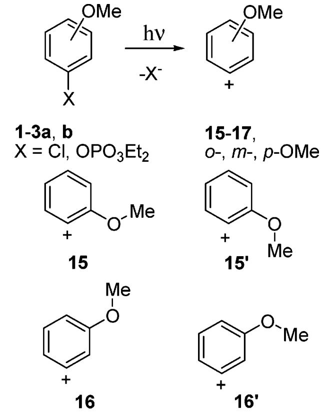
Trapping Experiments. A product study was then carried out in the presence of 1 M benzene and using acetone as the sensitizer. Under these conditions, biphenyls **12**−**14** were formed competitively at the expenses of anisole. In all of the cases, the amount of biphenyls increased with the solvent polarity, but to a different extent. Thus, **14** was the only product from both **3a** and **3b** in TFE, whereas with the ortho and meta chlorides and phosphates, the biphenyl reached a 40−50% yield in that solvent (Table 2). Direct and sensitized irradiation gave essentially the same product distribution, as it was demonstrated in the case of **3a**, which absorbed a sufficient part of the light from the 310 nm lamps for making direct irradiation in the presence of benzene feasible[11] (see Scheme 3 and Table 2).

The dependence of the yield of trapping products **12**−**14** on benzene concentration was explored under sensitized conditions. As it appears from Figure 1, a linear correlation was obtained when plotting the reciprocal of the ratio between the yield of biphenyl and the yield of the other photoproducts versus that of benzene concentration. The slope was 6.4 for **1a**, 1.06 for **2a**, and 67.7 for **3a**.

Photophysical Data. Some photophysical parameters were determined. Chlorides **1a**−**3a** were barely fluorescent, while the fluorescence from phosphates **1b**−**3b** reached a yield of some percents, with a lifetime of about 1 ns and minimal dependence on the solvent characteristics (Table 3). On the other hand, all of the above compounds except **1a** exhibited intense phosphorescence in EPA glass. Flash photolysis experiments showed no signal attributable to the triplet states in polar solvents.

Calculations. To test the viability of heterolytic fragmentation of the aryl−heteroatom bond as the initiating step, a series of calculations were carried out by a DFT approach, which has been shown to be well suited to characterize ionic mechanism. B3LYP(6-31G(d)) calculations were carried out for the three methoxyphenyl cations **15**−**17** in the gas phase and in MeCN bulk by the CPCM method.[12] For the 2- and 3-substituted isomers, two low-lying structures were located, according to the orientation of the methoxy group, away from or toward the divalent carbon (see later). The key features resulting from the calculations can be summarized as follows.

First, the structure of these ions was scarcely affected by the relative position of the substituent and divalent carbon, while it was quite different according to multiplicity. Thus, triplet cations **^{3}15**−**^{3}17** were all planar, with a geometry close to a regular hexagon, while in the singlets **^{1}15**−**^{1}17** a puckering of the ring and a small out of plane displacement were observed at C_1 (C_2−C_1−C_6 angle, 143.5, 146.0, 146.4° in the three isomers, dihedral angle at C_1, ≤5°) (see Table 4 and Figure 2).



The energies of the isomeric cations are also reported in the Table (relative to **15′**), where it appears that there was little difference among the triplets, whereas the meta isomer was markedly stabilized among the singlets. In particular, the ortho and meta isomers having the methoxy group pointing toward C_1 enjoyed some extra stabilization (compare **15′** and **16′** with **15** and **16**). With **15′** this amounted to 2.2 kcal/mol and involved a stabilizing interaction between methyl hydrogens and the divalent carbon. As for the relative order of the spin states, with the ortho isomer the triplet was the lowest state (by 2.5−4 kcal/mol in MeCN bulk, depending on the conformer), while with

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(11) The other chloroanisoles and the phosphates had a somewhat blue-shifted absorption and did not react conveniently with 310 nm lamps.

(12) See Supporting Information.

Table 2. Products from the Sensitized (0.9 M Acetone) Irradiation of *o*-, *m*-, and *p*-chloroanisole (**1a**−**3a**) and Methoxyphenyl Diethyl Phosphates (**1b**−**3b**) in the Presence of 1 M Benzene (in *italic*, Yields from the Nonsensitized Irradiation)

	products formed (% yield)		
solvent	**1a**	**2a**	**3a**
MeCN	**4** (17), **12** (20)	**4** (18), **5** (7), **13** (36)	**4** (79, *79*), **14** (18, *9*)
MeOH	**4** (65), **12** (16)	**4** (20), **6** (44), **13** (18)	**4** (20, *40*), **8** (7, *8*), **14** (71, *27*)
CF_3CH_2OH	**4** (11), **12** (45)	**4** (4), **7** (43), **13** (51)	**14** (100, *100*)
solvent	**1b**	**2b**	**3b**
MeCN	**4** (25), **12**(30)	**13** (11)	**14** (65)
MeOH	**4** (28), **12** (5)	**13** (7)	**14** (10)
CF_3CH_2OH	**4** (36), **12** (15), **11** (40)	**7** (25), **13** (34)	**14** (96)

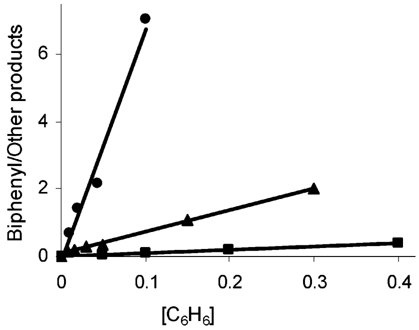

Figure 1. Ratio between the yield of biphenyls **12**−**14** and that of the other products from chloroanisoles **1a** (▲), **2a** (■), **3a** (●) vs the benzene concentration.

Table 3. Some Key Photophysical Parameters for Methoxyphenyl Chlorides and Phosphates

	Φ_{fluo}[a]	τ_{fluo}, ns[a]	E_T, kcal/ mol[b]
2a	0.0003		80
3a	0.021, *0.019*	1.55, *1.41*	80
1b	0.045, *0.012*	2.04, *1.66*	81
2b	0.040, *0.022*	2.46, *2.32*	82
3b	0.033, *0.042*	1.92, *1.90*	81

[a] In methanol, in italic in cyclohexane; the values in acetonitrile are intermediate. [b] From the phosphorescence in ethyl ether/pentane/ethyl alcohol at 77 K.

Table 4. *o*-, *m*-, and *p*-Methoxyphenyl Cations (**15**−**17**): Calculated (in MeCN Bulk) Angles and Dihedral Angles at C_1 and Relative Energies with Respect to the Lowest Isomer of Each Multiplicity (ΔE), to the Lowest Conformer of Each Isomer (ΔE_{conf}) and Singlet/Triplet Energy Difference (ΔE_{ST}) for Each Species

	$C_6C_1C_2$ deg	$C_1C_2C_3C_4$ deg	ΔE kcal/mol	ΔE_{conf} kcal/mol[a]	ΔE_{ST} kcal/mol
^{3}15	125.35	0.017	+2.2	2.2	−2.5
^{3}15′	124.59	−0.004	0[b]		−4.2
^{3}16	126.07	0.006	+2.1	0.8	5.7
^{3}16′	127.32	0.000	+1.3		5.5
^{3}17	127.10	0.000	−0.5		0.7
^{1}15	146.2	−0.874	+0.4	0.4	
^{1}15′	143.5	5.48	0[c]		
^{1}16	146.0	−5.14	−7.9	0.6	
^{1}16′	146.2	−4.37	−8.5		
^{1}17	146.4	0.032	−5.3		

[a] Sum of electronic energy and ZPVE. [b] Lowest configuration among the triplets, calcd $E = -345.755053$ hartree. [c] Lowest configuration among the singlets, calcd $E = -345.748338$ hartree (see Supporting Information).

the meta the singlet was stabilized with respect to the triplet by 5 kcal/mol, and in the para the two states were virtually isoenergetic (a 0.7 kcal/mol difference).

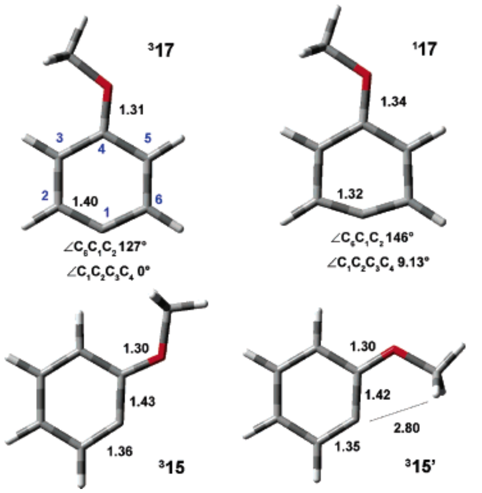

Figure 2. Bond lengths (Å), angles (∠, in deg), and dihedral angles (∠, in deg) for triplet and singlet 4-methoxyphenyl cation **^{1,3}17** and for the two conformers of the triplet 2-methoxyphenyl cation **^{3}15** and **^{3}15′** as obtained by B3LYP/6-31G(d) calculations in MeCN bulk.

Table 5. Triplet *o*-, *m*-, and *p*-cloroanisoles (^{3}**1**−^{3}**3**). Calculated (in MeCN Bulk) Angles and Dihedral Angles at C_1, C_1−Cl Distance [$d(C_1-Cl)$], ESP Charges at the Chloro Atoms [$Q(Cl)$], and at C_1 [$Q(C_1)$], and Energy Difference between the Conformers (ΔE_{conf})

	$C_2C_1C_6$ deg	$C_1C_2C_3C_4$ deg	$d(C_1-Cl)$ Å	$Q(Cl)$	$Q(C_1)$	ΔE_{conf} kcal/mol[a]
^{3}1a	121.71	4.74	2.37	−0.567	−0.02	3.9
^{3}1a′	122.157	3.39	2.48	−0.581	0.023	
^{3}2a	126.51	−1.981	3.15[b]	−0.569	0.004	1.3
^{3}2a′	127.21	−1.58	3.10[c]	−0.574	0.017	
^{3}3a	122.55	4.72	2.45	−0.615	0.022	

[a] Sum of electronic energy and ZPVE. [b] The chlorine atom displaced at 2.60 Å from C_4. [c] The chlorine atom displaced at 2.60 Å from C_4.

The calculations were extended to the triplet excited states of chloroanisoles (**^{3}1a**−**^{3}3a**), since these may be involved in the cleavage leading to the cations (vide infra), again using a DFT approach. The resulting energies are compared in Table 5. The lowest energy geometries of some of these states are represented in Figure 3.

In these states the C−Cl bond was severely stretched and the chlorine atom was displaced out of the plane, “followed” by the respective carbon atom, with some loss of skeleton planarity and a dihedral angle of 2−5°. The C−Cl bond was weakened and indeed virtually broken both in the gas phase and MeCN bulk (see the C−Cl distance of ca. 2.4 Å in Table 5).

Further stretching of the bond (by 0.1 Å increments) showed that only a small energy increase (2−3 kcal/mol) was required for bringing the chlorine atom to infinity. This process hardly involved charge separation in the gas phase (charge on the chloro atom equal to ca. −0.2, see the case of **^{3}3a** in Figure 3b), where

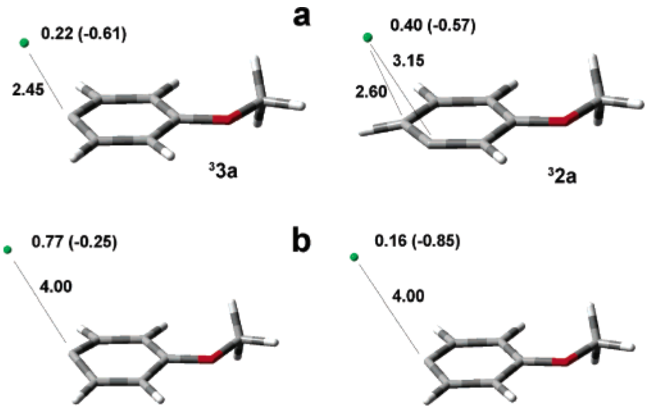

Figure 3. (a) Geometries, spin densities, and (in parentheses) ESP charges for triplet 4-chloroanisole ^{3}**3a** and 3-chloroanisole ^{3}**2a** from UB3LYP/6-31g(d) calculations in MeCN; (b) the same for ^{3}**3a** upon stretching of the C−Cl bond up to 4 Å in gas phase (left) and in MeCN (right).

the process had a clear homolytic character (0.77 spin on the Cl atom at 4 Å). On the contrary, in MeCN the process was essentially heterolytic (for ^{3}**3a** the charge at Cl was −0.85).

A noteworthy characteristic of the 3-methoxy derivative ^{3}**2a** was the displacement of the chlorine atom toward C_6. This led to an interaction with this atom [$d(C_6{-}Cl) = 2.6$ Å] that was stronger that than with C_1 [$d(C_1{-}Cl) = 3.1$ Å], thus giving some carbene character at C_1 and sp^3 character at C_6 (see Figure 3a, the C_6−Cl distance was far above the bonding length, though). The results with ^{3}**1a** were similar to those with ^{3}**3a**.

With the three chloroanisoles triplets, stretching of the C−Cl bond was accompanied by return to planarity, and in all of the cases the positively charged residue had practically the same geometry as the corresponding triplet phenyl cation.

Discussion

Photochemical Cleavage. The above data show a varied photochemical behavior for isomeric methoxyphenyl derivatives that however can be accounted for by a unitary proposal, as it will be shown in the following. The photoproduct distribution indicates a meta effect favoring solvolysis vs reduction. When the solvent is an alcohol, substitution of the Cl atom by an alkoxy group was the main process from **2a** (e.g., **6**/**4** = 1.5 in MeOH) and also acetonitrile acted as a nucleophile (**5**/**4** = 1). On the contrary, substitution had a smaller role with the para derivative **3a**, where reduction predominated (**8**/**4** = 0.25 in MeOH), and did not occur at all with ortho **1a** (**4** was the only product obtained in this case). Noteworthy, in polar solvents phosphates, **1b**−**3b** underwent substitution and reduction with very similar structure/medium dependence, thus supporting that common intermediates were involved in the photoreactions and resulted from the loss of either the chloro or phosphate group.

It appears that two kinds of photoprocesses are involved. In *apolar* media, the only process occurring is reduction, that is quite efficient with the chlorides **1a**−**3a** and negligible with the phosphates. This has been previously attributed to C−Cl homolysis from the triplet state:[8,13,14]

$$^3\mathrm{MeOC_6H_4Cl} \rightarrow \mathrm{MeOC_6H_4}^{\bullet} + \mathrm{Cl}^{\bullet} \qquad (1)$$

This fits with the weakening of this bond in ^{3}**1a**−^{3}**3a** evidenced by the present DFT analysis (see Figure 3, $d(C_1{-}Cl) \approx 2.5$ Å, rather than the bonding distance of 1.77 Å). Such cleavage is expected to occur with a rate constant of ca.1×10^6 s^{-1}, on the basis of the decay rate of the triplet transient measured by flash photolysis for ^{3}**3a** by Lemmetyinnen et al.[15] These authors found that the triplet was no more observed in MeCN and was substituted by a transient identified as the chloroanisole radical cation **3a**$^{\bullet+}$, conspicous in water-containing solutions (vide infra). Apparently, homolysis does not operate in polar solvents, and the triplet mainly undergoes physical decay rather than reaction. For the three chloroanisoles the quantum yield of reaction (Φ_r) in MeCN drops by a factor of 15−50 with respect to cyclohexane. On the other hand, Φ_r increases again by a factor of 10−30 in going from MeCN to methanol and trifluoroethanol up to 0.1−0.2. The V-shaped dependence of Φ_r on the solvent polarity (or better on the ion stabilizing power) well fits with the idea that a different (and faster) process sets in under such conditions, namely, heterolytic cleavage, similarly to what was observed with 4-chloroaniline:[16]

$$^3\mathrm{MeOC_6H_4Cl} \rightarrow \mathrm{MeOC_6H_4}^{+} + \mathrm{Cl}^{-} \qquad (2)$$

That photochemistry does not proceed from the singlet state is indicated by the fact that for the derivatives exhibiting fluorescence the parameters (Φ_F, τ_F, see Table 3) do not change significantly in the series of solvents considered, while Φ_r changes over 1 or 2 orders of magnitude. With the phosphates **1b**−**3b** the fluorescence rate k_f ($= \Phi_f/\tau_f$) is also independent of the position of the substituent ($k_f = (1.9 \pm 0.3) \times 10^7$ s^{-1}) and close to that measured for parent anisole (3×10^7 s^{-1}). A similar value is obtained for 4-chloroanisole **3a** ($k_f = 1.3 \times 10^7$ s^{-1}), while with the two other chlorinated derivatives the fluorescence is exceedingly weak. Some other decay path thus operates for ^{1}**1a** and ^{1}**2a**,[17a] but this does not hinder the reactions via the triplet. That isc is efficient with the present compounds, as in general for anisoles,[17b] also in polar media is indicated by the phosphorescence observed in EPA for all of the present reagents (except **1a**), and the viability of the triplet path is supported by the fact that sensitization by acetone leads in all of the cases to the same product distribution as direct irradiation.

Homolytic cleavage has no role with the corresponding arylphosphates, and the quantum yield of reaction of compounds **1b**−**3b** is at most ca. 0.01 in cyclohexane. The efficiency consistently grows with polarity, however, in a quite conspicuous way with the para-methoxy derivative **3b**, where it varies from 0.001 in C_6H_{12} to almost 0.3 in TFE.

Role of Phenyl Cations. Calculations show that indeed cleavage from the triplet chlorides and phosphates is possible and mimic the twofold reactivity with the results in vacuum, where the fragmentation is homolytic, and in MeCN bulk, where it is heterolytic for the three isomeric chloroanisoles considered

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(13) Da Silva, J. P.; Vieira Ferreira, L. F.; Ferreira Machado, I.; Da Silva, A. M. *J. Photochem. Photobiol., A* **2006**, *182*, 88.

(14) Protti, S.; Fagnoni, M.; Mella, M.; Albini, A. *J. Org. Chem.* **2004**, *69*, 3465.

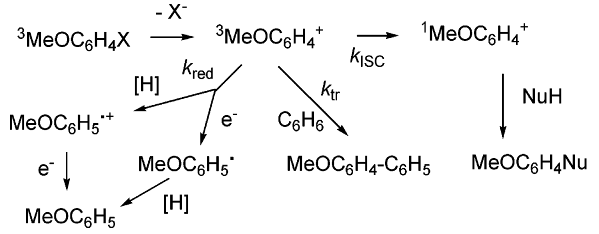
(15) Lemmetyinnen, H.; Konijnenberg, J.; Cornelisse, J.; Varma, C. A. G. O. *J. Photochem.* **1985**, *30*, 315.

(16) Freccero, M.; Fagnoni, M.; Albini, A. *J. Am. Chem. Soc.* **2003**, *125*, 1382.

(17) (a) The occurrence of a further decay from the singlet has been noted also for 3-fluoroanisole, see ref 7b. (b) The isc is the main path from the singlet in most anisoles, as observed in several cases, see for example, refs 7, 15, 18, and 19.

(18) Den Heijer, J.; Shadid, O. B.; Cornelisse, J.; Havinga, E. *Tetrahedron* **1977**, *33*, 779.

Scheme 4. Trapping of Singlet and Triplet Methoxyphenyl Cation



(see Figure 3). The latter mode of reaction leads to triplet cations **^{3}15**−**^{3}17**. The main chemical reaction of such species in solution is reduction to anisole via electron and H transfer. Previous studies with other chlorides, in particular 4-chloroaniline, suggested that the two steps may occur in either order (Scheme 4, left),[19] namely, either H abstraction to give 4-NH$_2$C$_6$H$_5^{•+}$ that is then reduced or electron transfer from the starting chloroaniline to give radical 4-NH$_2$-C$_6$H$_4^•$ and radical cation 4-NH$_2$C$_6$H$_4$-Cl$^{•+}$ as the intermediates. Aromatic radical cations are easily detected by flash photolysis, and previous detection of 4-MeOC$_6$H$_4$Cl$^{•+}$ (**3a**$^{•+}$) from **3a**[15] supports this mechanism.

Calculations predict a spin-dependent chemistry for phenyl cations, with the triplets *not* trapped by n nucleophiles.[19a] Triplet cations rather react with π-nucleophiles, as shown here by the formation of biphenyls **12**−**14** from all of the halides and phosphates in the presence of benzene. On the contrary, solvolysis to give products **6**−**9** is attributed to singlet cations **^{1}15**−**^{1}17**, predicted to be unselective electrophiles.[19a] This process occurs to some extent with the para derivative, and to a larger one with the meta isomer. Importantly, trapping by benzene occurs at the expenses *both* of reduction *and* of the substitution products, consistent with the idea that the photochemical reaction yields in all cases the triplet cation and it is the rate of ensuing isc that then determines the product distribution (see Scheme 4).

In fact, the singlet state of methoxyphenyl cation is markedly stabilized with respect to the triplet in the case of meta derivative **$^{3/1}$16**, while the two states are almost isoenergetic with para **$^{3/1}$17** (see Table 4 and Figure 4). Thus, reaction from the triplet cation competes with isc with meta and, to a degree, with the para isomer. The more ion stabilizing is the medium, the longer is the lifetime of the phenyl cation and the higher the probability of isc. This is indicated by the increasing role of solvolysis (Scheme 4, right) in the series CH$_3$CN < CH$_3$OH ≈ CF$_3$CH$_2$OH (apparently following the order of the ion stabilizing factors, $Y \approx -3.5$, -1.09, and 1.045,[20] counterbalanced in the last case by the poor nucleophilicity).

Competitive Trapping. The plots in Figure 1 give access to the rate ratios $k_{tr}/(k_{red} + k_{isc})$. Although phenyl cations have not been detected by flash photolysis, the rate of addition of 4-alkoxy (or hydroxy) phenyl cation to a π nucleophile (an alkene in water) has been estimated as $k_{tr} \approx 1 \times 10^8$ mol^{-1} s^{-1}.[19b] If, as it seem likely, the addition of both **^{3}16** and **^{3}17** to benzene occurs at a similar rate, the data in Figure 1 support that in TFE k_{isc} is 60 times as large with the former cation, where the process is markedly exothermic, than with the latter one (1×10^8 s^{-1} vs 1.7×10^6 mol^{-1} s^{-1}). Aschi et al. have shown that the minimum energy crossing point of S and T surfaces of some (4-substituted) phenyl cations is ca. 3 kcal mol^{-1} when the two states are isoenergetic,[21] as here with **17**, while it is negligible when either state is markedly stabilized (by some kcal mol^{-1}). Thus, successful trapping by a large enough benzene concentration shows that 3-methoxyphenyl cation (**16**) is initially formed in the triplet state, although in neat polar solvents, intersystem cross to the singlet (ground) state predominates and leads to solvolysis products. With **^{3}17**, isc is slower and competitive reduction in neat solvent and trapping by benzene have a larger role.

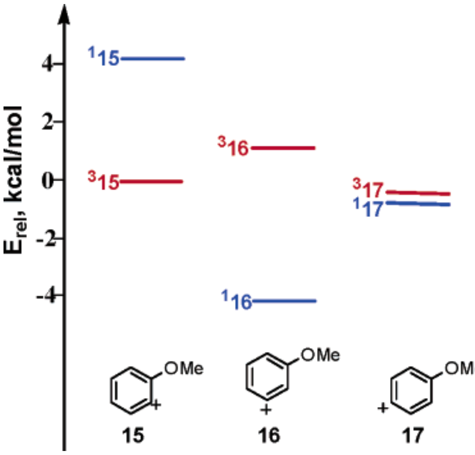


Figure 4. Relative energy of singlet and triplet methoxyphenyl cations.

The behavior of the ortho cation **$^{3/1}$15** is somewhat different. Reduction is virtually the only photoprocess in all of the solvents. In the presence of benzene, trapping is effective but never complete, and the slope in Figure 1 is less steep than with the para isomer. Since the triplet here is markedly below the singlet, isc to the latter state plays no role, and the low value of the $k_{tr}/(k_{red} + k_{isc})$ ratio is attributable to less effective trapping (small k_{tr}). Examination of the structure of the cation evidences that the conformer with the substituent toward C$_1$ (**^{3}15′**) is stabilized with respect to rotamer **^{3}15** (by 2.2 kcal/mol, see Table 4) because of hydrogen bonding involving the methyl group (see Figure 2).[22] It is reasonable to expect that hindering by the substituent makes a reaction with a relatively bulky nucleophile such as benzene inefficient, so that the rate constant decreases to $k_{tr} \approx 1 \times 10^7$ mol^{-1} s^{-1}, that is, an order of magnitude lower than with **^{3}17**.

A further aspect of the reactivity of these cations is fluoride abstraction from TFE to give **10**, observed when the 4-substituted ion **17** is generated from either the chloride or the phosphate. This reaction has been previously found in the decomposition of some phenyldiazonium salts.[23]

S versus T Methoxyphenyl Cations. Calculations show that triplet cations **^{3}15**−**17** differ little in energy, and all have a regular hexagonal structure (for details, see Supporting Information). These intermediates have a $\pi^5\sigma^1$ structure (see the formula below), as previously determined for parent triplet phenyl cation and some 4-substituted derivatives.[21,22,24] As a consequence, most of the charge is localized not at C$_1$, but on the carbon

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[19] (a) Guizzardi, B.; Mella, M.; Fagnoni, M.; Freccero, M.; Albini, A. *J. Org. Chem.* **2001**, *66*, 6353. (b) Manet, I.; Monti, S.; Fagnoni, M.; Protti, S.; Albini, A. *Chem.—Eur. J.* **2005**, *16*, 140.

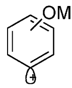
[20] Winstein, S.; Fainberg, A. H.; Grunwald, E. *J. Am. Chem. Soc.* **1957**, *79*, 4146; 5937.

[21] Aschi, M.; Harvey, J. N. *J. Chem. Soc., Perkin Trans. 2* **1999**, 1059.

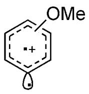
[22] For an analogous proposal on the stabilization by the methoxy group, see Filippi, A.; Lilla, G.; Occhiucci, G.; Sparapani, C.; Ursini, O.; Speranza, M. *J. Org. Chem.* **1995**, *60*, 1250.

[23] Canning, P. S. J.; McCrudden, K.; Maskill, H.; Sexton, B. *Chem. Commun.* **1998**, 1971.

bearing the methoxy group and on the substituent itself, independent of their position with respect to the divalent carbon (apart from the above-mentioned intramolecular $CH_3-C_1^+$ interaction in the ortho cation). Thus, the stabilizing effect due to the donation by the methoxy oxygen on the π^5 electron deficient system is exerted independently from the position, explaining the fact that the isomeric triplet cations all have the same energy (within 2 kcal/mol).

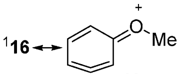


^{1}**15**-^{1}**17**



^{3}**15**-^{3}**17**

On the contrary, a marked positive charge at C_1 is apparent in singlet cations ($\pi^6\sigma^\circ$), justifying their strong and unselective electrophilic behavior. In these intermediates, the hexagonal structure is altered, with a puckering of C_1. The $C_2-C_1-C_6$ moiety has some character of a cumulate double bond, and the $C_3-C_4-C_5$ moiety has some character of an allylic carbocation. Therefore, donation from a methoxy group is more effective when the substituent is in position 3 (see formula **18**), as indicated by the shortening of the C−O bond (1.30 Å in cation ^{1}**16**, 1.31 in isomeric ^{1}**17**, 1.35 in anisole). This explains the peculiar stabilization of cation ^{1}**16** and the reversed S/T energetic order (Figure 4) with this isomer.



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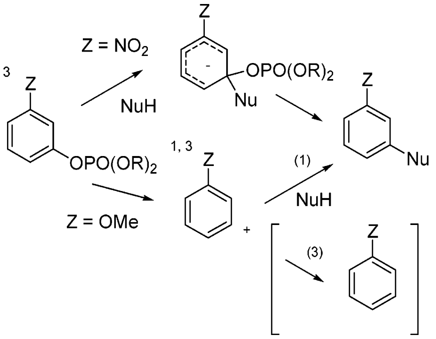
Conclusions. In conclusion, a unitary mechanism is proposed for the photochemistry of the three chloroanisoles and of the corresponding phosphates in polar solvents and involves a heterolytic S_N1 path. The efficiency of the photocleavage has no clear dependence on the substituent position, but there is a marked meta effect in the chemistry of the key intermediates, the phenyl cations, in the sense that the *m*-methoxy substituent stabilizes the singlet, making it the ground state. Thus, even if the triplet is formed first, isc is fast and is followed by solvent addition (resulting in overall solvolysis) with this isomer. This is an example of the characteristic unselective chemistry of singlet phenyl cations, which contrasts with the more selective triplet reactions predominating or exclusive with the other isomers.

The substituent orientation effect thus operates on the cation intermediate rather that on the primary photocleavage. Since electronic effects are transmitted to the ortho and/or para positions, one may have naively expected that the electron-withdrawing effect of the charge would have been better compensated for when the donating group is in those positions. However, both calculations and experiments clearly show that the meta substituted singlet is selectively stabilized. Thus, one can label this as a meta effect, although not involving the excited state, contrary to the cases discussed in the introduction. It is a peculiar, but coincidental, fact that a meta effect favoring solvolysis is observed both with *m*-nitrophenyl phosphate, because of the activation of the $S_N2(^3Ar)$ due to the enhanced positive charge at C_1 in the triplet of the reagent, and with *m*-methoxyphenyl phosphate, where, rather than the initial $S_N1(^3Ar)$ photoreaction, it is the isc of the intermediate cation that is affected (see paths 1 and 3 in Scheme 5).

Scheme 5. Photochemistry of *m*-Nitro- vs *m*-Methoxyphenyl Phosphate



Experimental Section

The photochemical reactions were performed by using nitrogen-purged solutions in quartz tubes and a multilamp reactor fitted with six 15 W phosphor coated lamps (maximum of emission 310 nm) for the irradiation. Chloroanisoles **1a**−**3a** are commercially available and were distilled before use. Phosphates **1b**−**3b** were obtained from the corresponding phenols[10,25] A sample of **5** was obtained from the corresponding aniline through a known procedure.[26] Ethers **4**, **6**, and **8**, **10** and phenol **11** were quantified by comparison with commercially available products. Product **9** was previously isolated and characterized.[14] The other photoproducts were recognized on the basis of elemental analysis and spectroscopic characterization. Details are reported as Supporting Information.

Calculations. Indication of the method used and optimized geometries are reported as Supporting Information.

Acknowledgment. Partial support of this work by MIUR, Rome, is gratefully acknowledged.

Supporting Information Available: Full experimental details of photoproducts, optimized geometries listed in Cartesian format, and energies calculated (B3LYP6-31G(d)) for triplet chloroanisoles **1a**−**3a** and for singlet and triplet methoxyphenyl cations **15**$^+$−**17**$^+$ (in gas phase and in MeCN bulk). This material is available free of charge via the Internet at http://pubs.acs.org.

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