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PHOTOCHEMISTRY OF AROMATIC COMPOUNDS

MECHANISM OF THE AMINE-ACCELERATED PHOTODEBROMINATION OF 5-BROMO-2-METHOXYPYRIMIDINE

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Abstract – Triethylamine accelerates the photodebromination of 5-bromopyrimidines, and much more so in methanol than in acetonitrile. The quantum yield in methanol is as high as 4, and additional data suggest that the amine-catalysed debromination is a photo-initiated free-radical chain reaction, the carrier being the $.CH_2OH$ radical; triethylamine acts as an electron donor in the initiation step and as a base catalyst in the chain reaction.

We have shown previously[1,2] that triethylamine accelerates the photodebromination of 5-bromo-2-methoxypyrimidine in polar solvents. We now report additional data on this system.

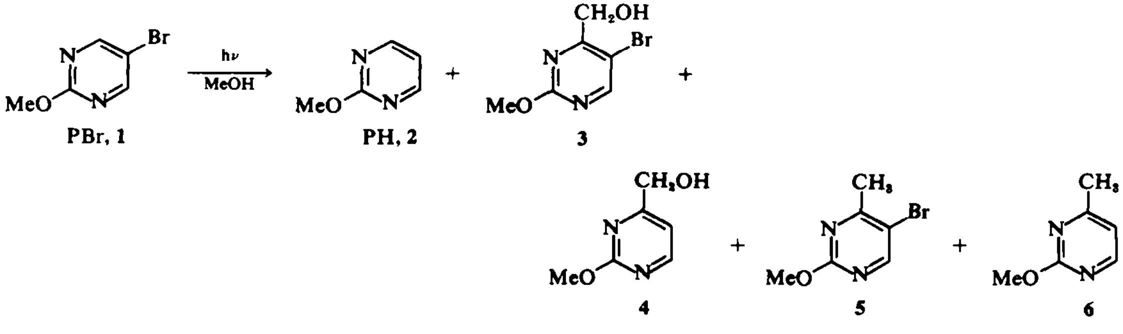
Quantum yields

(a) *In acetonitrile.* The quantum yield for disappearance of 5-bromo-2-methoxypyrimidine (PBr) in acetonitrile increases when triethylamine is added. The results are collected in Table 1. In this solvent, the only product formed is 2-methoxypyrimidine, and the quantum yield for disappearance of the starting material is the same as that for the formation of 2-methoxypyrimidine.

(b) *In methanol.* The irradiation of 5-bromo-2-methoxypyrimidine (PBr, **1**) in methanol yields, besides the dehalogenated pyrimidine (PH, **2**), solvent-incorporation compounds or structures derived from them (**3–6**). Preparative runs have shown[2] that these by-products are formed in small but detectable amounts when the concentration of starting material was around 10^{-2} M, but dropped sharply in more dilute solutions. To avoid kinetic complications arising from the formation of the by-products (**3–6**), the quantum yields were determined in more dilute solutions, some of them at $\sim 10^{-3}$ M, but mostly at $\sim 10^{-4}$ M. In these conditions, the quantum yields (defined as the ratio of the number of molecules transformed to the number of photons *absorbed*) for disappearance of starting material and formation of product are identical.

Despite of this precaution, the amine-catalysed photolyses in methanol showed unexpected complications, making the analysis of the kinetics very tedious and difficult. The main problem came from the observation that the rate of disappearance of PBr *increased* during a given run, this autocatalytic behaviour subsiding after variable conversions; further irradiation yields a constant and rather high quantum yield. The data are collected in Table 2.

The apparent autocatalysis cannot be ascribed to the accumulation of bromide ions, which have little effect even at high concentrations (Table 3), nor to the formation of triethylammonium ions, which actually depress the rate (Table 3). We found however that when a very small amount of air ($\sim 10^{-3}$ Torr) was admitted in the cell, the rate dropped sharply, and it required a fairly long irradiation time before the initial rate was resumed. This points to a very high sensitivity to small amounts of



PBr, **1** PH, **2** **3** **4** **5** **6** oxygen, and also explains why initial quantum yields are irreproducible. Oxygen apparently does not alter the rate of the uncatalysed reaction, since the quantum yield found in a thoroughly degassed solution and in a cell which was swept with nitrogen were the same within experimental error ($0{\cdot}1 \pm 0{\cdot}01$), whereas the degassing method has a dramatic influence on the rate of the catalysed reaction (Table 3).

It is also found that the quantum yield drops when the initial concentration of starting material is increased (Table 4), and that it rises for lower light intensities (Table 5).

Table 1. Influence of triethylamine on the quantum yield for the photodebromination of 5-bromo-2-methoxy-pyrimidine in acetonitrile

[PBr](M)	Et_3N(M)	ϕ
$2{\cdot}7\times10^{-4}$	—	$0{\cdot}09\pm0{\cdot}01$
$2{\cdot}7\times10^{-4}$	0·05	$0{\cdot}16\pm0{\cdot}02$
$2{\cdot}6\times10^{-4}$	0·1	$0{\cdot}24\pm0{\cdot}03$
$2{\cdot}6\times10^{-3}$	0·2	$0{\cdot}50\pm0{\cdot}03$
$2{\cdot}8\times10^{-4}$	0·2	$0{\cdot}46\pm0{\cdot}03$
$2{\cdot}5\times10^{-4}$	0·3	$0{\cdot}79\pm0{\cdot}03$
$2{\cdot}7\times10^{-4}$	0·4	$0{\cdot}90\pm0{\cdot}03$

Table 2. Quantum yields for the amine-catalysed photodebromination of 5-bromo-2-methoxypyrimidine in methanol

$[PBr]_0$	$1{\cdot}1\times10^{-3}$ M		$2{\cdot}2\times10^{-4}$ M		$2{\cdot}3\times10^{-4}$ M		$2{\cdot}2\times10^{-4}$ M		$2{\cdot}1\times10^{-4}$ M		$1{\cdot}2\times10^{-3}$ M	
$[Et_3N]_0$	$1{\cdot}1\times10^{-2}$ M		$1{\cdot}0\times10^{-2}$ M		0·19 M		0·19 M		0·20 M		0·20 M	
	% conv.	ϕ	% conv.	ϕ	% conv.	ϕ	% conv.	ϕ	% conv.	ϕ	% conv.	ϕ
	19	0·45	9	0·68	16	1·6	14	1·3	23	2·4	5	1·2
	25	0·46	17	0·68	28	1·6	28	2·0	38	3·5	25	3·1
	30	0·47	26	0·70	39	2·3	34	2·6	51	3·7	30	3·4
	35	0·48	40	0·67					63	3·9	44	3·5

Table 3. Influence of experimental conditions on the quantum yield of photodebromination of 5-bromo-2-methoxypyrimidine in methanol

$[PBr]_0$(M)	$[Et_3N]_0$(M)	Additive	% conv.	ϕ
$2{\cdot}7\times10^{-4}$	—	$Et_4N^+Br^-$, 0·19 M	10	0·24
$2{\cdot}1\times10^{-4}$	0·19	$Et_3NH^+Cl^-$, $1{\cdot}5\times10^{-4}$ M	26	1·49
			31	1·60
$2{\cdot}4\times10^{-4}$	0·19	$Et_3NH^+Cl^-$, 0·11 M	8	0·42
			13	0·56
$2{\cdot}2\times10^{-4}$	0·19	*a*	15	1·5
$2{\cdot}2\times10^{-4}$	0·19	*b*	7	0·15

[a] Vacuum degassed; [b] deoxygenated by N_2 bubbling.

Table 4. Concentration effects on the quantum yield in the presence of 0·01 *M* triethylamine

$[PBr]_0$(M)	$2{\cdot}20\times10^{-4}$	$1{\cdot}11\times10^{-3}$	$2{\cdot}23\times10^{-3}$
% conversion	10	10	10
Φ	0·68	0·50	0·35

Table 5. Influence of light intensity

I_0 (E/min)[a]	Irradiation time (hrs)	$I = I_0t$(E)	% 1	% 2	% 3	% 2/I
$2{\cdot}42\times10^{-6}$	1	$14{\cdot}5\times10^{-5}$	93·8	6·2	—	$4{\cdot}3\times10^4$
$1{\cdot}23\times10^{-6}$	4	$29{\cdot}6\times10^{-5}$	85·2	14·8	(traces)	$5{\cdot}0\times10^4$
$0{\cdot}65\times10^{-6}$	9	$35{\cdot}2\times10^{-5}$	75·8	22·2	2·0	$6{\cdot}3\times10^4$

The yields are measured by standardised VPC. $[PBr]_0 = 10^{-2}$ M; at such a high concentration, with $[Et_3N]_0 = 0{\cdot}2$ M, the induction period is very short, and the reported yields pertain to relative ϕ values. 1 = 5-bromo-2-methoxypyrimidine; 2 = methoxypyrimidine 3 = 5-bromo-4-hydroxymethyl-2-methoxypyrimidine.

[a] The light intensity refers to the full output of a HPK 125 W Philips mercury arc filtered through Pyrex.

DISCUSSION

The photodebromination of 5-bromo-2-methoxypyrimidine in methanol catalysed by triethylamine has a high quantum yield, is inhibited by traces of oxygen, and the quantum yield depends on the light intensity. All these features point to a free radical chain reaction. The following kinetic scheme leads to conclusions which are in agreement with the experimental results:

	rate	step
$PBr + h\nu \rightarrow PBr^{*}$	I_a	(0)
$PBr^{*} \rightarrow PBr$	$k_1[PBr^{*}]$	(1)
$PBr^{*} \rightarrow P\cdot + Br\cdot$	$k_2[PBr^{*}]$	(2)
$PBr^{*} + N \rightarrow PBr^{\cdot-} + N^{\cdot+}$	$k_3[PBr^{*}][N]$	(3)
$P + sH_2 \rightarrow PH + sH\cdot$	$k_4[P\cdot][sH_2]$	(4)
$Br\cdot + sH_2 \rightarrow HBr + sH\cdot$	$k_5[Br\cdot][sH_2]$	(5)
$PBr^{\cdot-} \rightarrow P\cdot + Br^{-}$	$k_6[PBr^{\cdot-}]$	(6)
$N^{\cdot+} + sH_2 \rightarrow NH^{+} + sH^{\cdot}$	$k_7[N^{\cdot+}][sH_2]$	(7)
$sH\cdot + N \rightarrow s^{\cdot-} + NH^{+}$	$k_8[sH\cdot][N]$	(8)
$s^{\cdot-} + NH^{+} \rightarrow sH\cdot + N$	$k_9[s^{\cdot-}][NH^{+}]$	(9)
$s^{\cdot-} + PBr \rightarrow s + PBr^{\cdot-}$	$k_{10}[s^{\cdot-}][PBr]$	(10)
$sH\cdot + sH\cdot \rightarrow HssH \text{ or } s + sH_2$	$k_{11}[sH\cdot]^2$	(11)

In this scheme, P· is the 5-(2-methoxypyrimidyl) radical, sH· is the solvent-derived radical ·CH_2OH, $s^{\cdot-}$ is the formaldehyde radical-anion $CH_2O^{\cdot-}$, s is formaldehyde and $N^{\cdot+}$ is the amine radical-cation.

Step 3 is an electron transfer from amine to excited substrate; the feasibility of this process is ascertained by electrochemical studies which are given later (Table 6). This electron transfer leads to the bromopyrimidine radical-anion which decomposes to a pyrimidyl radical and a bromide ion in step 6. The equilibrium shown by steps 8 and 9 emphasizes the ability of triethylamine to act as a base[3] towards the .CH_2OH radical, and is also the origin of the rate-depressing effect of triethylamine salts; such a proton abstraction from hydroxyalkyl radicals and the ensuing electron transfer to ground state substrate (step 10) have been used by Backlin and Sherman[4] to explain the high quantum yields found in the photodehalogenation of halobenzenes is isopropanol.

The quantum yield derived from this mechanism is

$$\Phi = \frac{k_2 + k_3[N]}{k_1 + k_2 + k_3[N]} + \frac{k_8 k_{10}[N][PBr]}{k_9[NH^{+}] + k_{10}[PBr]} \times \sqrt{\frac{k_2 + k_3[N]}{k_{11} I_a (k_1 + k_2 + k_3[N])}}$$

where the second term represents the contribution from the chain process. It is this chain reaction, summarized by

$$PBr^{-} \rightarrow P\cdot + Br^{-} \qquad (6)$$
$$P^{\cdot} + sH_2 \rightarrow PH + sH\cdot \qquad (4)$$
$$sH\cdot + N \rightleftharpoons s^{\cdot-} + NH^{+} \qquad (8,9)$$
$$s^{\cdot-} + PBr \rightarrow PBr^{\cdot-} \qquad (10)$$

which is the origin of the high quantum yield. This expression indeed shows that the quantum yield increases with added amine or at lower light intensity.

In order to explain the drop in quantum yield for high initial concentrations of PBr, we must introduce the hydroxymethylations as a supplementary chain-breaking process. The effect on the rate might be quite detectable, although only less than trace amounts of hydroxymethylated compounds would be formed. If we assume that the bromopyrimidine

Table 6. Electrochemical properties of pyrimidines

Compound	DMF[a] $-E_{1/2}$(V)	DMF[a] $-E_{=}$(V)	CH_3CN[a] $-E_{1/2}$(V)	CH_3CN[a] $-E_0$(V)	ΔE_{00}(eV)[b]	$-E_0 - E_{00}$(eV)[b]
5-Bromo-2-dimethylaminopyrimidine	1·52	—	1·56	1·60	3·2	−1·6
Pyrene	1·52	1·52	—	—	3·33	−1·81
Anthracene	1·41	1·41	—	—	3·31	−1·90
Naphthalene	1·90	1·90	—	—	3·99	−2·09
2-Methoxypyrimidine	1·75	—	1·76	1·77	4·0	−2·2
5-Bromo-2-methoxypyrimidine	1·33	*d*	1·33	*d*	3·9	−2·6[e]
5-Promo-2-phenylpyrimidine	1·17	—	1·19	1·22	3·9	−2·7

[a] $E_{1/2}$ is the polarographic half-wave potential *vs* the mercury pool, 0·1 M tetrabutylammonium iodide. E_0 is the redox potential determined by cyclic voltametry (0·8 to 200 H); we are very grateful to Dr. G. Anthoine for his very kind and active cooperation in measuring these potentials.

[b] In the case of the pyrimidines, ΔE_{00} is the value at the long wavelength tail where ϵ is about 10.

[c] The exothermicity of the process is equal to the values quoted in this column, corrected for the (constant) oxidation potential of the amine and the (small and practically constant) $e^2/\epsilon a$ term. The more negative the value of $-E_0 - \Delta E_{00}$, the more probable the photoinduced electron transfer.

[d] The reduction of 5-bromo-2-methoxypyrimidine is irreversible in the whole frequency range (0·8–200 Hz). It is however reasonable to assume that it should reduce at a less negative potential than 2-methoxypyrimidine.

[e] Calculated with $E_{1/2}$ instead of E_0.

and 2-methoxypyrimidine add irreversible hydroxymethyl radicals, and taking into account the negligible amounts of incorporation products (which means that at any time $[PBr] + [PH] = [PBr]_0$), we may add the following steps:

$$\begin{array}{lll} PBr\,(\text{and } PH) + sH\cdot & \rightarrow & PBrsH^{\cdot}\,(\text{and } PHsH^{\cdot}) \\ & & \text{rate} = k_{12}[PBr]_0[sH\cdot] \\ PBrsH\cdot \quad + sH^{\cdot} & \rightarrow & PBr\,(sH_2) + s \\ PHsH\cdot \quad + sH\cdot & \rightarrow & PH(sH_2) + s \end{array}$$

The corresponding rate expression is then:

$$\Phi = \frac{k_2 + k_3[N]}{k_1 + k_2 + k_3[N]} + \frac{k_8 k_{10}[N][PBr]}{k_9[NH^+] + k_{10}[PBr]} \times \left[\frac{1}{k_{11}}\sqrt{\frac{k_{12}^2[PBr]_0}{4I_a^2} + \frac{k_{11}(k_2 + k_3[N])}{I_a(k_1 + k_2 + k_3[N])}} - \frac{k_{12}[PBr]_0}{2k_{11}I_a}\right]$$

Although rather complicated, this expression shows that in the absence of added amine salt, *i.e.* $k_9[NH^+] \ll k_{10}[PBr]$, the quantum yield will drop at higher initial concentrations of PBr, and that the amount of solvent incorporation products should increase.

We conclude that:

(a) The photo-induced electron transfer from amine to excited bromopyrimidine is probably the initiation step of the reaction. This transfer should indeed be equally efficient in methanol and in acetonitrile, which have similar dielectric constants (MeOH: 32; MeCN: 35), but less so in isopropanol ($\epsilon = 18{\cdot}3$); it was actually found that the quantum yield in isopropanol ($[PBr]_0 = 2{\cdot}3 \times 10^{-4}$ M, $[Et_3N] = 0{\cdot}19$ M) is only 0·26 for 15% conversion. In a different case, it was found that pyrene is photoreduced to 4,5-dihydropyrene in methanol in the presence of 0·5 M Et_3N + 0·5 M NaOH much more efficiently than with 1M NaOH.[5] It appears thus that electron transfers from amines can play a major role in the photoreduction of aromatic compounds.

(b) The basicity of the amine towards the hydroxyalkyl radical is of importance in triggering the chain reaction; this explains why N,N-dimethylaniline is less efficient than triethylamine in the photoreduction of pyrene.[5]

(c) When a hydrogen atom is removed from acetonitrile, the resulting radical is not able to be undergo a proton abstraction and converted to an active species. This is most probably the reason why the amine-induced photodebromination in this solvent is not a chain reaction. Our data in acetonitrile are however too scanty to allow any further elaboration on the mechanism.

Feasibility of the photo-induced electron transfer

Our suggestion that triethylamine acts as an electron donor towards the photoexcited pyrimidine requires that this process must be exoenergetic. The change in partial molar free enthalpy $\Delta G°$ for the reaction

$$PBr^* + N \rightarrow PBr^{\cdot -} \cdots\cdots N^{\cdot +}$$

is given by(6–7)

$$\Delta G° = E(D/D^+) - E(A/A^-) - \Delta E_{00}(A) - e^2/\epsilon a \quad [1]$$

where $E(D/D^+)$ is the oxydation potential of the donor, $E(A/A^-)$ is the reduction potential of the acceptor, $\Delta E_{00}(A)$ is the energy of the 0–0 band of the lowest electronic transition of the acceptor and $e^2/\epsilon a$ is the electrostatic interaction between the ions formed in a medium of dielectric constant ϵ and at a distance a apart.

The electrochemical oxydation of aliphatic amines[8] in acetonitrile and dimethylsulphoxide is totally irreversible, so that the correct value of $E(D/D^+)$ is not known. It has been found however that these amines do quench the fluorescence of aromatic hydrocarbons by transfering an electron.[6, 9] In Table 6 we compare the relevant electrochemical and spectroscopic data of a few pyrimidines with the corresponding values for aromatic hydrocarbons whose fluorescence is quenched by amines at diffusion-controlled rates.

The gas phase spectrum of 5-bromopyrimidine shows a weak, well structured n → π* absorption at the long wavelength tail; in solution in methanol, this band is strongly blue-shifted and appears only as a shoulder on the very strong π-π* transition. In the case of 2-methoxy-5-bromopyrimidine and 2-dimethylamine-5-bromopyrimidine this shoulder has completely disappeared and we feel safe in assuming that the lowest excited state of our pyrimidines is π → π* in nature.

The multiplicity of the excited state involved in the electron transfer is not known. The bromopyridines, like most monocyclic bromo-aromatics, show luminescence neither at room temperature nor at 77°K, and the actual lifetimes of the excited singlet or triplet states cannot be estimated. The use of singlet excitation energies in Eq[1] implies that it is the lowest excited singlet state which is accepting the electron. The sequence of the heterocyclics in Table 6 will nevertheless be retained if the singlet–triplet energy separation is fairly constant in the series.

The data of Table 6 show that an electron transfer from triethylamine to most of the photo-excited pyrimidines is as exoenergetic as the transfer to excited naphtalene, and thus diffusion-controlled. 5-bromo-2-dimethylaminopyrimidine is however a borderline case and, interestingly, this compound shows the least amine-enhanced photodebromination.

EXPERIMENTAL

Quantum yields. 2×10^{-4} and 2×10^{-3} M solns of 5-bromo-2-methoxypyrimidine were irradiated in quartz cells 5 cm and 1 cm pathlength respectively. The cells were fitted with a side-arm holding spectrophotometric quartz cuvettes 1 cm and 0·1 cm thickness; the solns were degassed by numerous freeze-pump-thaw cycles. During the irradiations, the solns were vigorously stirred with a glass-coated iron rod actuated by a fast-rotating magnet. The transparency of the cell walls was carefully checked before and after every run. Conversions were monitored by UV spectroscopy (Cary 14 and Unicam SP 1800); for the runs containing triethylamine (freshly distilled from KOH and kept under N_2), the spectra were run against a reference cell containing the same concentration of amine. It was checked that the addition of triethylamine has absolutely no effect on the absorption spectrum of the pyrimidines. The samples were irradiated with the 296–297 nm doublet and the continuum up to 302 nm from a Super Pressure Osram HBO 200 W mercury arc selected by a High-Intensity Bausch & Lomb grating monochromator. The intensity of the incident light was measured with the potassium ferrioxalate actinometer;[10] the maximum light output was of the order of 10^{-8} E/min falling on an area approximately 3 cm^2.

In most experiments, all the light was absorbed; when this was not the case, or when the products started to absorb appreciably, appropriate corrections were made to calculate the amount of light absorbed by the substrate. Methanol Merck "für Analyse" and acetonitrile Merck spectroscopic grade were used as such.

Polarography. Polarograms were recorded with a Metrohn Polarecord E261 appatatus. A hammer knocking on the capillary imposed a 0·8 sec lifetime to the drop. The potentials are measured against a mercury pool serving as the reference electrode. Dried and purified N_2 was bubbled through the soln for at least 20 min before recording; the supporting electrolyte was always 0·1 molar tetrabutylammonium iodide freshly recrystallised from EtOAc. The dimethylformamide was dried over K_2CO_3 and distilled under reduced pressure in an atmosphere of N_2.

For cyclic voltammetry (0·8 to 200 Hz), a Hewlett-Packard 202A triangular wave generator was used; the I=f(E) curves were photographed with a Polaroid camera attached to a Hewlett-Packard 141A oscilloscope.

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