PHOTOINDUCED REACTIONS OF BENZO[*b*]PHENAZINE§

Elisa Fasani, Mariella Mella, and Angelo Albini

Dip.Chimica Organica, v.Taramelli 10, 27100 Pavia, Italy

Abstract- While the photochemistry of azines is generally dominated by hydrogen abstraction from $n\pi^*$ states, benzo[*b*]phenazine has low-lying $\pi\pi^*$ states and undergoes both [4+4] dimerization (the main product is the less hindered biplanemer (**2**), but a small amount of the alternative dimer (**3**) is also formed) and self-sensitized photo-oxygenation to yield the *endo*-peroxide (**5**) (better obtained with an added sensitizer). Compound (**5**) undergoes decomposition by O-O bond cleavage to yield the quinone (**4**) and the diol (**6**).

The photochemistry of polynuclear azines is rather limited in scope. Most reported reactions involve inter- or intramolecular hydrogen abstraction by $n\pi^*$ excited states,[1,2] e.g. reduction or reductive dimerization of acridine,[3-5] fragmentation of 2-alkylquinoline[6] etc. This contrasts with the large variety in the photochemistry of other heterocycles, e.g. ring rearrangement in monocyclic azines, ring rearrangement as well as addition of alkenes and of singlet oxygen with azoles.[1]

Extending the conjugation is expected to lower the $\pi\pi^*$ states with respect to the $n\pi^*$ states, and therefore a change in the photochemical behaviour may be expected when the lowest states take a $\pi\pi^*$ character. Looking for a suitable model to demonstrate this principle, we turned to benzo[*b*]phenazine (**1**), in view of the fact that the reported thermal chemistry of this molecule (in particular, easy oxidation, electrophilic substitution, and Diels-Alder addition in positions 6, 11)[7,8] indicates a behaviour more similar to polycondensed arenes than to azines. Indeed, we report here that **1** offers the first examples of [4+4] photocycloaddition and of singlet oxygen addition in the class of azines.

RESULTS AND DISCUSSION

Irradiation (λ>500 nm) of a 4×10^{-3} M solution of **1** in deaerated dichloromethane led to the formation of a white precipitate. This was highly insoluble in most organic solvents, showed the same elemental analysis of the starting material and a molecular peak twice the mass of **1** in the mass spectrum. It was unaltered by refluxing in toluene and likewise by heating the crystals up to 310°C, when it melted and decomposed yielding back **1**.

§ This paper is dedicated to Prof. Rolf Huisgen on occasion of his 75th birthday.

The ^{1}H-nmr spectrum showed two AA'BB' systems and a methylene singlet at δ 5.2. These data identified this compound as a [4+4] dimer of **1** (a "biplanemer"),[9] similar to those obtained from anthracene and its derivatives[10] (Scheme 1). One of the two AA'BB' systems, at *ca.* δ 7.7, could be attributed to the quinoxaline protons, the other one at *ca.* δ 7.0 to the benzene protons; noteworthy, the BB' part of the benzene absorption was unusually shielded (δ 6.8). This is in accordance with formula (**2**), since in this case these protons undergo a specific shielding effect by the ring current of the quinoxaline ring sitting in front of it.

When the irradiation was carried out in isopropanol, a white precipitate formed again. This was washed with CH_2Cl_2 and yielded a tiny amount of a relatively more soluble product, while the main part of the solid was identical to compound (**2**). The more soluble product showed very similar properties to compound (**2**), and in particular the ^{1}H-nmr spectrum was qualitatively identical, except for the fact that the benzene BB' absorption was less shielded with respect to **2** (δ 7.0). Thus, this material was recognized as the alternative biplanemer (**3**), where all C-H bonds are on the periphery of the molecule, and none sits over the center of an aromatic ring.

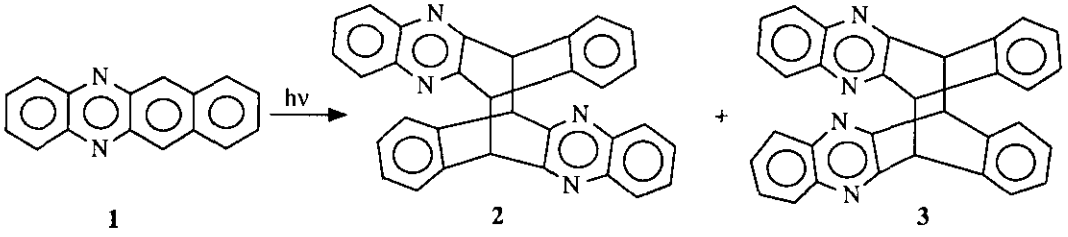
Irradiation (visible light) of crystalline **1** led to no detectable reaction after several days.

Table 1. Products from the irradiation (λ>500 nm) of benzo[*b*]phenazine.

Solvent	Conditions	Time	Work-up	Products (%)
CH_2Cl_2	Ar purged	4 h	a	**2**(60)
i-PrOH	Ar purged	7 h	a	**2**(57), **3**(14)
CH_2Cl_2	O_2 satd	1 h	b	**2**(10), **4**(22), **6**(5)
9:1 CH_2Cl_2-MeOH	O_2 satd[c]	20 min	b	**4**(45), **6**(20)
MeOH	O_2 satd[c]	20 min	a	**5**(44)

---

a. chromatography. b. filtration of the precipitate. c. in the presence of Rose Bengal.

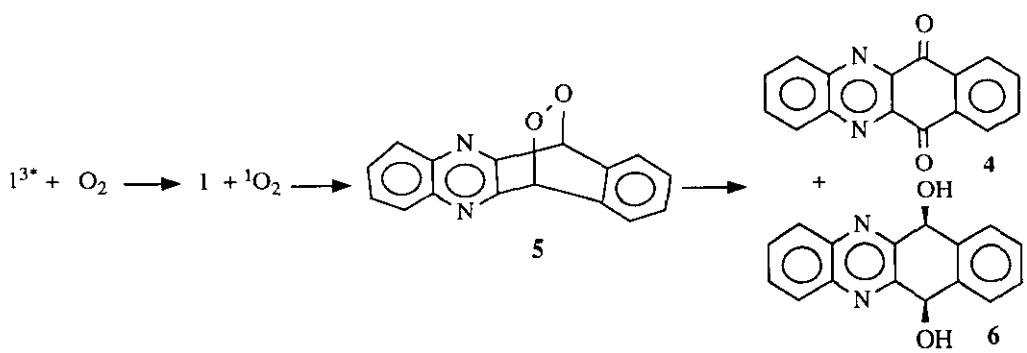


1 **2** **3**

Scheme 1.

Irradiation (λ>500 nm) of an oxygen saturated CH_2Cl_2 solution of **1** caused a much faster reaction than in deaerated solution. Dimer (**2**) was a minor product in this case. Chromatography of the raw photolysate gave a

fraction containing an ill-characterized material as well as the quinone (**4**), identical to a sample prepared by thermal oxidation of **1**,[8] as the main individual product. This led to suspect the involvement of singlet oxygen in the reaction. Indeed, irradiation of **1** in the presence of Rose Bengal in either 9:1 CH_2Cl_2-MeOH or in neat MeOH (light absorbed mainly by the dye) followed by chromatographic separation gave a product distribution similar to the previous case. Work-up was simpler in the experiment in neat MeOH, since here a white precipitate formed during irradiation and showed to be a single product. When pure this material was stable at room temperature, although it became greenish after some days, and less stable in solution where a green untractable precipitate formed in some hours. Characterization by elemental analysis and spectroscopy, showed this to be the *endo*-peroxide (**5**); in particular, in the ^{1}H-*nmr spectrum*, the singlet at δ 6.3, corresponding to a ^{13}C-nmr signal at δ 81 was assigned to the bridgehead methine. Brief refluxing in toluene gave **4** as a main product; by chromatography on a flash silica gel column part of this product eluted unchanged, and part was transformed in a *ca.*1 to 1 mixture of **4** and of the dihydroxy derivative (**6**) taken to have *cis* stereochemistry in view of its origin. It is thus clear that **5** is the main product from **1** both by direct irradiation in oxygen saturated solution and by sensitized photo-oxygenation, although it is liable to decomposition in solution or during work-up. Indeed, the ^{1}H-nmr spectrum of the raw photolysate before chromatography showed that **5** was the main product in all experiments in the presence of oxygen (Scheme 2).



Scheme 2.

In conclusion the photochemical behaviour of benzo[*b*]phenazine is at a variance with what observed with other azines, including phenazine[5,11] and benzo[*a*]phenazine.[12] In the other cases both singlet and triplet lowest excited states are $n\pi^*$ (or the $n\pi^*$ state is so near to the $\pi\pi^*$ state that it "mixes" with it), and the chemistry is more or less efficient hydrogen abstraction.[1,2] On the contrary **1**, although it has high-lying n_N

orbitals, as shown e.g. by the easy formation of *N*-oxides,[13] has low-lying $\pi\pi^*$ states both as far as the singlet and the triplet are concerned. Although detailed photophysical studies are not available at present, it is fully reasonable that the (fluorescing)[13] singlet is involved in a [4+4] cycloaddition *via* an excimer. The less hindered biplanemer (**2**), is, as one may expect, by far the main product. However, polarity has some effect on the preferred excimer conformation(s), and in *i*-PrOH a minor amount of the more hindered dimer (**3**) is formed. No such dimerization is known for azines, but acridizinium salts, where the excited states are necessarily $\pi\pi^*$, are known to dimerize, a reaction suggested to occur *via* a non emitting excimer.[14]

On the other hand, the triplet shows no radicalic character (no hydrogen abstraction even in *i*-PrOH), and only transfers energy to oxygen, and thus causes self-sensitized oxidation in the presence of oxygen. The formation of the *endo*-peroxide (**5**) from ground state (**1**) and $^1O_2$ fits with the previously mentioned reactivity of this azine with dienophiles.[7] It may be noted that, while oxygen sensitization by acridine triplet has been previously documented,[15] addition of singlet oxygen to an azine is reported only for strongly activated substrates such as *meso*-diphenyl substituted benzoquinolines and benzoquinazolines.[16] Compound (**5**), like anthracene *endo*-peroxide,[17] and unlike its derivatives carrying a stabilizing substituent at the bridgehead positions, does not undergo retrocycloaddition to **1** + O_2, but rather decomposes through O-O bond cleavage. The following evolution of the thus formed oxy diradical may lead to a complex mixture, but e.g. on silica gel follows a simple pattern with disproportionation to yield the quinone (**4**) and the diol (**6**).

EXPERIMENTAL

Benzo[*b*]phenazine (**1**) was prepared according to the reported procedure[18] and purified by chromatography on neutral alumina eluting with toluene and recrystallization. 6,11-Dihydrobenzo[*b*]phenazine-6,11-dione (**4**) was prepared by oxidation of (**1**) as previously reported.[8] ^{1}H-Nmr and ^{13}C-Nmr spectra were recorded on a Bruker AC300 spectrometer in $CDCl_3$ solutions and chemical shifts were reported in δ; ir spectra were measured by means of a Perkin Elmer 180 instrument on KBr dispersions and are reported in cm^{-1}. Merk 60 silica gel was used for column chromatography.

Irradiations were carried out in an immersion well apparatus containing 100 ml solution by means of a 125W medium pressure mercury arc (Philips HPK) through a yellow glass filter ($\lambda > 500$ nm).

Irradiation in deaerated CH_2Cl_2. A solution of compound (**1**) (100 mg, 0.4 mmol) in CH_2Cl_2 (200 ml) was flushed for 20 min with argon, and then irradiated while maintaining a slow stream of argon through the solution. The white precipitate formed was filtered and washed with 10 ml CH_2Cl_2 to yield 60 mg (60%) dimer (**2**), mp 313°C, with decomposition (tlc showed that **1** was the only product present after melting). Anal. Calcd for $C_{16}H_{10}N_2$: C, 83.45, H, 4.38, N, 12.15. Found: C, 83.5; H, 4.5; N, 12.0; . Mass spectrum 460 m/z, 230 m/z (base peak). ^{1}H-Nmr, 5.2 (s, 2H), 6.8 and 7.2 (AA'BB' system, J_{AB}=7 Hz, $J_{AB'}$=3 Hz, 4H), 7.6 and 7.8 (AA'BB' system, J_{AB}=7 Hz, $J_{AB'}$=3 Hz, 4H). Ir 3045, 2980, 1500, 775, 760 cm^{-1}. The filtrate contained some starting material, but compound (**3**) was not detected.

Irradiation in deaerated i-PrOH. A solution of **1** (70 mg, 0.27 mmol) in *i*-PrOH (200 ml) was irradiated as above. The white precipitate was filtered and washed with 20 ml CH_2Cl_2. The precipitate was identical to compound (**2**) (40 mg, 57%), while evaporation of the filtrate gave product (**3**) as a white solid (10 mg, 14%), mp 275°C. Anal. Found C, 83.2, H, 4.4, N, 12.4. ^{1}H-Nmr, 5.2 (s, 2H), 7.0 and 7.1 (AA'BB' system, J_{AB}=7

Hz, $J_{AB'}$=3 Hz, 4H), 7.4 and 7.8 (AA'BB' system, J_{AB}=7 Hz, $J_{AB'}$=3 Hz, 4H). ^{13}C-Nmr, 53.5 (CH), 127.2 (CH), 128.1 (CH), 128.3 (CH), 129.2 (CH), 139.9, 140.0, 156.6. Ir, 2980, 1500, 765, 755, 740 cm^{-1}.

Irradiation in oxygen saturated CH_2Cl_2. A solution of **1** (100 mg, 0.4 mmol) was flushed with oxygen for 10 min and irradiated as above. A precipitate formed, was filtered and showed to be identical with **2** (10 mg, 10%). The solution was evaporated and chromatographed to give a fraction (10 mg) of a white solid turning to green after some hours, and products (**6**) (6 mg,5%) and (**4**) (25 mg, 22%). The ^{1}H-nmr spectrum of the filtrate before chromatography showed that compound (**5**) (see below) was the main product. Quinone (**4**) was identical to a sample prepared by thermal oxidation as above. ^{1}H-Nmr, 7.95 and 8.5 (AA'BB' system, J_{AB}=7 Hz, $J_{AB'}$=3 Hz, 4H), 8.05 and 8.5 (AA'BB' system, J_{AB}=7 Hz, $J_{AB'}$=3 Hz, 4H); ir, 1690, 1310, 1210, 990, 770, 715. *cis*-6,11-Dihydro-6,11-dihydroxybenzo[*b*]phenazine (**6**) was recrystallized from nitroethane yielding white crystals with a bluish luster, mp 309-311°C. Anal. Calcd: C, 72.71, H, 4.38, N, 10.60. Found: C, 72.5, H, 4.4, N, 10.7. ^{1}H-Nmr, 4.7 (2H, exch), 5.85 (s, 2H), 7.4 and 7.8 (AA'BB' system, J_{AB}=7 Hz, $J_{AB'}$=3 Hz, 4H), 7.8 and 8.1 (AA'BB' system, J_{AB}=7 Hz, $J_{AB'}$=3 Hz, 4H). Ir, 3400, 1195, 1130, 1045, 760, 740.

Sensitized irradiation. A solution of **1** (100 mg) and Rose Bengal (20 mg) in either 9:1 CH_2Cl_2-MeOH (200 ml) or in neat MeOH (200 ml) was flushed with oxygen and irradiated as above. In the first case the solution was evaporated, extracted with toluene (20 ml) and evaporated again. ^{1}H-Nmr of the residue showed **5** to be the main product. Chromatography gave the products reported in Table 1. In the second case the precipitate formed, was filtered and washed with some MeOH to yield the *endo*-peroxide (**5**) (50 mg, 44%), mp 285-90°C (darkening and decomposition at 140°C). Anal.Calcd for $C_{16}H_{10}N_2O_2$: C, 73.27, H, 3.84, N, 10.68. Found: C, 73.0, H, 3.6, N, 10,5; ^{1}H-Nmr, 6.3 (s, 2H), 7.4 and 7.5 (AA'BB' system, J_{AB}=7 Hz, $J_{AB'}$=3 Hz, 4H), 7.8 and 8.01(AA'BB' system, J_{AB}=7 Hz, $J_{AB'}$=3 Hz, 4H). ^{13}C-Nmr, 81.0 (CH), 125.0 (CH), 129.2 (CH), 129.3 (CH), 130.3 (CH), 135.9, 141.1, 151.5. Ir, 1500, 1460, 895, 838, 760.

Irradiation in the solid state. A finely ground sample of crystalline (**1**) (50 mg) was evenly spread on a 10 x 5 cm glass slide and illuminated by two 15W phosphor-coated lamps with emission in the visible for 2 days. The material was dissolved in CH_2Cl_2 and no change was detected by chromatographic and spectroscopic techniques.

AKNOWLEDGMENT

Partial support of this research by MURST and CNR is gratefully acknowledged.

REFERENCES

1. O. Buchardt, Photochemistry of Heterocyclic Compounds, John Wiley & Sons, New York, 1976.

2. D. G. Whitten, in ref. 1, p. 524.

3. D. G. Whitten and Y. J. Lee, *J .Am. Chem. Soc.*, 1971, 93, 961.

4. G. Vermeersch, J. Marko, N. Febvay-Garot, S. Caplain, and A. Lablache-Combier, *J. Chem. Soc., Perkin Trans. 2*, 1984, 2027.

5. C. D. Buckley and K. A. McLauchlan, *J. Photochem.*, 1984, 27, 311. S. Yamaguchi and N. Hirota, *J. Phys. Chem.*, 1984, 88, 4631.

6. F. R. Stermitz, C. C. Wei, and C. M. O'Donnel, *J. Am. Chem. Soc.*, 1970, 92, 2745. S. Prathapan, S. Loft,

and W. C. Agosta, *J. Am. Chem. Soc.*, 1990, 112, 3940.

7. J. A. Van Allan, R. E. Addel, and G. A. Reynolds, *J. Org. Chem.*, 1962, 27, 2873.

8. J.A.Van Allan, G.A.Reynolds, and R.E.Addel, *J.Org.Chem*, 1963, 28, 520

9. H. Okamoto, M. Kimura, K. Satake, and S. Morosawa, *Bull. Chem. Soc. Jpn*, 1993, 66, 2436.

10. D. O. Cowan and R. L. Drisko, Elements of Organic Photochemistry, Plenum Press, New York, 1976, ch. 2. H. D. Becker, *Chem. Rev.*, 1993, 93, 145. J. B. Birks, J. H. Appleyard, and R. Pope, *Photochem. Photobiol.*, 1963, 2, 493.

11. G. A. Davis, J. D. Gresser, and P. A. Carapellucci, *J. Am. Chem. Soc.*, 1971, 93, 2179. S. M. Japar and E. W. Abrahammson, *J. Am. Chem. Soc.*, 1971, 93, 2179. A. Albini, G. Bettinetti, M. DeBernardi, and S. Pietra, *Gazz. Chim. It.*, 1970, 100, 700. M. N. Usachena, I. V. Drozdenko, and I. A. Dolidze, *Teor. Eks. Khim.*, 1983, 19, 592.

12. G. W. Suter, U. P. Wild, K. Brenner, and Z. Ruziewicz, *Chem. Phys.*, 1985, 98, 455.

13. D. Bergmann, R. Kraessig, F. Kummer, W. Seiffert, and H. Zimmermann, *Ber. Bunsen. Ges. Phys. Chem.*, 1971, 79, 564.

14. J. Bendig, B. Geppert, and D. Kreysig, *J. Prakt. Chem.*, 1978, 320, 739. C. K. Bradsher, L. E. Beavers, and J. H. Jones, *J. Org. Chem.*, 1957, 2, 1740.

15. A. A.Gorman, I. Hamblett, and M. A. J. Rodgers, *J. Am. Chem. Soc.*,1984, 106, 679.

16. K. Gollnick and G. O. Schenck, in J. Hamer, Ed., 1,4-Cycloaddition Reactions, Academic Press, New York, 1967, p. 255.

17. J. Rigaudy, J. Baranne-Lafont, A. Defoin, and N. K. Cuong, *Tetrahedron*, 1978, 34, 73.

18. O. Hinsberg, *Liebigs Ann. Chem.*, 1901, 319, 257.

Received, 9th May, 1994