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A NOVEL PHOTOCHEMICAL RING CONTRACTION OF 11a-METHYLPTEROCARPANS+

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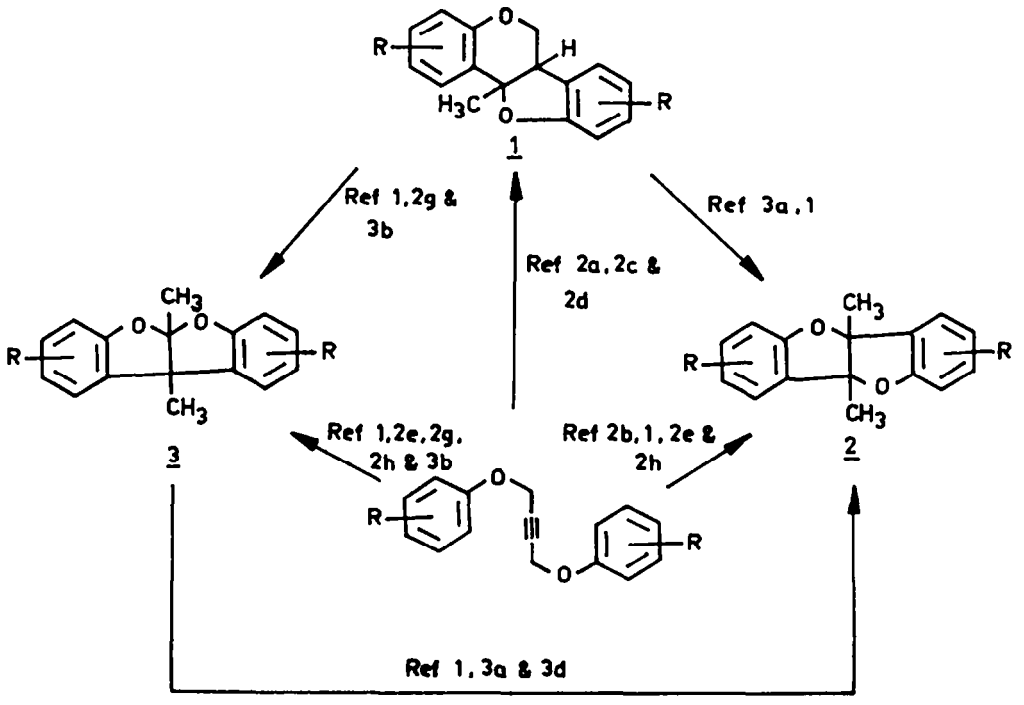
Abstract - A novel photochemical ring contraction of 6H-(benzofuro)(3,2-c)(1)11a,6a-dihydro-11a-methylbenzopyrans, 1 or shortly, 11a-methylpterocarpans to the respective 4b,9b-dihydro-4b,9b-dimethylbenzofuro(3,2-b)benzofurans 2 is reported. This transformation of 1 ⟶ 2 is envisaged to proceed through a mechanism involving the intermediacy of 6. An unusual acceleration of this photochemical rearrangement by bases has been observed.

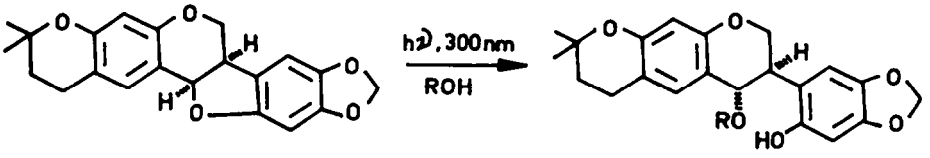
Previous publications from our laboratory[1] and elsewhere[2a-2h] have demonstrated the variety of transformations that ensue on the thermolysis of 1,4-diaryloxybut-2-ynes in high boiling solvents (Vide scheme 1).

SCHEME 1



The high propensity of 6H-(benzofuro)(3,2-c)(1)11a,6a-dihydro-11a-methyl-benzopyrans or shortly, 11a-methylpterocarpans 1 to undergo ring contractions in presence of acidic reagents[2g,3a], in polyethyleneglycol at 270°C[1] and under mass spectral conditions[1], suggested a strong potential for an interesting study of the photochemistry of these compounds. Further impetus to take such a study came from the disclosures on the photolysis of natural pterocarpans by Rall et al.[4a,4b] who observed the formation of the isoflavan derivatives as outlined in scheme 2.

SCHEME 2



Results and Discussion

Irradiation of a 10^{-3} molar methanolic solution of 2-8-dimethyl-11a-methyl-pterocarpan 1a[2a,2d] using a 300 nm. light source for 40 hrs. and a quartz vessel led to the formation of a solid product, mp 174°, in 78% yield. The product was identified as 4b,9b-dihydro-4b,9b,3,8-tetramethylbenzofuro(3,2-b)benzofuran 2a, on the basis of its analytical and spectral data and by comparison and mixed melting point determination with the authentic sample[3b]. This transformation was found to be general and yields were good[5]. Strikingly the photolysis of the 2,8-dichloropterocarpan 1f was slow (Table 1). It is interesting to note that

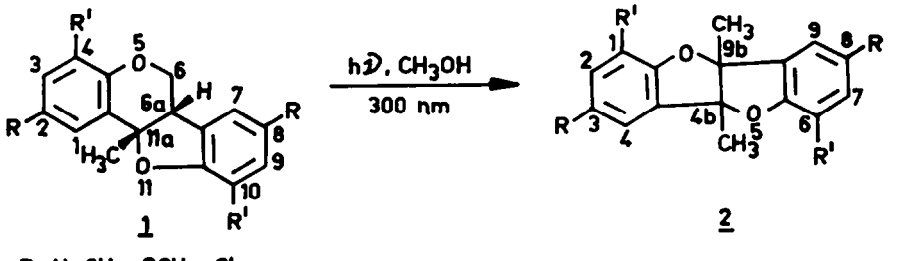
Table 1. Photolysis of 11a-methylpterocarpans 1[a]

S.No.	Starting compound	R	R^1	Product	R	R^1	mp°(lit.mp°)	Yield %
1.	1a	CH_3	H	2a	CH_3	H	174(174)[3b]	78
2.	1b	Cl	H	2b	Cl	H	207(207)[2b]	65
3.	1c	OCH_3	H	2c	OCH_3	H	144-145(145)[2b]	80
4.	1d	H	H	2d	H	H	125-126(126)[3b]	72
5.	1e	H	CH_3	2e	H	CH_3	202-203(203)[2b]	76
6.	1f	H	Cl[b]	2f	H	Cl	226-228(228)[2b]	50

a. The irradiation time is 40 hrs. and solvent is methanol.

b. In this case the irradiation time is 60 hrs.

photolysis of totally different substrates, viz., anthracene endoperoxides also lead to the formation of 2[3c,3d].



1

R=H, CH_3, OCH_3, Cl

2

With a view to get some insight into the mechanism of this novel photochemical ring contraction, the photolysis of 1a was investigated in various solvents like MeOH, C_6H_6, EtOAc, t-butanol, cyclohexane and acetic acid. The photoreaction is faster in polar solvents such as methanol and slower in non polar solvents such as cyclohexane. Another notable feature is that the reaction course is not altered by the nature of the solvent employed. The irradiation of 1a was carried out in the presence of added acids to see whether the reaction is faster than photolyses under neutral conditions and acid catalysed thermal ring contraction reactions. Unexpectedly, the acid does not seem to have any significant effect either on the reaction course or on the rate, under photolytic conditions.

The photolysis of 1a was investigated in the presence of bases with a view to find out whether the ring contraction proceeded through the intermediacy of any o-allylphenol and its subsequent cyclisation either by a (1,5)homosigmatropic shift or by an acid catalysed cyclisation. Since o-allylphenols are known to lead to dihydrobenzofurans under thermal and photochemical conditions[6,7], we initially reasoned out that added bases would convert any such o-allylphenolic intermediate that is formed, into its conjugate base, viz., phenoxide ion and thus would enable its isolation and identification since o-allylphenoxide cannot undergo cyclisation either thermally or by a 1,5-homosigmatropic shift pathway.

When a 10^{-3} molar methanolic solution of 1a, containing ten molar equivalents of sodium methoxide was irradiated for 10 hrs, the starting material disappeared completely and furnished 2a in 82% yield as the sole product. Work up of the alkaline extract did not yield any product. The significant rate acceleration (40 hrs in neutral methanol compared to 10 hrs, in the presence of sodium methoxide) was rather unexpected, particularly in view of the neutral nature of the substrate and non availability of any acidic proton that can be abstracted by sodium methoxide under such conditions. When 1a was treated with sodium methoxide in the dark under similar conditions, there was no reaction and the starting compound was recovered fully, thus indicating this reaction to be a photochemical one. The limiting concentration to obtain a perceivable base effect was found to be three molar equivalents in the case of sodium methoxide. This study was extended to a few other bases like, Et_3N and t-butoxide, but the photolysis of 1a in NaOMe/MeOH was found to be the fastest. The photolysis of the other 11a-methylpterocarpans in the presence of sodium methoxide in methanol was found to be similarly fast.

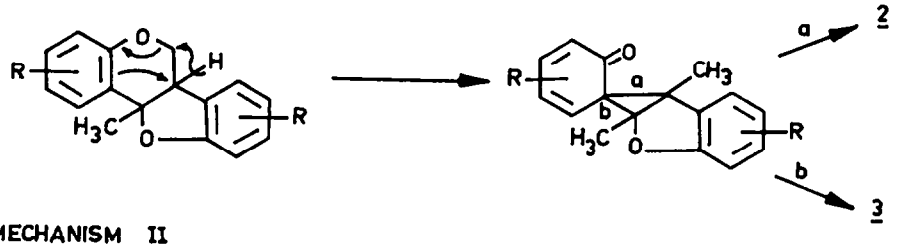
A search into organic photochemistry literature indicated only a few examples of base catalysis of photoreaction of neutral substrates[8]. However the photolyses of enolisable ketones in presence of sodium methoxide have been well documented in literature[9]. A more thorough search of literature revealed an interesting report by Kitamura et al.[10] on the photochemical behaviour of sodium allylphenoxides (ortho, meta and para) compared to those of the respective allylphenols. A striking difference was observed in the reactivity as well as in the course of the reaction. The remarkable higher photoreactivity of allylphenoxides, especially that of o-allylphenoxide was ascribed to the efficiency of intramolecular electron transfer. From these observations it was clear that a base sensitive intermediate was involved in the phototransformation 1 $\longrightarrow$ 2 and that this intermediate is converted to 2 more rapidly in the presence of the base, compared to in the absence of the base.

Mechanistic investigations

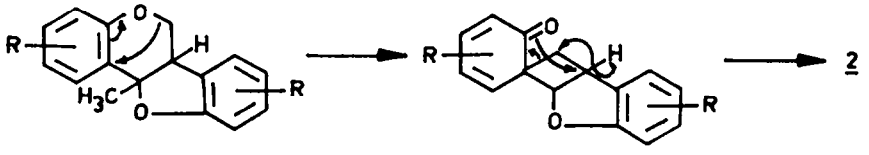
Several mechanisms (Vide Scheme 3) were considered to rationalise this photochemical transformation, on the basis of literature reports. Mechanism II is based on the photolysis of dihydrobenzopyran[11a,11b] and mechanism I is based on the photolysis of dihydrobenzopyran and photochemical furan ⇌ acyl cyclopropenone interconversion. Mechanism III is based on the photolysis of natural pterocarpans[4a,4b] and mechanisms IV and V are based on the photolysis of o-allylphenols and o-allylphenoxides[7,10].

SCHEME 3

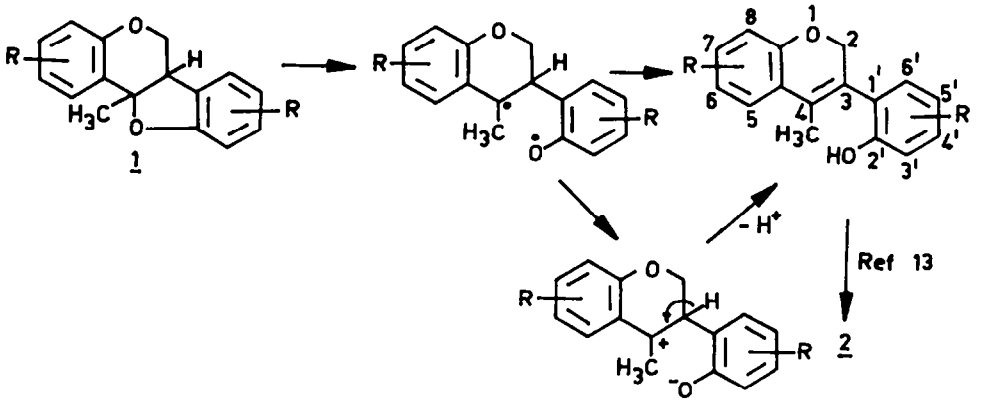
MECHANISM I



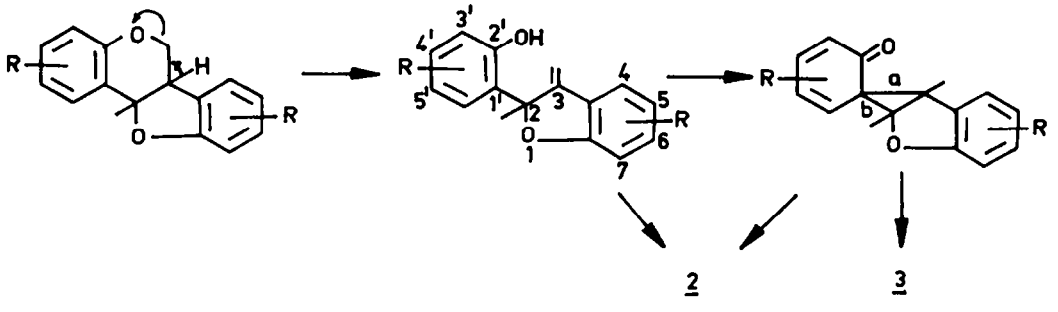
MECHANISM II

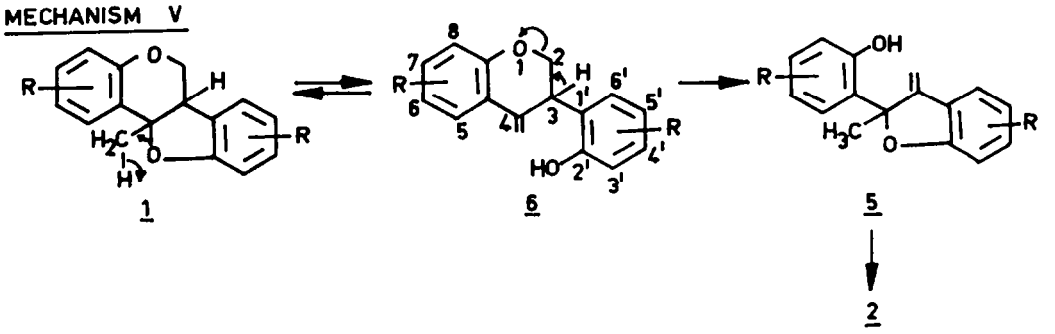


MECHANISM III



MECHANISM IV





These mechanisms can be broadly classified into those involving non-phenolic intermediates and those involving distinct phenolic intermediates. With a view to trap acyl cyclopropane or acyl cyclobutane intermediates, if any, involved in the transformation of 1 ⟶ 2, the photolysis of 1a was carried out in n-butylamine as the solvent as well as the trapping reagent[12]. In the event, it led to the formation of only 2a and none of the trapped adducts.

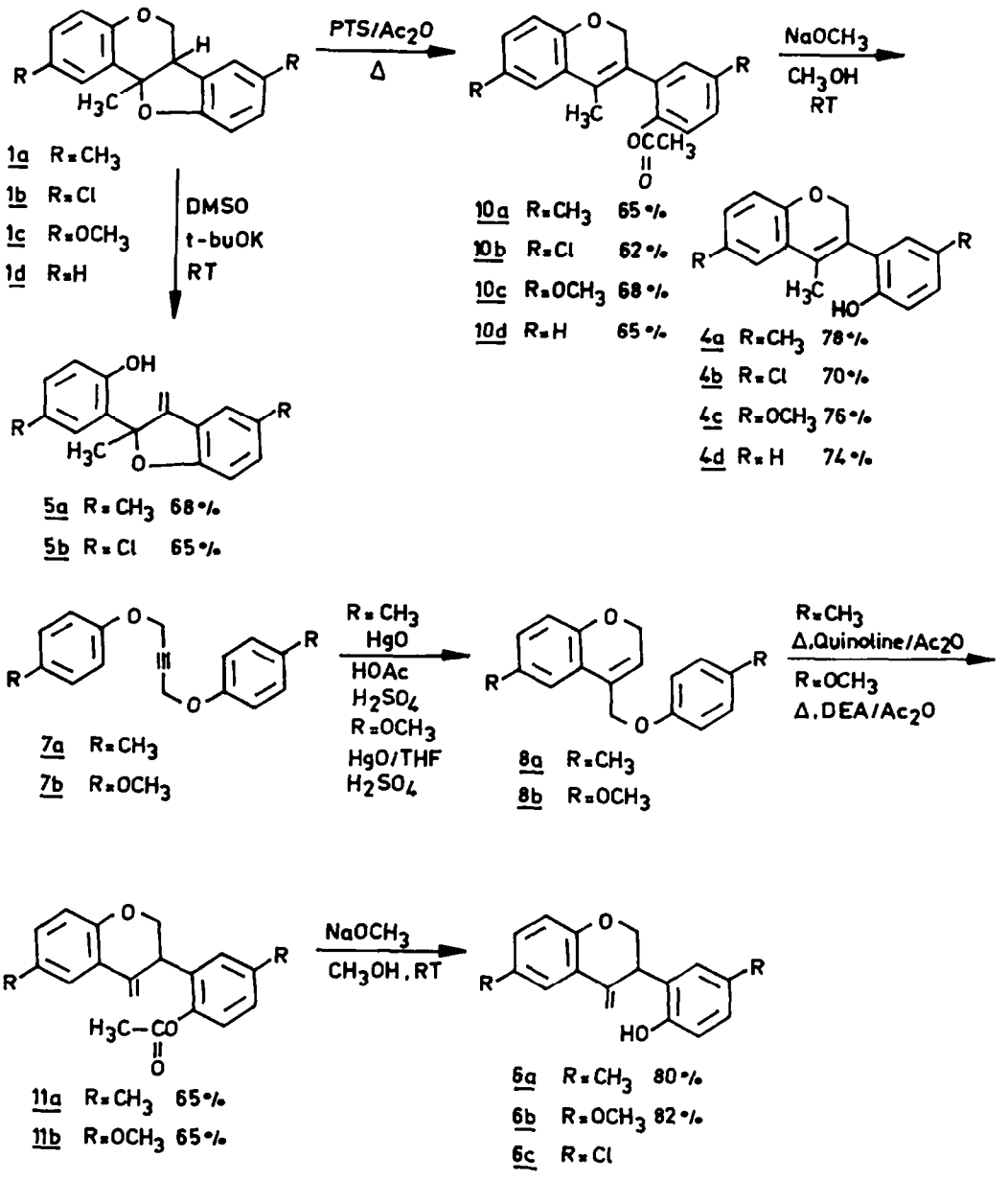
Further, to distinguish between these two mechanistic types, photolysis of 6a-deutero-11a-methylpterocarpan 13 was planned. While mechanisms I and II envisage the shift of the H at the 6-a position to the 6-c position, this hydrogen is either lost to the medium or is transferred to one of the oxygens, according to the other three mechanisms. The synthesis of 13 was accomplished as follows. Mercuric II ion mediated cyclisation of 1,4-di(4-methylphenoxy)-but-2-yne 7a in acetic acid-d_1 and sulphuric acid-d_2 (catalytic amount) afforded the 3-deutero chromene 9 as a solid mp.74-75°, in 60% yield[13a]. From its NMR spectrum the deuterium incorporation was found to be 78-80%. Rearrangement of this 3-deuterochromene 9 in refluxing N,N-diethylaniline for 3 hrs. furnished the required 6a-deuteropterocarpan 13 as a white solid, mp.140-142, in 60% yield[13b]. The deuterium incorporation in this product 13 was found to be 80% from its ^1H NMR and mass spectrum.

Irradiation of 13 in methanol using 300 nm light source for 40 hrs. led to the formation of the undeuterated benzofuro(3,2-b)benzofuran 2a in 78% yield as indicated by the mass spectrum (M^+ 266) and NMR spectrum. On the basis of this finding, mechanisms I and II have been eliminated.

The suspected phenolic intermediates, viz., 4-methyl-3-(2-hydroxyphenyl)-chrom-3-enes, 4a-4d, 2-(2-hydroxyphenyl)-2-methyl-3-methylenedihydrobenzofurans, 5a and 5b, and 3-(2-hydroxyphenyl)-4-methylenedihydrobenzopyrans, 6a and 6b, were synthesised as outlined in Scheme 4 and their photochemical behaviour was investigated in detail to arrive at the most plausible mechanism among the remaining three, i.e., mechanisms III, IV and V.

The preference displayed by the pterocarpans to undergo rupture of the furan ring in the presence of acidic reagents[14a,14b] and of the pyran ring in the presence of strong bases[14a,2e], has been exploited in the present instance for the preparation of the required phenolic compounds 4a-4d and 5a and 5b. Thus exposure of the 11a-methylpterocarpans 1a-1d respectively to the action of acetic anhydride in the presence of p-toluenesulphonic acid at reflux temperature afforded the corresponding acetates, 10a-10d[15] in 60-68% yield as viscous liquids which have been characterised by UV,IR,NMR and Mass spectra. Treatment of the crude acetates 10a-10d with sodium methoxide in methanol at room temperature for a period of 4 to 6 hrs. furnished the respective isoflavenes 4a-4d[15] in 70-80% yield.

SCHEME 4



Reaction of 1a with potassium t-butoxide in dimethylsulfoxide at room temperature afforded the methylenedihydrobenzofuran 5a as gum in 68% yield[16]. Compound 5b was prepared similarly from 1b by the action of potassium t-butoxide in dimethylsulfoxide in 65% yield.

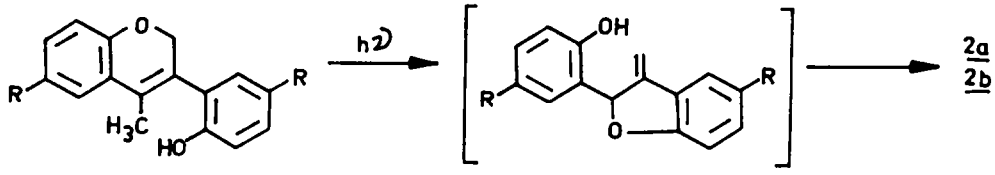
Claisen rearrangement of 8b[2g] in *N,N*-diethylaniline at reflux temperature in the presence of acetic anhydride for 6 hrs. furnished the acetate 11b[17] in 65% yield as a viscous liquid after purification by column chromatography over alumina, without any contamination by the endocyclic isomer. However attempts to

obtain 11a under similar conditions from the rearrangement of 8a either gave rise to the 4-methylisoflavene 10a or to a mixture of 10a and 11a. After investing considerable efforts, we found out that the use of quinoline in the place of N,N-diethylaniline afforded the desired exomethylene acetate 11a in 65% yield, after a column chromatographic purification over basic alumina. Treatment of the acetates 11a and 11b respectively with sodium methoxide in methanol at room temperature for 6 hrs. yielded the desired products 6a and 6b as gums in 65% yield.

Photolysis of 4a in methanol using 300 nm light source for 10 hrs. led to the formation of 2a in 70% yield, as reported earlier by us[15]. This transformation was complete in 2 hrs. when 4a was irradiated in methanolic solution in the presence of 10 equivalents of sodium methoxide. The photolysis of 1b was investigated in greater detail using HPLC and FT-NMR analyses.

The retention times of 1b, 2b, 4b and 5b on reverse phase microsil-18 column (300 x 5 mm) using a solvent system of 90% acetonitrile-10% water were found to be 3 min. 6 sec., 3 min. 42 sec., 2 min. 54 sec. and 2 min. 42 sec. respectively. When the photolysis of 4b in methanol was monitored through HPLC under the above mentioned conditions, it clearly indicated the formation of 5b by giving rise to the peak with retention time of 2 min. 42 sec. Mixed injection with authentic sample of 5b further confirmed this. One could see the gradual decrease in the concentration of the chromene 4b and build up of the intermediate 5b over a period of 4-6 hrs. of irradiation, and subsequent formation of the final product 2b (Scheme 5). It may be mentioned here that the retention time of 6c was found to be same as that of 5b under the above conditions of analysis. However the FT-NMR analysis and comparison with authentic mixtures of 4b and 5b, and 4b and 6c[18], eliminated this possibility of 6c being the intermediate in the above instance and clearly confirmed the involvement of 5b as the intermediate.

SCHEME 5



4a R = CH_3
4b R = Cl

5a R = CH_3
5b R = Cl

When a solution of 4b in benzene-d^6 [NMR δ values (C_6D_6) 1.2 (s, 3H), 3.7 (m, 2H), 5.2-5.9 (m, ArH)] taken in a quartz NMR tube was irradiated with 300 nm light and the progress of this photolysis reaction monitored by FT-NMR, formation of signals due to the exomethylene protons of the 5b (at 4.1 and 4.6 ppm in C_6D_6) were clearly seen. One could see the signals characteristic of the isoflavene 4b, the methylenedihydrobenzofuran 5b and the final product 2b (at 0.9 and 1.3 ppm in C_6D_6 due to 2b), in the FT-NMR spectrum recorded after two hours of irradiation. The signals due to the exomethylene protons of 5b gradually disappeared giving rise to more of the signals of 2b in 15 hrs. time in benzene-d_6. All these compounds, 1b, 2b, 4b, 5b and 6c could easily be distinguished from NMR and

showed distinct non overlapping signals with which they could be identified. Considerable upfield shift of signals was observed in benzene-d_6 compared to deuterochloroform.

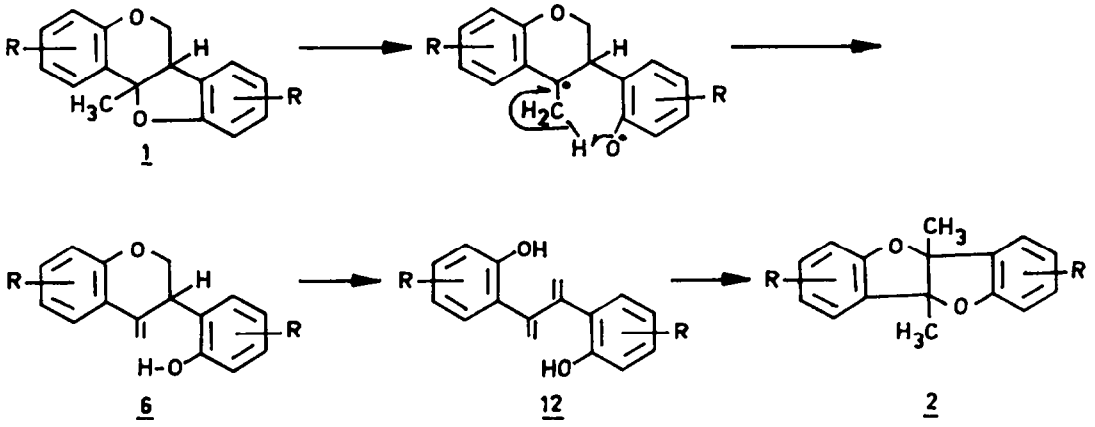
Irradiation of 5a and 5b in methanol or in benzene yielded the respective benzofuro(3,2-b)benzofurans 2a and 2b within 6 hrs. in 80% yield whereas in the presence of sodium methoxide in methanol the photolysis of 5a was complete in 2 hrs. In parallel dark reactions, under basic conditions, the starting material 5a was recovered. In neutral conditions in dark, cyclisation of 5a to 2a was observed to take place over a period of 35 hrs. to 48 hrs.

In the light of these findings, photolysis of 6a was studied in detail, as in this case an additional possibility prevails, viz., the isomerisation of the exomethylene double bond to the endocyclic position, leading to 4a which is known to undergo this photochemical transformation to 2a[15]. The irradiations were carried out in methanol and also in dry benzene. The reaction was complete in 15 hrs. in benzene and in 10 hrs. in methanol and afforded a solid product in both the cases, melting at 172-174° which is identical in all respects with an authentic sample of 2a. As described before, the progress of this photolysis was also carefully followed by FT-NMR. The NMR analysis of the photolysis reaction mixture of 6a [NMR δ values (C_6D_6) of 6a, 3 (s, 2H), 3.9 (s, 1H), 4.4 (s, 1H), 5-6 (m, ArH)] in benzene at earlier reaction periods indicated the formation of 1a [NMR δ values (C_6D_6) of 1a, 2.3 (s, 1H, bridgehead H), 2.8-3.1 (m, OCH_2), 5.6-6.7 (m, ArH)] in addition to the formation of the product 2a. At the end of 3 hrs. the ratio of 6a:1a:2a was 80:15:5 and after 6 hrs. the ratio was 60:20:20 and finally after 10 hrs., the ratio was 25:10:65. At no instance was there any evidence for the formation of the chromene 4a. These observations eliminate the possibility of 4a being formed as an intermediate in the photochemical transformation of 6 ⟶ 2.

From these experimental findings, it was clear that all the three mechanisms, viz., III, IV and V are pertinent in the photochemical ring contraction of 1 ⟶ 2. In the light of these observations, the photolysis of 1b was followed both by HPLC and FT-NMR. The follow up of the photolysis of 1b in methanol by HPLC (see experimental for details) showed a peak with retention time of 2 min. 42 sec. which could be due to either 5b or 6c and its subsequent decay, leading to the increase in the intensity of the peak with retention time of 3 min. 42 sec., characteristic of the final product 2b. The peaks due to 4b was not seen at all at any stage of the HPLC analysis in this reaction. The photolysis of 1 ⟶ 2 in deuterobenzene as solvent was then followed by FT-NMR over a period of time. Before the start of the actual analysis, authentic sample mixtures of 1b, with the exomethylenedihydrobenzofuran 5b, and the isoflavene 4b were made and the instrument conditions were standardised upto a detection level of 1% of any of these suspected intermediates. Analysis of the photolysis reaction mixture of 1b at different intervals of time did not show any evidence for the intermediacy of 4b and 5b. The signals characteristic of 4b and 5b were not at all observed at any stage during the analysis. On the other hand, the NMR spectrum of the photolysis reaction mixtures at earlier intervals showed new signals attributable to the exomethylene protons of 6c, (3.9 and 4.4 in C_6D_6) apart from the signals due to the starting compound 1b and the final product 2b. When the reaction was followed by CW NMR the intermediate 6c could not be detected, indicating the presence of extremely low concentration of this intermediate and its high photoreactivity and rapid conversion to 2b.

On the basis of the above data, the photochemical ring contraction 1 ⟶ 2 can be rationalised as outlined in Scheme 6. Further evidence for the mechanism was obtained by carrying out the large scale photolysis of 1 in dry benzene. The product after work up, was identified as 6.

SCHEME 6



One could speculate a 7-atom transition state for the formation of the intermediate 6 over the 5-atom transition state which would lead to the isoflavene 4 from the initially formed diradical. It is likely that steric factors and statistical factors may favour the abstraction of methyl hydrogen over that of the benzylic methine hydrogen by the phenoxide radical. At present, there is no evidence from our work for the butadiene intermediate 12 and it is purely a speculation. However, this hitherto unknown class of 2,3-di-(2-hydroxyphenyl)butadienes 12 can be expected to be highly photoreactive[19] and that is perhaps the reason for our failure to detect them in the photochemical transformation of 1 ⟶ 2. While, this photochemical reaction has to involve a multiphoton process, we have not yet looked into the photon count or the quantum yield aspects. Also, the origin of the acceleration of this photochemical transformation brought out by bases, particularly in the first step is not fully understood.

To our knowledge, this appears to be one of the few instances, where a base has been found to accelerate the rate of a photochemical reaction of a neutral substrate. This reaction also demonstrates the dramatic substituent effect brought out by the 11a-methyl group in the photolysis of pterocarpans.

Acknowledgement

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EXPERIMENTAL

General considerations:

Melting points reported are uncorrected. Ultraviolet spectra were recorded in methanol (spectrograde) using Beckman DGBT model and Shimadzu-240 model. Infrared spectra were recorded on Perkin-Elmer-257 and 1310 model instruments. The NMR spectra were taken using Varian XL-100 and EM-390 spectrometers, with $CDCl_3$ as solvent and tetramethylsilane (TMS) as the internal standard. The chemical shifts reported are in δ scale. Mass spectra were taken using Varian Mat CH-7 spectrometer.

1. Irradiation of 11a-methylpterocarpan 1 in methanol: General Procedure: Photoreactions were carried out in Rayonet Photoreactor (New England Ultraviolet Company). The 10^{-3} molar solution of 1 was purged with argon for 20 minutes and irradiated for 40 hrs. using 300 nm lamps in a quartz vessel. After the completion of the reaction, the solvent was removed under reduced pressure and the product 2 was purified by recrystallisation, using methanol. The structure of 2 was confirmed by spectral data and comparison with authentic sample[1]. For all the photochemical reactions, parallel dark reactions were carried out. In all these cases starting material was recovered fully (Table 1).

2. Irradiation of 11a-methylpterocarpans in presence of sodium methoxide: General Procedure: The compound 1 (100 mg.) was dissolved in methanol (100 ml.) containing ten equivalents of sodium methoxide (200 mg.) and the solution was purged with argon for 20 minutes. The solution was then irradiated for 10 hrs., except in the case of 1f, which was irradiated for 25 hrs. The products were isolated and characterised, as in previous occasions (experiment 1).

3. Synthesis of 6a-deutero-2,8,11a-trimethylpterocarpan 13

a) Synthesis of 3-deutero-(4'-methylphenoxy)methylchrom-3-ene 9: To the acetic acid-d_1 (prepared from the hydrolysis of acetic anhydride in presence of D_2O and D_2SO_4), under anhydrous conditions, 2.2 g. (0.01 moles) of red mercuric oxide and 10 g. (0.037 moles) of 1,4-bis(4-methylphenoxy)-2-butyne 7a was added. The mixture was refluxed for 40 minutes in an oil bath. Then, the reaction mixture was cooled, and the acetic acid was neutralised by the addition of solid sodium carbonate. The solid reaction mixture was extracted into ether (3 x 100 ml.), washed with 5% sodium hydroxide (3 x 50 ml.) and water (4 x 50 ml.). The ethereal layer was dried and evaporated to yield 6.2 g. of the crude deutero chrom-3-ene 9 which on passing through an alumina neutral column (100 g.) using hexane as eluent yielded 6 g. of pure 9, (60%) - mp. 74-75°C (72° reported for the undeuterated compound)[13]. From the proton NMR analysis, using the relative ratios of 3-H proton signal at δ 5.8 for the O-CH_2 signal at δ 4.8 and from the mass spectral analysis the deuterium incorporation has been found to be 78% (while analysing the mass spectrum the contribution due to undeuterated isomer of 9, viz., 8a was taken into consideration).

b) Synthesis of 6a-deutero-2,8-dimethyl-11a-methylpterocarpan 13: 1.0 g. of 3-deutero-4-(4-methylphenoxy)methyl-6-methylchrom-3-ene 9 was refluxed in 25 ml. dry N,N-diethylaniline for 2.5 hrs. After the completion of the reaction, the solvent was removed under reduced pressure and the product was worked-up by extracting into ether and washing with dilute hydrochloric acid. The ether layer was dried and evaporated to yield 3 (650 mg.) as a white solid. This on recrystallisation with methanol yielded pure 3 (600 mg., mp. 140-142 [60%]). The proton NMR analysis indicated the presence of 18% of 2a also, in addition to the desired deutero 11a-methylpterocarpan, 3. The deuterium content was found to be 80% from the analysis of the mass spectrum.

4. Photolysis of 6-deutero-2,8-dimethyl-11a-methylpterocarpan 13: The compound 13 (100 mg.) was dissolved in methanol (100 ml.) and irradiated for 40 hrs. using 300 nm lamps. Evaporation of the solvent and trituration of the residual solid with a little methanol yielded a solid, (78 mg., mp. 172-174°) which has been found to be identical in all respects with authentic 2a. Mixed mp with 2a showed no depression. The mass spectrum showed M^+ at 266 and indicated no retention of deuterium.

5. Synthesis of 3-(2'-hydroxyaryl)chrom-3-ene 4: General Procedure:

a) Synthesis of 3-(2'-acetoxyaryl)chrom-3-ene 10: General Procedure: The compound 1 (1 g.) in 20 ml. of acetic anhydride was refluxed for 3-6 hrs. in presence of catalytic amount of p-toluenesulphonic acid. At the end of the reaction, solvent was removed under reduced pressure and the reaction mixture was extracted into ether (2 x 50 ml.). The organic layer was washed with saturated sodium carbonate, dried and evaporated. The crude product was passed over a short-plug of neutral alumina, using hexane or benzene/hexane mixtures. The product thus obtained was homogeneous on tlc, yield varied from 62-68% (Table 2) and characterised by IR, NMR and UV. For 10a data: NMR ($CDCl_3$) δ 2.0 (t, 3H, J = 1 Hz) 2.2 (s, 3H) 2.3 (s, 3H) 2.4 (s, 3H) 4.8 (q, 2H, J = 1 Hz) 6.8-7.3 (m, 6H); IR (neat) cm^{-1} 3000(m), 2920(s), 1720(s), 1500(m), 1370(m), 1220(s), 1200(s), 840(s); UV(MeOH) 317 (ε 4800), 276 (ε 4700).

b) Synthesis of 2'-hydroxy-4-methylisoflavene 4: General Procedure: 1.5 mmoles of 10 was dissolved in methanol (30 ml.) containing sodium methoxide (98 mg. 1.8 mmoles) and stirred for 4-6 hrs. at room temperature. The solvent was removed under reduced pressure and the reaction mixture was neutralised with acetic acid and extracted into ether layer. The ethereal solution was washed with water and dried. On evaporation it yielded 4, homogeneous on tlc (70-80% yield). The products were characterised by NMR, IR and UV. For 4a data: NMR ($CDCl_3$) δ 2.0 (t, 3H, J = 1 Hz), 2.2(s, 3H), 2.3(s, 3H), 4.8(q, 2H, J = 1 Hz), 6.8-7.3(m, 6H); IR (neat) cm^{-1} 3400(broad), 1540(m), 1220(m), 810(m); UV 317 (ε 4800), 276 (ε 4700).

Table 2. Synthesis of 2'-acetoxy-4-methylisoflavene 10

S.No.	Starting material 1	Reaction time	Product 10	Yield %
1.	1a	3 hrs.	6,5'-dimethyl 10a	65
2.	1b	8 hrs.	6,5'-dichloro 10b	62
3.	1c	3 hrs.	6,5'-dimethoxy 10c	68
4.	1d	4 hrs.	Unsubstituted 10d	65

6. Synthesis of 2-(2-hydroxyaryl)-2-methyl-3-methylenedihydrobenzofuran 5: General Procedure: The compound 1 (4 mmoles) was dissolved in anhydrous dimethylsulfoxide (5 ml.) containing potassium t-butoxide (2.3 g. 20 mmoles). The reaction mixture was stirred at room temperature overnight. The reaction mixture was poured into ice water and neutralised very carefully with acetic acid (excess should be avoided). The mixture was then extracted with ether and washed with water. The ethereal layer was dried and evaporated under reduced pressure. The yield of the crude product was 65-68%. Further purification was effected by preparative tlc. During this purification a part of it cyclised to yield 2: yield of 5a from 1a is 68% (gummy liquid); yield of 5b from 1b is 65% (gummy liquid). The product 5 was characterised by NMR, IR and UV. For 5a data: NMR ($CDCl_3$) δ 1.85(s, 3H), 2.2(s, 3H), 2.3(s, 3H), 4.85(s, 1H), 5.5(s, 1H), 6.4-7.0(m, 6H); IR (neat) cm^{-1} 3400(s), 3000(m), 2900(m), 1600(m), 1540(m), 1520(m), 1210(m); UV 332 (ε 2184), 322 (ε 2202), 290 (ε 1395).

7. Synthesis of 6-methyl-4-methylene-3-(2-hydroxy-5-methylphenyl)-dihydrobenzopyran 6a:

a) Preparation of 6-methyl-4-(p-methylphenoxymethyl)-chrom-3-ene 8a: This compound was prepared as described by Thyagarajan et al.[13].

b) Claisen rearrangement of 8a: The compound 8a (1.3 g.) (1.26 mmoles) was refluxed in quinoline (8 ml.) in presence of acetic anhydride (1.2 ml.) and sodium acetate (0.5 g.) for 4 hrs. The boiling point of the medium was found to be 202°C. The reaction mixture was cooled and extracted with ether. The ethereal layer was washed with sodium bicarbonate and dried. The removal of ether and quinoline under reduced pressure yielded crude product 11a (1.2 g.), which was purified by passing over either neutral or basic alumina, using hexane as eluent to yield pure 11a as a viscous liquid in 65% yield (1 g.). It was homogeneous on tlc. ^{1}H-NMR ($CDCl_3$) δ: 2.1(s, 3H), 2.2(s, 3H), 2.3(s, 3H), 4.2-4.4(m, 3H), 4.7(d, 1H, J = 1 Hz), 4.56(d, 1H, J = 1 Hz), 6.8-7.5(m, 6H); IR (neat) cm^{-1} 3100(m), 2980(s), 2960(s), 1720(s), 1560(m), 1450(m), 1320(m); UV(MeOH) 312(ε 1924.5), 285(ε 2340.2), 254.6(ε 3958).

c) Hydrolysis of acetate 11a: A solution of the acetate 11a (15 mmoles) in methanol (20 ml.) containing sodium methoxide (880 mg. 20 mmoles) was stirred at room temperature for 6 hrs. After the completion of the reaction, the solvent was removed under vacuum and the product neutralised very carefully at 0°C with acetic acid. The reaction mixture was then extracted with ether, washed with water and dried. On evaporation it yielded the corresponding phenol 6a (80%) as a gum. Proton NMR (δ): 2.2(s, 3H), 2.3(s, 3H), 4.2-4.4(m, 3H), 4.8(d, 1H, J = 1 Hz), 5.6(d, 1H, J = 1 Hz), 6.8-7.3(m, 6H); IR (neat) cm^{-1} 3400(broad), 2900(m), 1520(m), 1480(m), 800(m); UV(MeOH) 320(ε 1924.5), 285 (ε 2640.2), 254(ε 3942.4).

8. Synthesis of 6-methoxy-4-methylene-3-(2'-hydroxy-5'-methoxyphenyl)-dihydrobenzopyran 6b:

a) Synthesis of 6-methoxy-4-(p-methoxyphenoxymethyl)-chrom-3-ene 8b: This chromene was prepared from 7b as per the reported procedure of Bates et al.[2g].

b) Claisen rearrangement of 8b: The compound 8b (1.48 g.) (0.005 moles) was refluxed in N,N-diethylaniline (8 ml.), in the presence of acetic anhydride (1.2 ml.) (0.01 moles). The boiling point of the mixture was around 192°C. After the reaction was over (4 hrs.), the solvent was removed under vacuum and extracted with ether. The ethereal layer was washed with saturated sodium bicarbonate and water. The organic layer was dried and evaporated, to yield the crude product, 6-methoxy-4-methylene-3-(2'-acetoxy-5'-methoxyphenyl)-dihydrobenzofuran 11b, as a gum; yield 1.2 g., which on purification over neutral alumina using hexane:benzene (50:50) as eluent yielded pure 11b (970 mg., 65%), as a viscous liquid, homogeneous on tlc. NMR ($CDCl_3$) δ: 2.1(s, 3H), 3.6(s, 3H), 3.7(s, 3H), 4.1-4.3(m, 3H), 4.7(d, 1H, J = 1 Hz), 5.6(d, 1H, J = 1 Hz), 6.7-7.3(m, 6H); IR (neat) cm^{-1} 2920(s), 1720(s), 1450(m), 1360(m), 1230(m); UV(MeOH) 314(ε 1914.5), 287(ε 2860.4), 258.7(ε 3865.7).

c) Hydrolysis of 6-methoxy-4-methylene-3-(2'-acetoxy-5'-methoxyphenyl)-dihydrobenzopyran 11b: The compound 11b was hydrolysed as in the case of 11a using sodium methoxide in methanol. The product 6b was obtained in 82% yield as a gum and characterised by NMR, IR and UV. Proton NMR δ: 3.8(s, 3H), 3.9(s, 3H), 4.2-4.4(m, 3H), 4.9(d, 1H, J = 1 Hz), 5.7(d, 1H, J = 1 Hz), 6.7-7.3(m, 6H); IR (neat) cm^{-1} 3400(broad), 2900(m), 1510(m), 1480(m), 820(m); UV(MeOH) 318(ε 2010.2), 290(ε 2340.2), 258(ε 3958.2).

9. Irradiation of 4-methyl-2'-hydroxyisoflavenes 4: General Procedure: The isoflavene 4 (0.38 mmoles) was dissolved in methanol (100 ml.) and purged with argon for 20 minutes. The solution was irradiated in a Rayonet Photoreactor using 300 nm lamps for 10 hrs. The products, benzofuro(3,2-b)benzofurans 2 were isolated after the removal of the solvent and recrystallised from methanol. They were compared with authentic samples with respect to spectral data and mixed melting point (Table 3).

Table 3. Irradiation of 2'-hydroxy-4-methylisoflavenes 4

S.No.	Starting material	Product	Yield %
1.	4a	2a	70
2.	4b	2b	60
3.	4c	2c	66
4.	4d	2d	70

10. Irradiation of 4a in benzene: The compound 4a (100 mg. 0.38 mmoles) was dissolved in benzene (100 ml.) and irradiated under the above mentioned conditions for 15 hrs. The product isolated was 75 mg. (75%) and it was identified to be 2a.

11. Irradiation of isoflavene 4a in presence of sodium methoxide: The isoflavene 4a (100 mg. 0.38 mmoles) was dissolved in methanol (100 ml.) containing sodium methoxide (176 mg. 4 mmoles) and irradiated for 2 hrs. using 300 nm lamps. The product was isolated after removing the solvent under reduced pressure and neutralising the reaction mixture with dilute hydrochloric acid (1N) and extracting into ether. The ether layer was washed with water and dried. The crude product 2a 75 mg. (75%) was obtained after the evaporation of the ether solvent and compared with the authentic sample[1].

12. Follow-up of the photolysis of 4b with FT-NMR: For this analysis the compound 4b (40 mg.) was dissolved in benzene-d_6 (0.5 ml.) and the irradiations were carried out in quartz NMR tubes. Prior to the start of the actual analysis various mixtures of 4b with 2b and 5b were made and instrument conditions were standardized upto a detection level of 1%. The spectra were recorded on FT-mode. The spectra were recorded after every 30 minutes interval for 6 hrs. This analysis clearly showed the formation of exomethylenedihydrobenzofuran 5b and absence of 6c in this photolysis reaction. The reaction mixture indicated characteristic olefinic proton signals at δ 4.1 and 4.6 in C_6D_6. The spectra also indicated the slow build-up of benzofuro-benzofuran 2b over the period of time.

13. Follow-up of the photolysis of 4b with HPLC: The compound 4b (100 mg.) was dissolved in methanol (100 ml.) and irradiated for 8 hrs. in Rayonet Photoreactor, using 300 nm lamps. The samples were withdrawn for every 15 minutes of irradiation and samples were analysed by HPLC using Micromeritics-LC-1700. After a few trials the ideal conditions for analysis were found to be Microsil-18 reverse phase column (300 mm x 5 mm), UV 254 nm detector and flow rate of 2 ml/min. The solvent system employed was 90% acetonitrile + 10% water. The retention times for 2b, 4b, 5b and 6c were found to be 3 min. 42 sec., 2 min. 54 sec., 2 min. 42 sec. and 2 min. 42 sec. respectively. This analysis clearly showed the increase in the intensity of peak having retention time 2 min. 42 sec. due to either 5b or 6c and drop in the concentration of 4b, i.e., peak having retention time 2 min. 54 sec. over a period of time. However the FT-NMR analysis and comparison with authentic mixtures of 4b and 5b and 4b and 6c eliminated the possibility of 6c being the intermediate in the above instance and clearly confirmed the involvement of 5b as the intermediate.

14. Irradiation of 2-methyl-2-(2-hydroxyaryl)-3-methylenedihydrobenzofuran 5: General Procedure: The compound 5 (0.4 mmoles) was dissolved in methanol and irradiated for 3.5 hrs. The product 2 was isolated by usual work-up. Yield of 2a from 5a is 80%; mp. 172-174 and no depression was observed on admixture with an authentic sample of 2a. Also the spectral data are identical with those of authentic 2a. Yield of 2b from 5b is 82%; mp. 205-207 and no depression on admixture with an authentic sample of 2b was observed. The spectral data are identical with those of authentic 2b.

15. Irradiation of 5a in presence of sodium methoxide: The compound 5a (100 mg.) was dissolved in methanol (100 ml.) containing sodium methoxide (174 mg.) (4 mmoles) and irradiated for 2 hrs. The product 2a was isolated, as in previous occasions (82 mg., 82%, mp. 172-174 with authentic sample of 2a and mixed melting point of 172-174).

16. Irradiation of 4-methylene-3-(2'-hydroxyaryl)dihydrobenzopyrans 6: General Procedure: The compound 6 (0.4 mmoles) was dissolved in methanol (100 ml.) and irradiated using 300 nm lamps for 10 hrs. The products 2 were isolated after usual work-up. Yield of 2a from 6a is 78%; mp. 172-174 and mixed melting point with an authentic sample of 2a showed no depression. The IR and NMR spectra are superimposable. Yield of 2c from 6b is 80%; mp. 144-145 and mixed melting point with an authentic sample of 2b showed no depression. The IR and NMR spectra are superimposable.

17. Irradiation of 6a in benzene: The compound 6a (200 mg. 0.76 mmoles) was dissolved in 200 ml. of dry benzene and irradiated for 15 hrs. Samples were withdrawn at 3 hr. intervals, worked-up and analysed by proton NMR. The relative ratios of components in the mixture were calculated by proton NMR integration, for values at δ 1.69 (11a-CH_3, 3H), δ 1.71 (4b, 9b-CH_3, 6H) and δ 5.6 (1H) (exopyran).

18. The HPLC follow-up of photolysis of 2,8-dichloro-11a-methylpterocarpan 1b: The compound 1b (100 mg.) was dissolved in 100 ml. of methanol and irradiated for 40 hrs. The samples were withdrawn periodically at every 30 minute interval. These samples were analysed by high pressure liquid chromatography using Micromeritics LC-1700. The analysis parameters were stated already. The retention times for 1b, 2b, 4b and 5b were found to be 3 min. 6 sec., 3 min. 42 sec., 2 min. 54 sec. and 2 min. 42 sec. respectively. The analysis clearly showed no peak with retention time of 2 min. 54 sec., i.e., 4b at any interval of photolysis. This was further confirmed by analysing the mixture of authentic 4b and photolysis product mixture of 1b. However, an intense peak having same retention time as 5b, viz., 2 min. 42 sec., was observed for first 10 hrs. of analysis. So, from the HPLC analysis, the presence of 4b in the photolysis reaction mixture of 1b was ruled out.

19. Follow-up of the photolysis of 1b with FT-NMR: For this analysis the compound 1b (40 mg.) was dissolved in benzene-d_6 (0.5 ml.) and the irradiations were carried out in a quartz NMR tube. Prior to the start of analysis the mixtures of 1b with 4b, 2b and 5b were made. The spectra of these mixtures were recorded on FT-mode and conditions were standardised upto a detection level of 1% of either of 4b or 5b. The NMR spectra were recorded after every 15 minutes of irradiation for a period of 8 hrs. These spectra clearly indicated peaks at δ 3.9 and 4.4 in C_6D_6, characteristic of exomethylene protons. When the NMR spectrum of a mixture of 5b and the photolysis product of 1b was recorded under identical instrumental conditions, it indicated non-overlapping signals due to 5b and a new exomethylene product formed in the reaction. In a similar way the NMR spectrum of mixture of 4b and photolysis product of 1b was recorded. It also indicated non-overlapping peaks due to 4b and photolysis reaction products of 1b. Signals characteristic of 4b were not at all observed in the NMR spectrum of the photolysis reaction mixture of 1b at any instance. The exomethylene proton signals were not observed when the spectrum was recorded by CW-mode, indicating the low concentration of this species (1%-5%) in the photolysis mixture. The spectra also indicated the formation of the product 2b. From this experiment it was clear that 4b and 5b were not involved in the photochemical ring contraction of 1b $\longrightarrow$ 2b and some other exomethylene compound is involved.

20. Large scale photolysis of 11a-methylpterocarpans: General Procedure: The compound 1 (1.0 g. 4 mmoles) was dissolved in dry benzene (50 ml.) and irradiated in a Rayonet reactor for 6 hrs. The benzene layer was washed with 50% KOH. The alkali portion was carefully neutralised with acetic acid and extracted with ether. The ether layer was washed with water, dried and evaporated under vacuum. The products were identified to be 6a and 6b in the case of photolysis of 1a and 1c respectively. The products were compared with authentic samples, prepared earlier. Yield 50 mg. (5%). In the case of 1b the product was identified to be 6c, based on the NMR spectrum. Proton NMR of 6c in $CDCl_3$: δ 4.2-4.4(m, 3H), 4.9(d, 1H, J = 1 Hz), 5.7(d, 1H, J = 1 Hz), 6.8-7.4(m,6H).

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+ Paper dedicated to Prof. C.L. Stevens, Wayne State University, Detroit, Michigan, U.S.A. on the occasion of his 60th birthday.

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19. As can be seen, the molecular frame work of 12 contains units of o-allylphenol, cross conjugated o-hydroxyphenyl-1,3-butadiene and o-hydroxystyrene all of which are known to undergo photochemical reactions of various types.