The Synthesis and Electrochemical Study of New 2,2′-Dialkyl Viologens

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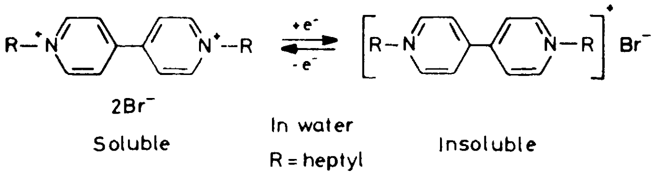
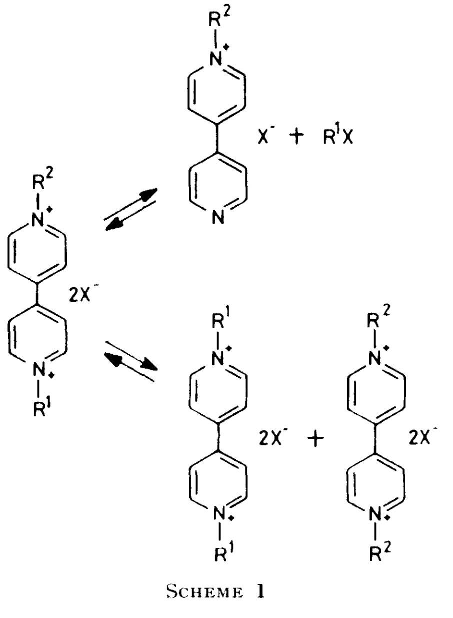
Recent chemical evidence has shown that the alkyl groups of dialkylbipyridinium dihalides (viologens) exchange in the presence of nucleophiles. In order to study the long-term electrochemical reversibility of these materials, three new viologens have been synthesized which contain alkyl groups symmetrically substituted on the 2-positions of the bipyridine nucleus, and in one of which the alkyl groups are also bonded to the nitrogens of the pyridines forming six-membered cyclic systems. This compound exhibits no observable alkyl group exchange in the presence of nucleophiles. An electrochemical study of the new substituted viologens is reported along with a comparison with the parent compound.

DIALKYLBIPYRIDINIUM DIHALIDES belong to a unique class of materials which can be reduced at potentials between 0.0 and −1.0 V to form stable radical cations, that are purple in colour, hence the trival name viologens. In addition to use as redox indicators for biological systems[1] and as herbicides in agriculture (Paraquat is *NN*′-dimethyl-4,4′-bipyridinium dichloride),[2] viologens have recently been used as the main component of electrochemical display cells[3] because the parent dication is water soluble, whereas the reduced radical cation is not, and so when an image is written in a display configuration, the reduced material precipitates and imparts memory capabilities to the system.



It has long been known that alkylated pyridinium salts are unstable in the presence of nucleophiles.[4] For instance, ethylpyridinium bromide is smoothly dealkylated upon treatment with triphenylphosphine. In a display configuration, when various salts, counter-ions, and metals are present, this type of reaction is highly likely to occur and is very deleterious. In systems in which unsymmetric viologens are used, scrambling of the alkyl groups is possible (Scheme 1).

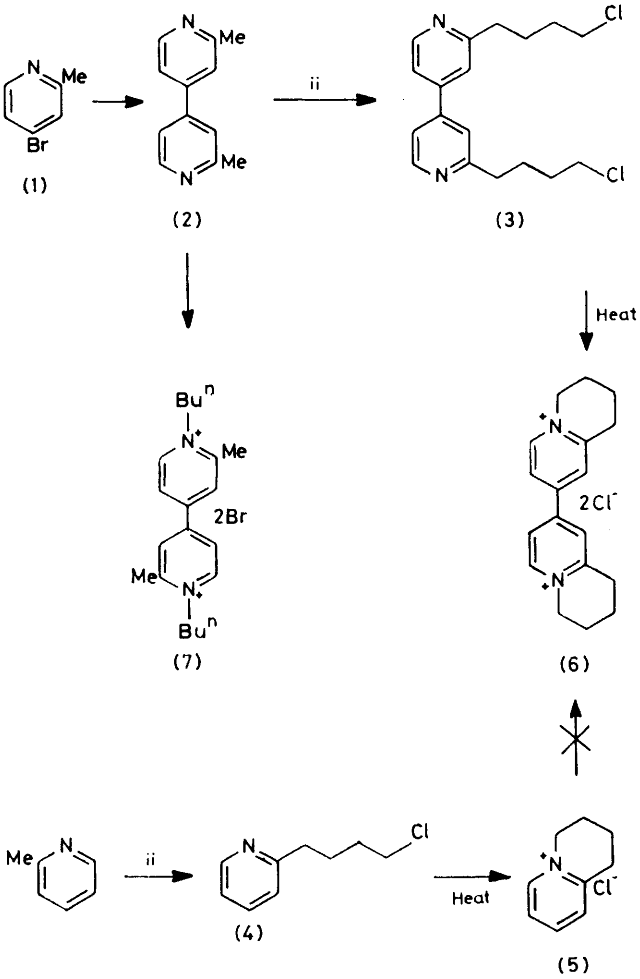


SCHEME 1

We therefore set out to synthesize a viologen analogue in which this alkylation–dealkylation would not occur and thus a more stable electrochromic system would result. We have accordingly synthesized the bis(cycloalkylated) viologen (6), since it was felt that the added stability of the six-membered cyclic salt would prevent the dealkylation from occurring. If, however, the N^+–CH_2 bond were cleaved the pendant alkyl halide group would remain in close proximity to the nitrogen atom and the salt would probably be reformed. Thus, the equilibrium in Scheme 1 would be shifted far to the left.[5]

Synthesis.—Two methods for the synthesis of the bis(cycloalkylated) viologen (6) were investigated. The first began with metallation of 2-picoline with butyl-lithium at −78 °C.[6] Alkylation of the resulting orange anion with 1-chloro-3-iodopropane gave (4) in 80% yield, which was heated in refluxing toluene for 1 h. The cycloalkylated pyridine salt precipitated in quantitative yield. Finally, it was hoped that (5) could be dimerized to the radical cation of (6) by treatment with aqueous sodium cyanide following the procedure of Winters *et al.*[7] Unfortunately, treatment of (5) in aqueous acetone with sodium cyanide (5 mol. equiv.) led to only a faint blue colour, the colour of the radical cation of (6). Upon oxidation of this solution with iodine, only trace amounts (<5%) of the desired product were isolated, the remainder being starting material. Despite variation of the reaction time (from several hours to several days), temperature, and solvent (protic and aprotic), yields of >10% were never obtained. A model study using *N*-methyl-2-picolinium iodide also led to <10% yields of the desired dimer, compared with a 50% yield reported by Winters *et al.*[7] We therefore used the following alternative method.

4-Bromo-2-methylpyridine[8] was coupled using a catalytic amount of tetrakis(triphenylphosphine)-nickel(0)[9,10] and zinc dust as the reductant to give 2,2′-dimethyl-4,4′-bipyridine (2)[11] in 42% yield. Compound (2) was readily metallated with butyl-lithium at −78 °C, and the resulting dark blue dianion was treated with 1-chloro-3-iodopropane to give a 50% yield of (3) after column chromatography. Compound (3) was immediately converted into the stable bis(cycloalkylated) bipyridinium salt (6) by heating in acetonitrile.*



SCHEME 2 *Reagents:* i, $2Bu^nBr$; ii, Bu^nLi; then $I[CH_2]_3Cl$

The desired product precipitated as a yellow solid and was purified by recrystallization from methanol–ether. For comparison, the viologen derived from 2,2′-dimethyl-4,4′-bipyridine (2) was also synthesized simply by the reaction of (2) with excess of butyl bromide. The viologen (7) was isolated in 74% yield after recrystallization.

Electrochemical Measurements.—Cyclic voltammograms were first recorded for all new viologens synthesized (see Table). The samples were dissolved in acetonitrile containing 0.1M tetrabutylammonium tetrafluoroborate and placed in a specially designed cell (see Experimental section) with a platinum button working electrode. The apparatus was continuously flushed with argon, although it was not rigorously sealed under an inert atmosphere. As indicated in the Table, all compounds displayed reversible first and second reduction peaks on the cyclic voltammetry time-scale. It is apparent from these data that the addition of electron-donating alkyl groups shifts the position of the first reduction to higher potential. This is consistent with the fact that donating groups should stabilize the parent dication. Conversely, the alkyl groups seem to have no effect on the position of the visible absorption band of the radical cation. It appears that the reduction potential is much more sensitive to electronic effects than is the $\lambda_{max.}$ value.

Although the reversibility of the redox cycle for all intermediates was established on the cyclic voltammetry time-scale (15 s), it was necessary to evaluate the radical cation stabilities on a time-scale more relevant to their possible application as display materials, and therefore controlled-potential reverse coulometry was employed. A solution of the desired viologen (*ca.* 1 mM) was reduced at constant potential (*ca.* 100 mV past the first reduction peak) for a fixed time interval giving a known amount of the radical cation. The solution was then oxidized at *ca.* 0.0 V until current passage ceased. The long-term stability of the system was then computed from the ratio of the current necessary for oxidation to the dication, to the current used to generate the cation radical. It became obvious that the reversibilities of the new viologens (6) and (7) on long time-scales were very poor using our electrochemical apparatus described earlier. Solutions of these reduced radical cations would discharge their purple colour in only a few seconds, while similar solutions of the parent radical cation (Paraquat) would remain purple for several hours. Apparently these new viologen analogues were very sensitive to oxygen.[12] In the presence of traces of air the reduced form of these materials would be oxidized back to the dication state. This occurred for both (6) and (7); however, compound (6) also appeared to under-

Electrochemical and spectroscopic data of viologens [a]

Compound	Ep_{CATH_1} [b]	Ep_{AN_1} [b]	Ep_{CATH_2} [b]	Ep_{AN_2} [b]	$\lambda_{max.}$	ε [c]	Reversibility [d]
Dioctylviologen dibromide	−0.402	−0.342	−0.882	−0.752	600	14 400	92
Dimethylviologen dichloride (Paraquat)	−0.44	−0.36	−0.830	−0.740	600		90
(6)	−0.560	−0.485	−0.886	−0.813	600	16 300	90
(7)	−0.484	−0.385	−0.898	−0.799	600	13 900	91
(9)	−0.562	−0.470	−0.954	−0.864	600	13 000	88

[a] I.r. compensation was not corrected for in these studies. [b] In V *vs.* aqueous saturated calomel electrode, measured at a sweep rate of 200 mV s^{-1}. [c] The molar extinction coefficient refers to the radical cation generated from the given viologen by electrochemical reduction. [d] The reversibility is the ratio of the current used to oxidize the viologen radical cation to the current used to generate it (see text).

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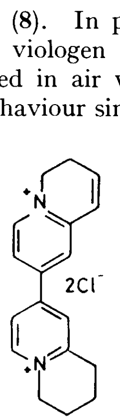
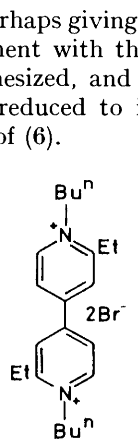
* Acetonitrile is the solvent of choice for these reactions because the monosalt is soluble and the disalt is not, and so easy purification of the products is possible.

go chemical decomposition in air. The only obvious difference between (6) and (7) is a proton β to the pyridine ring in (6) which might be eliminated when the material is reduced to the radical cation, perhaps giving a product similar to (8). In partial agreement with this explanation, the viologen (9) was synthesized, and it rapidly decomposed in air when it was reduced to its radical cation, behaviour similar to that of (6).



(8)



(9)

These evaluation difficulties could be overcome, however, if all materials were studied in the complete absence of air. This was accomplished by performing the electrochemical measurements in a dry box (Vacuum Atmosphere). When this was done, all compounds showed reversible coulometry. These data are also in the Table, along with the extinction coefficients of the coloured radical cations. It should be noted that the bis(cycloalkylated) viologen (6) has a greater molar extinction coefficient than either dioctyl viologen or (7).

EXPERIMENTAL

Electrochemical Studies.—All viologens tested were dissolved in dry acetonitrile (freshly distilled from CaH_2) containing tetrabutylammonium tetrafluoroborate (0.1M). The electrochemical cell consisted of a 100-ml beaker fitted with a Teflon cap through which were placed a platinum button working electrode, a platinum wire counter electrode housed in a tube with a fine fritted end, and an aqueous calomel reference electrode. The system was flushed with argon for 5 min before each run. Measurements were made using a Princeton Applied Research model 170 electrochemical system. Cyclic voltammetry was performed at a sweep rate of 200 mV s^{-1} from 0.0 to −1.8 V. Constant-potential coulometry was performed in the foregoing cell except that the platinum button electrode was replaced by a platinum cage and the solution was stirred.

Chemical Synthesis.—M.p.s were determined on a Thomas–Hoover capillary melting point apparatus. ^{1}H N.m.r. spectra were determined on a Varian HA-100 spectrometer using tetramethylsilane as an internal standard. Exact mass determinations were performed on an AEI MS-30 spectrometer using perfluorokerosene (PFK) as an internal reference. All reactions were performed under an inert atmosphere of argon, and transfers were done *via* a syringe.

4-*Bromo*-2-*picoline* (1). This material was made essentially by the procedure of Abramovitch [8a] from 4-nitro-2-picoline *N*-oxide and phosphorus tribromide. This reaction has been reported to be non-reproducible; [8b] however, if the reaction time is extended to 90 min from the reported 30 min, the material can be isolated in 54% yield as the hydrochloride (recrystallized from acetonitrile); ^{1}H n.m.r.: δ (free base; $CDCl_3$) 2.70 (s, 3 H, Me), 7.70 (d, 1 H, *J* 2.5 Hz), 7.75 (s, 1 H), and 8.70 (d, 1 H, *J* 2.5 Hz) (Found: C, 34.9; H, 3.3; N, 6.7. Calc. for C_6H_7BrClN: C, 34.6; H, 3.4; N, 6.7%).

2,2′-*Dimethyl*-4,4′-*bipyridine* (2). 4-Bromo-2-picoline hydrochloride (1)-HCl (3.0 g, 14.4 mmol) was neutralized with a cold aqueous slurry of potassium carbonate, extracted with ether, and the extract dried (K_2CO_3), concentrated, and taken up in dry dimethylformamide (15 ml) (DMF). The organometallic catalyst used was generated *in situ* from zinc dust (0.936 g, 14.4 mmol), triphenylphosphine (1.51 g, 5.8 mmol), and dichlorobis(triphenylphosphine)nickel(II) (0.47 g, 0.72 mmol) in DMF (50 ml) at room temperature for 30 min. The catalyst mixture, consisting of the red tetrakis(triphenylphosphine)nickel(0) species, was cooled to 0 °C and (1) in DMF was added during 15 min. The solution was then heated at 40 °C for 10 h, water was added, and the resulting solution extracted with ether. The combined organic layers were dried (K_2CO_3) and evaporated to dryness. The residue was dissolved in chloroform and extracted with 10% aqueous hydrochloric acid. The aqueous layers were combined, neutralized (K_2CO_3), and extracted with chloroform. After removal of solvent, the solid residue was recrystallized from hexane to give pure (2) (0.56 g, 42% yield); m.p. 84—85 °C (lit.,[11,12] 81—83 °C); ^{1}H n.m.r.: δ($CDCl_3$) 2.55 (s, 6 H), 7.15 (d, 1 H, *J* 5 Hz), 7.20 (s, 1 H), and 8.4 (d, 1 H, *J* 5 Hz).

2,2′-*Bis*-(4-*chlorobutyl*)-4,4′-*bipyridine* (3). A solution of 2,2′-dimethyl-4,4′-bipyridine (2) (1.0 g, 5.4 mmol) in dry tetrahydrofuran (THF) (50 ml) was cooled to −78 °C and butyl-lithium (12.0 mmol, 2.2 equiv.) was added dropwise over 15 min. The solution immediately turned dark blue. After the addition was complete, the solution was allowed to warm to −30 °C for 5 min and then cooled back to −78 °C. 1-Chloro-3-iodopropane (2.44 g, 12 mmol) dissolved in THF (5 ml) was added slowly over 10 min. As the iodide was added, the colour of the dianion solution was discharged, eventually becoming light yellow. The mixture was allowed to warm slowly to room temperature. After quenching with ice–water, the solution was extracted with ether. The extracts were dried ($MgSO_4$) and evaporated *in vacuo*, and the resulting crude oil was chromatographed on silica gel (eluant: ethyl acetate–hexane, 2 : 1) to give (3) (1.47 g, 81% yield); ^{1}H n.m.r.: δ($CDCl_3$) 1.6 (m, 4 H), 2.8 (t, 4 H, *J* 7 Hz), 3.4 (t, 4 H, *J* 6 Hz), 7.15 (d, 1 H, *J* 5 Hz), 7.20 (s, 1 H), and 8.4 (d, 1 H, *J* 5 Hz) (Found: M^+, 336.116 5. Calc. for $C_{18}H_{22}Cl_2N_2$: M^+, 336.115 9).

1,1′,2,2′,3,3′,4,4′-*Octahydro*-8,8′-*biquinolizinium dichloride* (6). A solution of 2,2′-bis-(4-chlorobutyl)-4,4′-bipyridine (3) (1.0 g, 3 mmol) in dry acetonitrile (50 ml) was heated under reflux for 2 h, and a yellow solid separated. Recrystallization from methanol–ether gave the pure *dichloride* (6) in 95% yield; m.p. 210 °C (decomp.); ^{1}H n.m.r.: δ[$CDCl_3$–$(CD_3)_2SO$ + trace D_2O] 2.05 (4 H, m), 3.30 (t, 4 H, *J* 6 Hz), 4.65 (t, 4 H, *J* 6 Hz), 8.30 (d, 2 H, *J* 6 Hz), 8.46 (s, 2 H), and 8.90 (d, 2 H, *J* 6 Hz); $\nu_{max.}$ (KBr) 1 650, 1 580, and 850 cm^{-1} (Found: C, 64.0; H, 6.3; N, 8.31. $C_{18}H_{22}Cl_2N_2$ requires C, 64.3; H, 6.5; N, 8.33%).

NN′-*Dibutyl*-2,2′-*dimethyl*-4,4′-*bipyridinium dichloride* (7). A solution of 2,2′-dimethyl-4,4′-bipyridine (2) (0.5 g, 2.7 mmol) and bromobutane (7.4 g, 50 mmol) in dry acetonitrile (25 ml) was heated under reflux for 14 h, and a yellow precipitate separated. Recrystallization from methanol–ether gave the pure *dibutyl compound* (7) in 74% yield; m.p. 224 °C (decomp.); ^{1}H n.m.r.: δ[$CDCl_3$–$(CD_3)_2SO$–D_2O] 1.0 (t, 6 H, *J* 7 Hz), 1.42 (m, 4 H), 1.95 (m, 4 H), 3.05 (s, 6 H), 4.70br (4 H), 8.55br (2 H), 9.05 (s, 2 H), and 9.25br (2 H) (Found: C, 52.2; H, 6.8; N, 5.97. $C_{20}H_{30}Br_2N_2$ requires C, 52.4; H, 6.55; N, 6.1%).

2,2′-*Diethyl*-4,4′-*bipyridine*. Following the procedure used for (3), 2,2′-dimethyl-4,4′-bipyridine (2) was metallated with butyl-lithium and then treated with methyl iodide (2.2 equiv.). 2,2′-Diethyl-4,4′-bipyridine was isolated as an oil (51% yield) after chromatography on silica gel (with ethyl acetate as eluant); ^{1}H n.m.r.: δ($CDCl_3$) 1.34 (t, 6 H, *J* 7 Hz), 2.86 (q, 4 H, *J* 7 Hz), 7.22 (d, 2 H, *J* 5 Hz), 7.28 (s, 2 H), and 8.46 (d, 2 H, *J* 5 Hz).

NN′-*Dibutyl*-2,2′-*diethyl*-4,4′-*bipyridinium dibromide* (9). A solution of 2,2′-diethyl-4,4′-bipyridine (2.0 g), prepared as just described, in bromobutane (25 ml), was heated at reflux for 18 h. The precipitated salt was filtered off and washed with hexane. Recrystallization from methanol–ether gave the pure *dibromide* (9) in 70% yield; m.p. 218 °C (decomp.); ^{1}H n.m.r.: δ[$CDCl_3$–$(CD_3)_2SO$ + trace D_2O] 1.0 (t, 6 H, *J* 7 Hz), 1.39 (t, 6 H, *J* 8 Hz), 1.42 (m, 4 H), 1.95 (m, 4 H), 2.85 (q, 4 H, *J* 8 Hz), 4.70br (4 H), 8.6br (2 H), 9.10 (s, 2 H), and 9.2br (2 H) (Found: C, 54.0; H, 6.9; N, 5.55. $C_{22}H_{34}Br_2N_2$ requires C, 54.3; H, 7.0; N, 5.8%).

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