Hydrolysis Studies of Chalcogenopyrylium Trimethine Dyes. 1. Product Studies in Alkaline Solution (pH ≥ 8) under Anaerobic and Aerobic Conditions

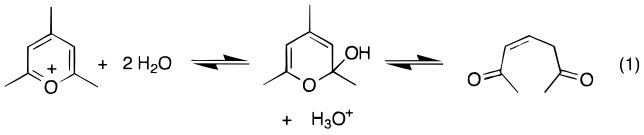
David N. Young and Michael R. Detty*

Department of Medicinal Chemistry, School of Pharmacy, State University of New York at Buffalo, Amherst, New York 14260

Received January 22, 1997[⊗]

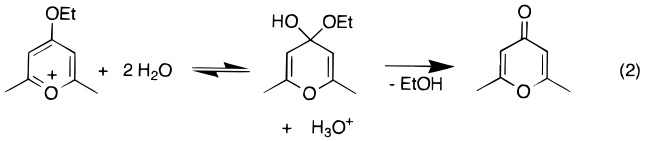
Hydrolyses of chalcogenopyrylium dyes **1**−**9** give product distributions that are both heteroatom and oxygen dependent. Under anaerobic or aerobic conditions at pH 8, hydrolyses of dyes **1**−**4**, which each contain a pyrylium ring, give 2-pentene-1,5-diones **10**−**13**, respectively, in >90% yield from addition of hydroxide to the 2-position of the pyrylium ring followed by ring opening and tautomerization. Telluropyrylium dye **8** under anaerobic conditions over the pH range 6.9−11.0 gives a 1:1 mixture of telluropyranylidene aldehyde **14** and tris(telluropyranylidenemethyl)methane **15** derived from addition of hydroxide to the central carbon of the trimethine bridge. Under aerobic conditions, tellurophene **30(Te,Te)** and trace amounts of telluropyranone **29** were also produced via oxidative mechanisms with relative yields of **30(Te,Te)** increasing with pH over the pH range 6.9−11.0 and with oxygen concentration. Thiopyrylium dye **9**, seleno-/thiopyrylium dye **5**, selenopyrylium dye **6**, and seleno-/telluropyrylium dye **7** gave hydrolysis products derived from addition of hydroxide to the 2-position of the selenopyrylium ring (thiopyrylium ring for **9**) as well as to the central carbon of the trimethine backbone under both anaerobic and aerobic conditions. The resulting seleno- or thio-hemiketals ring-opened to the corresponding seleno ketones, which were then hydrolyzed to the 2-pentene-1,5-diones **11**−**13** from **5**−**7**, respectively, and **11** from **9**. Under aerobic conditions, some oxidation of the seleno-hemiketals from **5** and **6** were observed to give selenophenes **30(Se,S)** and **30(Se,Se)**, respectively, as well as oxidation of the telluro-hemiketal from **7** and **8** to give tellurophenes **30(Te,Se)** and **30(Te,Te)**, repectively. Chalcogenopyranones **27**−**29** were also produced in modest yields in the aerobic reactions.

The hydrolysis of pyrylium salts to give pseudobases (2-pentene-1,5-diones) as shown in eq 1 is a well studied reaction.[1] The intermediates involved in the formation of the diketone are most likely the cyclic hemiacetals, which can give the diketone presumably via a thermal, electrocyclic rearrangement to the enol followed by tautomerization. Studies have shown that the conversion of the hemiacetal to the diketone is pH independent over the pH range of 3−10.[2] The steps of the hydrolysis are reversible, and kinetic schemes describing the hydrolyses of various pyrylium systems include appropriate equilibria.[1,2]



(1)

A second hydrolysis pathway available to the pyrylium nucleus is addition of water (hydroxide) to the 4-position as illustrated in eq 2 for 4-ethoxypyrylium salts.[1,3] This pathway is observed at low pH with loss of ethanol from the initial addition products generating the 4*H*-pyran-4-ones. At higher pH, a ring-opening pathway similar to eq 1 is observed.



(2)

In pyrylium dyes with more extended π-frameworks, the addition of water (hydroxide) to the 2- or 4-position as well as any vinylogous π-carbon is a possible reaction. Little is known about the relationship between the heavier chalcogen atoms S, Se, and Te found in thiopyrylium, selenopyrylium, and telluropyrylium dyes, respectively, and the types and ratios of hydrolysis products as well as the relative rates of hydrolysis. Such information gains significance with respect to dye series **1**−**9**,

[⊗] Abstract published in *Advance ACS Abstracts,* June 15, 1997.

(1) Balaban, A. T.; Dinculescu, A.; Dorofeenko, G. N.; Fischer, G. W.; Koblik, A. V.; Mezheritskii, V. V.; Schroth, W. *Pyrylium Salts: Syntheses, Reactions, and Physical Properties*; Advances in Heterocyclic Chemistry, Supplement 2, Katritzky, A. R., Ed.; Academic Press: New York, 1982; pp 66−73.

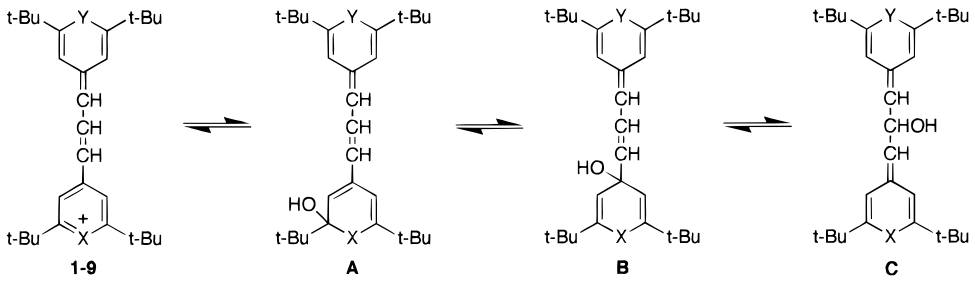
(2) Williams, A. *J. Am. Chem. Soc.* **1971**, *93*, 2733−2737.

(3) Salvadori, G.; Williams, A. *J. Am. Chem. Soc.* **1971**, *93*, 2727−2733.

(4) Photodynamic therapy (PDT) is a recent development in the treatment of cancer in which a photochemical sensitizer produces a cytotoxic reagent (singlet oxygen, superoxide, radicals) or reaction in the tumor upon irradiation. Dyes **3**−**8** in the series contain at least one heavy atom (Se or Te), which promotes higher quantum yields for singlet oxygen generation, and have been found useful in animal studies [Detty, M. R.; Powers, S. K. Photodynamic Therapy Using Seleno- or Telluropyrylium Salts. US Patent 5,047,419 (Sep, 1991) and Powers, S. K.; Detty, M. R. Photodynamic Therapy with Chalcogenapyrylium Dyes. In *Photodynamic Therapy of Neoplastic Disease*; Kessel, D., Ed.; CRC Press, Boca Raton, FL, 1990, pp 308−328]. The challenge to chemists in the design of sensitizers for PDT is to produce materials that (1) absorb light of >650 nm where tissue is most transparent, (2) are photochemically efficient at producing the cytotoxic event, (3) are nontoxic in the absence of light, and (4) differentiate normal and transformed tissue. Clinical protocols using porphyrin-derived sensitizers have received FDA approval recently for the treatment of various lesions of the neck, lung, bladder, and skin. For recent reviews, see: (a) Rosenthal, D. I.; Glatstein, E. *Ann. Med.* **1994**, *26*, 405. (b) Henderson, B. W.; Dougherty, T. J., Eds. *Photodynamic Therapy: Basic Principles and Clinical Aspects*; Marcel Dekker: New York, 1992; pp 1−459. (c) Penning, L. C.; Dubbelman, T. M. *Anti-Cancer Drugs* **1994**, *5*, 139. (d) Cannon, J. B. *J. Pharmaceut. Sci.* **1993**, *82*, 435−446. (e) Pass, H. I. *J. Nat. Cancer Inst.* **1993**, *85*, 443.

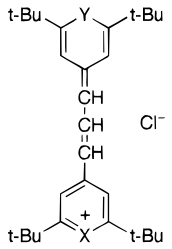
S0022-3263(97)00115-1 CCC: $14.00

Scheme 1



which includes sensitizer candidates for photodynamic therapy.[4−8] As *in vivo* agents, the hydrolysis products of these dyes are potential metabolites in treatments utilizing them. Little is known about the hydrolysis products of trimethine dyes such as **1**−**9** or the effect of the different heteroatoms on the hydrolysis products.

In this manuscript, we describe the products derived from hydrolysis of dyes **1**−**9** at alkaline pH under both anaerobic and aerobic conditions. The types of hydrolysis products observed are strongly dependent both on the identity of the chalcogen atoms in the π-framework and on the presence or absence of molecular oxygen during the hydrolysis.

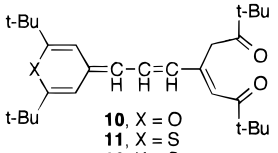


1, X = Y = O
2, X = O, Y = S
3, X = O, Y = Se
4, X = O, Y = Te
5, X = Se, Y = S
6, X = Y = Se
7, X = Se, Y = Te
8, X = Y = Te
9, X = Y = S

Results and Discussion

The hydrolysis of dyes **1**−**9** would be initiated by the formal addition of water or hydroxide to the cationic π-framework. For these symmetrical dyes, addition can occur either at the 2-position (**A**) or the 4-position (**B**) of either heterocyclic ring, or at the central carbon of the trimethine backbone (**C**) as shown in Scheme 1. The reversibility of the hydroxide addition at the pH of hydrolysis determines whether product formation is under kinetic or thermodynamic control.

Part A. Product Studies at pH 8 under Anaerobic Conditions. At pH ≥ 8, hydrolysis of dyes **1**−**8** gave product mixtures on a time scale convenient for product studies. Telluropyrylium dyes **4**, **7**, and **8** gave complete loss of dye (5×10^{-4} M) within 3 h at ambient temperature in solutions of 0.25 M dibasic potassium phosphate (pH 8), which had been rigorously degassed. Pyrylium dye **1**, thiopyrylium dye **2**, and selenopyrylium dyes **3** and **6** (all at 5×10^{-4} M) gave complete loss of dye within 24 h at ambient temperature under the same conditions. Selenopyrylium dye **5** (5×10^{-4} M) was less reactive at ambient temperature, and hydrolysis products were obtained after 15 h at 60 °C in degassed solutions of 0.25 M dibasic potassium phosphate. Thiopyrylium dye **9** was much less reactive than the other dyes of the series, and product studies were conducted at pH 12. The hydrolysis reaction mixtures were prepared by the slow addition of a degassed solution of dye in MeOH to degassed buffer. The concentration of MeOH did not exceed 1% by volume.



10, X = O
11, X = S
12, X = Se
13, X = Te

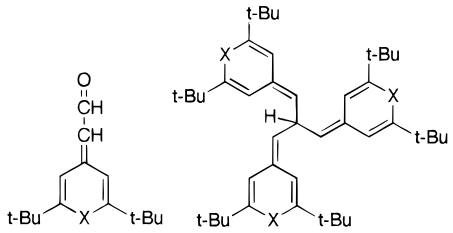
Hydrolyses of Dyes 1−4 at pH 8. Hydrolysis of dye **1** in phosphate-buffered aqueous solution at pH 8 gave predominantly enedione **10** (>95%), which has been referred to as a pseudobase in earlier studies,[1,2] from spectroscopic data under both aerobic and anaerobic conditions. The ^{1}H NMR spectrum of compound **10** was characterized by four different *tert*-butyl singlets (δ 1.28, 1.16, 1.15, 1.13), three one-proton olefinic singlets (δ 6.44, 5.86, 5.58), a two-proton aliphatic singlet (δ 4.28), and two doublets [δ 6.10 (J = 15 Hz), 5.42 (J = 12 Hz)] and a doublet of doublets for the trimethine linkage [δ 6.68 (J = 12, 15 Hz)]. The high-resolution, positive FAB mass spectrum gave a parent ion with m/z 441.3329 for $C_{29}H_{44}O_3 \cdot H^+$ (calcd 441.3369), which is consistent with pseudobase **10**. The infrared spectrum of **10** showed two carbonyl stretching frequencies at 1713 and 1670 cm^{-1}, consistent with nonconjugated and conjugated carbonyls, respectively. On the basis of the spectral data, the product **10** is predominantly in the keto form in $CDCl_3$ with little (<10%) of the enol tautomer present.

Other minor polymeric/oligomeric products were present as indicated by numerous small singlets in the *tert*-butyl region (δ 1.1−1.3) and mass spectral identification of a self-condensation product of **10** with m/z 863 for $C_{58}H_{86}O_5 \cdot H^+$ by positive FAB mass spectroscopy. Diketone **10** was sensitive to chromatography on silica gel or to acidic conditions in solution in that some salt of dye **1** was regenerated (λ_{max} 595 nm in CH_2Cl_2) as at least one of the products. Pseudobase **10** was also sensitive to chromatography on neutral or basic alumina with oligomeric/polymeric materials being formed as well as dye **1**.

Similar results were obtained upon hydrolysis of dyes **2**−**4** in which the corresponding pseudobases **11**−**13**, respectively, were isolated as >93% of the hydrolysis product mixtures under either aerobic or anaerobic conditions. These materials regenerated some salt of the corresponding pyrylium dye on silica or under acidic

(5) Detty, M. R.; Merkel, P. B.; Hilf, R.; Gibson, S. L.; Powers, S. K. *J. Med. Chem.* **1990**, *33*, 1108−1116.
(6) Modica-Napolitano, J. S.; Joyal, J. L.; Ara, G.; Oseroff, A. R.; Aprille, J. R. *Cancer Res.* **1990**, *50*, 7876−7881.
(7) Powers, S. K.; Walstad, D. L.; Brown, J. T.; Detty, M. R.; Watkins, P. J. *J. Neurooncol.* **1989**, *7*, 179−183.
(8) Kessel, D. *Photochem. Photobiol.* **1991**, *53*, 73−78.

conditions as well as oligomeric materials. The IR and NMR spectral properties of **11**−**13** were quite similar to those of **10**. Compounds **11**−**13** also appeared to be predominantly (>90%) in the keto form.



14, X = Te
16, X = Se
18, X = S

15, X = Te
17, X = Se
19, X = Se, Te
20, X = S

Hydrolysis of Telluropyrylium Dye 8 at pH 8 under Anaerobic Conditions. Hydrolysis of telluropyrylium dye **8** in rigorously degassed phosphate buffer at pH 8 gave two major products in a 1:1 ratio. These products were identified as telluropyranylidene aldehyde **14** and tris(telluropyranylidenemethyl)methane **15**. Each of these compounds was isolated in 45% yield following chromatography on silica gel. The spectral properties of **14** and **15** were identical to those of authentic samples.[5,9] No other products were detected.

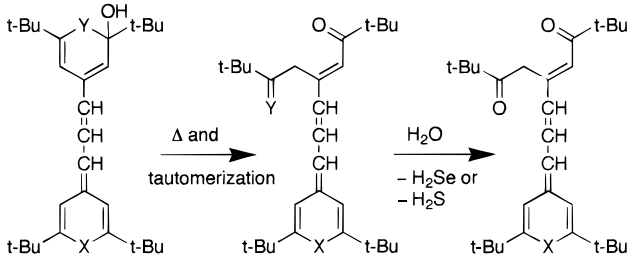
Hydrolysis of Selenopyrylium Dye 6 at pH 8 under Anaerobic Conditions. Selenopyrylium dye **6** gave products derived from both intermediates **A** and **C** of Scheme 1. Hydrolysis of selenopyrylium dye **6** in rigorously degassed phosphate buffer at pH 8 gave two major products in a 1:1 ratio. These two components of the product mixture were separated via chromatography on basic alumina eluted with 10% ethyl acetate/dichloromethane (35% isolated yield for each relative to starting **6**). Aldehyde **16**, identical in all respects to an authentic sample,[5] was identified as one product while the second component was identified as the tris(selenopyranylidenemethyl)methane **17**. The ^{1}H NMR spectrum of **17** displayed two three-proton singlets at δ 6.50 and 6.16, a three-proton doublet at δ 5.05, a one-proton quartet at δ 4.34, and two *tert*-butyl singlets at δ 1.21 and 1.16. The field desorption mass spectrum of **17** gave a nominal mass of m/z 820 ($C_{43}H_{64}{}^{80}Se_3$) for the expected product.

Pseudobase **12** was identified as a third component in 10% yield based on the ^{1}H NMR spectrum of the crude product mixture, which contained signals identical to the spectrum of the product produced from hydrolysis of **3**. Attempts to isolate **12** via chromatography on silica gel or alumina generated selenopyrylium dye chromophore **3** (λ_{max} 665 nm in dichloromethane).

Hydrolysis of Chalcogenopyrylium Dye 5 at pH 8 under Anaerobic Conditions. Hydrolysis of the mixed seleno-/thiopyrylium dye **5** in rigorously degassed phosphate buffer at pH 8 gave pseudobase **11** as the major component of hydrolysis (93% relative yield). Chalcogenopyranyl aldehydes[5] **16** and **18** were detected at 5% and 2% yields, respectively, relative to **11** (by ^{1}H NMR).

Hydrolysis of Chalcogenopyrylium Dye 7 at pH 8 under Anaerobic Conditions. Hydrolysis of the mixed seleno-/telluropyrylium dye **7** (5×10^{-4} M) in rigorously degassed phosphate buffer at pH 8 gave a mixture of pseudobase **13**, aldehydes **14** and **16**,[5] and a mixture of tris(chalcogenopyranylidenemethyl)methanes **15**, **17** and Se_2Te and $SeTe_2$ combinations **19** by ^{1}H NMR. The relative yield of **13** was approximately 30% of the product mixture as determined from the ^{1}H NMR spectrum of the crude product mixture. Aldehydes **14** and **16** were isolated in 25% yield (36% relative yield based on the ^{1}H NMR integral of the aldehyde protons) following chromatography on silica gel as an inseparable 55:45 mixture of **14** and **16**. The tris(chalcogenopyranylidenemethyl)methane components were isolated in 20% yield (32% relative yield based on the ^{1}H NMR integral of the aliphatic methines) and showed nearly a statistical distribution of all possible heteroatom combinations (**15**, **17** and Se_2Te and $SeTe_2$ combinations **19**) by both ^{1}H NMR and field desorption mass spectroscopy (FDMS).

Scheme 2



21(X,Y)
X,Y = O, S, Se, Te

22(X,Y)
X,Y = O, S, Se, Te

11, X = S
12, X = Se
13, X = Te

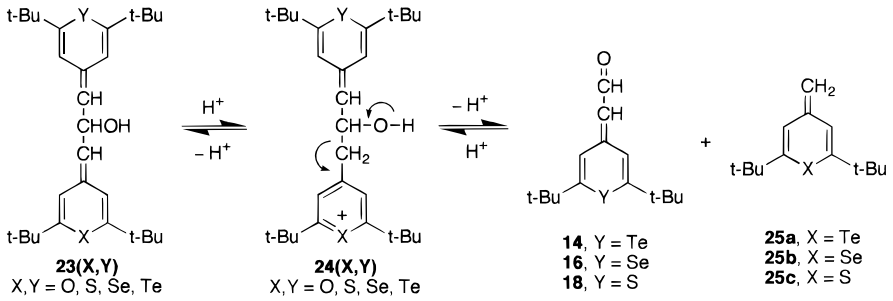
Hydrolysis of Thiopyrylium Dye 9 at pH 12. Hydrolysis of thiopyrylium dye **9** (5×10^{-4} M) in rigorously degassed phosphate buffer at pH 12 gave a complex mixture of products from which pseudobase **11**, thiopyranyl aldehyde **18**, and tris(thiopyranylidenemethyl)methane **20** were identified in nearly equal proportions. Compounds **18** and **20** were separable from the product mixture via careful chromatography. The composition of the product mixtures was time dependent, and mass spectral analysis of the product mixtures showed increasing amounts of higher molecular weight components with reaction time. These higher molecular weight compounds were composed primarily of three components with m/z 689 ($C_{44}H_{64}O_2S_2{\cdot}H^+$), m/z 705 ($C_{44}H_{64}OS_3{\cdot}H^+$), and m/z 927 ($C_{58}H_{86}OS_4{\cdot}H^+$) by positive FAB mass spectroscopy.

Compound **20** was characterized by two, three-proton olefinic singlets at δ 6.50 and 6.17, a three-proton olefinic doublet at δ 4.75 (J = 9 Hz), a one-proton quartet at δ 4.16 (J = 9 Hz), and two *tert*-butyl singlets at δ 1.22 and 1.17. The positive FAB mass spectrum of **20** gave a parent ion with m/z 677 for $C_{43}H_{64}S_3{\cdot}H^+$.

Discussion of Part A. Formation of Pseudobases 10−13. The addition of hydroxide to the 2-position of the dyes **1**−**4** (intermediate **A** of Scheme 1) leads to the formation of the pseudobases **10**−**13**. For pyrylium dye **1** and the mixed pyrylium/chalcogenopyrylium dyes **2**−**4**, addition of hydroxide to the 2-position of the pyrylium ring to give alcohols **21(X,O)** leads to ring-opening. Thermal rearrangement of alcohols **21(X,O)** followed by tautomerization would give the pseudobases **10**−**13**, respectively, as shown in Scheme 2.

For dyes **5**−**7**, addition of hydroxide to the 2-position of the selenopyrylium ring leads to alcohols **25**−**27**. Thermal rearrangement and tautomerization of **21(X,Se)** would give seleno ketones **22(X,Se)**, which can then be hydrolyzed to pseudobases **11**−**13** as shown in Scheme 2.

Scheme 3



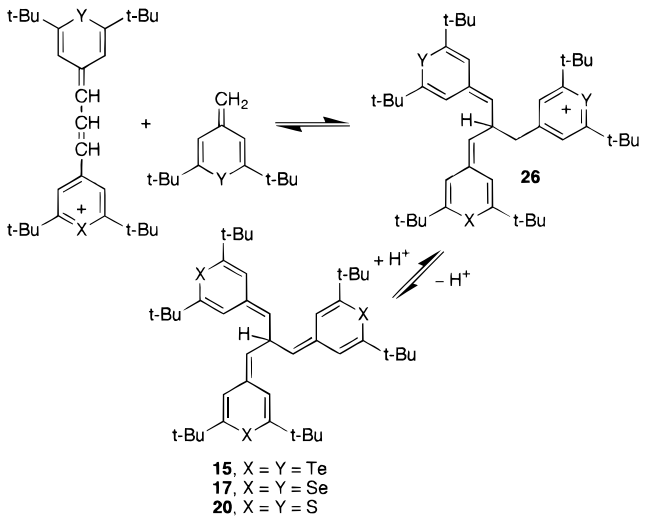
A similar route may be invoked for thiopyrylium dye **9**. For dye **9**, ring-opening of alcohol **21(S,S)** to thione **22(S,S)** is followed by hydrolysis of the thione at pH 12. Under these basic conditions, **22(S,S)** and **11** were both reactive toward condensation reactions to give higher molecular weight materials. Products with *m*/*z* 689 ($C_{44}H_{64}O_2S_2 \cdot H^+$), *m*/*z* 705 ($C_{44}H_{64}OS_3 \cdot H^+$), and *m*/*z* 927 ($C_{58}H_{86}OS_4 \cdot H^+$) correspond to condensation of **11** with aldehyde **18**, condensation of thione **22(S,S)** with aldehyde **18**, and self-condensation of thione **22(S,S)**, respectively.

Formation of Chalcogenopyranyl Aldehydes 14, 16, and 18 and Tris(chalcogenopyranylidenemethyl)methanes 15, 17, 19, and 20. In contrast to dyes **1**−**7** and **9**, telluropyrylium dye **8** gave no detectable products derived from addition of hydroxide to the 2-position under rigorously anaerobic conditions. Instead, both products were derived from addition of hydroxide to the central carbon of the trimethine bridge to give alcohol **23(Te,Te)** (alcohol **C** of Scheme 1). This also appears to be a major hydrolysis pathway for **6**, **7**, and **9**, as well. As shown in Scheme 3, protonation of the alcohols **23(X,Y)** leads to chalcogenopyrylium intermediates **24(X,Y)**, which can then fragment to give aldehydes **14**, **16**, and **18** and 4-methylidene chalcogenopyrans **25**. The route of Scheme 3 would also be followed to give trace amounts of chalcogenopyranyl aldehydes detected in the hydrolysis of dye **5**. With dye **5**, the corresponding tris(chalcogenopyranylmethylidene) methanes were not detected in the product mixture.

The 4-methylidene chalcogenopyrans **25** can react with starting dye as shown in Scheme 4 to give a new chalcogenopyrylium intermediate **26**. The loss of a proton from the initial adduct **26** leads to the tris(chalcogenopyranylidenemethyl)methanes **15**, **17**, **19**, and **20**. The reversibility of the steps shown in Scheme 4 has been demonstrated via heteroatom scrambling in the synthesis of unsymmetrical dyes **5** and **7**[9] and is consistent with the formation of a statistical mixture of tris(chalcogenopyranylidenemethyl)methane products from dye **7** in the current study.

Part B. Product Studies at pH 8 under Aerobic Conditions. The hydrolysis studies under aerobic conditions were carried out in 0.25 M dibasic potassium phosphate which was air-saturated. The dyes **1**−**8** (5×10^{-4} M) in MeOH were added slowly to the buffer at the temperatures indicated for the anaerobic reactions. Dye **9** (5×10^{-4} M) was hydrolyzed at pH 12. The final concentration of MeOH in the hydrolysis mixture did not exceed 1% by volume.

Scheme 4



Hydrolysis of Pyrylium Dyes 1−4 at pH 8 under Aerobic Conditions. Hydrolysis of **1**−**4** in aerated phosphate buffer at pH 8 gave product mixtures nearly identical to the anaerobic products. The major product in each case was the corresponding pseudobase **10**−**13** (>95%). Small quantities (<3%) of thiopyranone **27** from **2**, selenopyranone **28** from **3**, and telluropyranone **29** from **4** were detected by ^{1}H NMR in the aerobic product mixtures as well as trace amounts of aldehydes **18**, **16**, and **14**, respectively. Compounds **27**−**29** were identical spectroscopically to authentic samples prepared by other means.[10]

Hydrolysis of Symmetrical Dyes 6, 8, and 9. Hydrolysis of Telluropyrylium Dye 8 at pH 8 under Aerobic Conditions. Hydrolysis of **8** in aerated phosphate buffer at pH 8 gave four monomeric products as determined by ^{1}H NMR. Telluropyranyl aldehyde **14** was produced in 35% relative yield and tris(telluropyranylidenemethyl)methane **15** was produced in 25% relative yield. Two new products were produced: telluropyranone **29** in 7% relative yield and tellurophene **30(Te,Te)** in 33% relative yield. Compound **30(Te,Te)** was identical spectroscopically to an authentic sample of **30(Te,Te)**[11] prepared by other means. These materials were separable via careful flash chromatography on silica gel eluted with CH_2Cl_2.

Tellurophene **30(Te,Te)** is formed via an oxidative rearrangement involving the 2-position of the telluropyrylium ring. Oxidation of the alcohol formed by addition of water (hydroxide) to the 2-position of the telluropyrylium ring (intermediate **A** of Scheme 1) would lead to this product.

Hydrolysis of Dye 6 at pH 8 under Aerobic Conditions. Hydrolysis of **6** in aerated phosphate buffer

(9) Detty, M. R.; Young, D. N.; Williams, A. J. *J. Org. Chem.* **1995**, *60*, 6631−6635.
(10) Detty, M. R.; Hassett, J. W.; Murray, B. J.; Reynolds, G. A. *Tetrahedron* **1985**, *45*, 4853−4861.
(11) Detty, M. R. *Organometallics* **1991**, *10*, 702−711.

at pH 8 gave four major products as determined by ^{1}H NMR. Aldehyde **16** was produced in 37% relative yield, tris(selenopyranylidenemethyl)methane **17** was produced in 5% relative yield (by ^{1}H NMR), and two new products: selenopyranone **28**[10] in 42% yield and selenophene **30(Se,Se)** in 16% yield. Pseudobase **12** was not detected.

The ^{1}H NMR spectrum of **30(Se,Se)** was quite similar to that observed for **30(Te,Te)** and was characterized by three one-proton singlets for the selenophene (δ 7.30) and selenopyranyl protons (δ 6.82 and 6.33), two doublets [δ 6.00 (J = 12 Hz) and 6.53 (J = 15 Hz)] and a doublet of doublets [δ 7.07 (J = 12, 15 Hz)] for the trimethine bridge between the rings, and four *tert*-butyl singlets (δ 1.37, 1.28, 1.27, 1.21). The field desorption mass spectrum displayed a parent ion cluster of m/z 566 for $C_{29}H_{42}O^{80}Se_2$. The infrared spectrum displayed a carbonyl stretching frequency at 1670 cm^{-1}.

Selenophene **30(Se,Se)** is most likely formed via a path similar to the formation of tellurophene **30(Te,Te)**. Under aerobic conditions, oxidation of the 2-hydroxy addition product **21(Se,Se)** is faster than ring opening to and hydrolysis of the seleno ketone **22(Se,Se)**.

Hydrolysis of Dye 9 at pH 12 under Aerobic Conditions. Hydrolysis of dye **9** in phosphate buffer at pH 12 gave a mixture of products from which pseudobase **11**, aldehyde **18**, tris(thiopyranylmethylidene)methane **20**, and thiopyranone **27** were identified. On the basis of the ^{1}H NMR spectrum of the mixture, **18**[5] and **27**[10] were present in nearly equal amounts and were isolated in 20 and 22% yields, respectively, following chromatography on silica gel. Pseudobase **11** and tris(thiopyranylidenemethyl)methane **20** were detected at 5−10% yields relative to **18** and **27** by ^{1}H NMR, but were not isolated. The higher molecular weight components that were observed in the anaerobic reactions were also observed in the aerobic reactions.

Hydrolysis of Unsymmetrical Chalcogenopyrylium Dyes. Hydrolysis of Dye 5 at pH 8 under Aerobic Conditions. Hydrolysis of **5** in aerated phosphate buffer at pH 8 gave a multicomponent product mixture. Pseudobase **11** was a minor component of the aerobic product mixture, formed in approximately 7% relative yield by ^{1}H NMR. Aldehydes **16** and **18** were isolated in 30% yield as an inseparable 2:1 mixture, respectively. Pyranones **27** and **28**[10] were isolated in 45% yield as an inseparable 4:3 mixture, respectively.

New products, consistent with selenophene **30(Se,S)** and/or thiophene **30(S,Se)**, were present in roughly 5% yield. The field desorption mass spectrum of the crude product mixture gave parent ion clusters with nominal mass m/z 518 for $C_{29}H_{42}OS^{80}Se$ [for either **30(Se,S)** or **(S,Se)**]. The ^{1}H NMR spectrum of the mixture displayed two new singlets for the selenophene/thiophene protons at δ 7.28 and 7.07, four new olefinic singlets at δ 6.68, 6.54, 6.29, 6.27, and overlapping doublets in each of the δ 5.90−5.95 and δ 6.25−6.35 regions. The doublet-of-doublet patterns for the central methine carbons were contained in the δ 6.90−7.10 region.

Hydrolysis of Dye 7 at pH 8 under Aerobic Conditions. Hydrolysis of the mixed seleno-/telluropyrylium dye **7** in aerated phosphate buffer at pH 8 gave a product mixture with six significant components by ^{1}H NMR. The major component was pseudobase **13** (35% relative yield). The second most abundant product was tellurophene **30(Te,Se)**[11] (29% relative yield) with no **30(Se,Te)** detected by ^{1}H NMR. Pyranones **28** and **29** were present in 14 and 7% relative yields, respectively. Aldehydes **14** and **16** were present in 10 and 5% relative yields, respectively.

Careful flash chromatography on silica gel gave **30(Te,Se)** in 25% isolated yield, a 2:1 mixture of **14** and **16**, respectively, in 15% isolated yield, and a 2:1 mixture of **28** and **29**, respectively, in 10% isolated yield. Pseudobase **13** did not survive the chromatography.

Part C. Effects of pH and Oxygen Concentrations on Product Distributions. Changes in pH as well as changes in oxygen concentration led to different distributions of products in the hydrolysis reactions. The effects of pH changes on product distributions under both anaerobic and aerobic conditions were examined as well as the effects of increasing oxygen concentrations at common values of pH with dyes **6** and **8**.

Product Studies with Telluropyrylium Dye 8 over the pH Range 6.9−11.0. Under anaerobic conditions, hydrolysis of **8** gave one-to-one mixtures of aldehyde **14** and tris(telluropyranylidenemethyl)methane **15** at pH 6.9, 8.4, 9.6, and 11.0 in degassed phosphate buffers. The apparent rate of hydrolysis increased with pH.

In aerated buffer, however, the product distribution from **8** was pH dependent. At pH 6.9, the product ratio from **8** was 40% for **14**, 21% for **15**, 6% for telluropyranone **29**, and 33% for tellurophene **30(Te,Te)**. At pH 8.4, the product ratios were 35:25:7:33; at pH 9.6, the product ratios were 25:15:8:52; and at pH 11.0, the product ratios were 18:6:9:67 for **14**:**15**:**28**:**30(Te,Te)**.

In oxygenated buffer (purging the reaction with O_2), tellurophene **30(Te,Te)** was nearly the exclusive product from **8** at both pH 8.4 and 11.0. No **15** was detected, and the ratio of **14**:**28**:**30(Te,Te)** was 3:2:95 at pH 8 and 1:1:98 at pH 11.0.

In this sequence of reactions, the relative yields of products derived from hydroxide addition to the 2-position of the dye increased with pH and with oxygen concentration. Under anaerobic conditions, no changes in product ratios were observed with increasing pH.

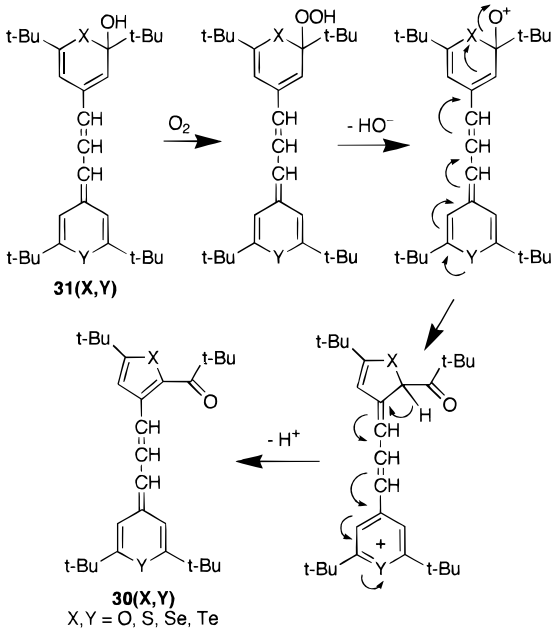
Product Studies with Dye 6 at pH 8.4 and 11.0. Under anaerobic conditions, the ratio of aldehyde **16** to tris(selenopyranylidenemethyl)methane **17** to pseudobase **12** was 45:45:10. At pH 11.0, the product ratio was 37:37:26 for **16**:**17**:**12**.

In aerated and oxygenated buffers at pH 8.4, selenopyranone **28** and selenophene **30(Se,Se)** were also formed as products in addition to **16** and **17** while **12** was not detected. The product ratios for **16**:**17**:**28**: **30(Se,Se)** at pH 8.4 were 37:5:42:16 in aerated buffer and 30:3:45:22 in oxygenated buffer. In aerated pH 11.0 buffer, the product ratios for **12:16**:**17**:**28**:**30(Se,Se)** were 5:25:18:17:35.

As with telluropyrylium dye **8**, the relative yields of products derived from hydroxide addition to the 2-position of dye **6** increased with pH and with oxygen concentration. However, the changes in product ratios were much smaller than those observed with **8**.

Discussion of Parts B and C. Effects of pH and Oxygen on Product Distributions. For **8**, where hydrolysis products at pH 8 under anaerobic conditions are derived from hydroxide addition to the central carbon of the trimethine bridge, increasing pH had no effect on the product ratio. For selenopyrylium dye **6** where pseudobase **12** is formed by hydrolysis of seleno ketone **22(Se,Se)**, an increase in pH under anaerobic conditions increased the relative yield of pseudobase **12**, presumably by increasing the rate of seleno ketone hydrolysis. One

Scheme 5



can conclude that the telluropyrylium ring is not prone to ring-opening reactions with hydroxide.

Under aerobic conditions, products derived from tertiary alcohols **A** of Scheme 1 increased with increasing pH. Increased oxygen concentrations also increase the relative yields of hydrolysis products derived from alcohols **A**. This suggests that the addition of hydroxide is reversible allowing intermediates **A**−**C** to equilibrate and that the rate-determining step (irreversible step) in the hydrolysis can change with pH and with oxygen concentration. Based on the aerobic product studies and the effects of increasing oxygen concentration, the tertiary alcohol derived from hydroxide addition to the 2-position of telluropyrylium dye **8** was much more readily oxidized than the tertiary alcohol derived from selenopyrylium dye **6**. Thus, the heteroatoms adjacent to the tertiary alcohol appear to influence the rates of oxidation.

Formation of Chalcogenophene Products. The formation of the chalcogenophene products under aerobic conditions is rationalized in Scheme 5. The addition of water or hydroxide to the 2-position of **1**−**9** leads to alcohol intermediates represented by **31(X,Y)** in Scheme 5. If oxidation of the alcohol were competitive with ring opening, then oxidative ring contraction[10] would lead to the observed products. Alcohols **31** with X = Te are apparently more readily oxidized than alcohols **31** with X = O, S, or Se. The yields of the chalcogenophene products increased both with pH and with O_2 concentration. Oxygen becomes a more efficient oxidant as pH increases primarily due to increased rates of electron transfer to give superoxide.[12] The apparent increase in rate of the oxidation of tertiary alcohols **31** with increasing pH and increasing O_2 concentration is consistent with this observation. The formation of superoxide under aerobic conditions might provide an oxidative path for degradation of the chalcogenopyrylium dyes during hydrolysis.

Formation of Pyranones 27−29. In rigorously degassed buffer, the product mixtures do not contain **27**−**29**. These products appear only upon introduction of O_2 to the reaction mixtures, which implicates an oxidative pathway to these products. The yields of aldehydes **14**, **16**, and **18**, on the other hand, are relatively unchanged between aerobic and anaerobic conditions. However, the yields of tris(chalcogenopyranylidenemethyl)methanes (**15**, **17**, **19**, and **20** from **6**−**9**) are greatly diminished under aerobic conditions relative to anaerobic conditions.

These observations suggested several routes to the formation of the chalcogenopyranones **27**−**29**. The apparent necessity of O_2 in the formation of **27**−**29** excludes a direct hydrolytic fragmentation of tertiary alcohols **B** of Scheme 1 as a route to these compounds. In the presence of O_2, tertiary alcohols **B** might be readily oxidized to give **27**−**29**. However, we have neither detected nor isolated a product derived from the other "half" of the alcohols **B** of Scheme 1.

Another plausible route to the formation of the chalcogenopyranones is the oxidation of the 4-methylidene chalcogenopyrans **25** after they are generated from fragmentation of alcohols **24(X,Y)** (Scheme 3). Oxidation of these species would prevent the subsequent formation of the tris(chalcogenopyranylidenemethyl)methanes in the product mixtures.

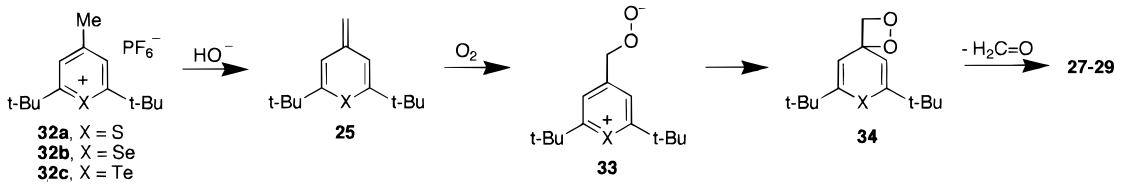
The slow addition of a CH_3CN solution of 4-methylthiopyrylium hexafluorophosphate **32a** to aerated pH 8.4 phosphate buffer over a 1-h period at ambient temperature gave a product mixture from which thiopyranone **27** was isolated in 15% yield (Scheme 6). Similar reactions with 4-methylselenopyrylium hexafluorophosphate **32b** and with 2,6-di-*tert*-butyl-4-methyltelluropyrylium hexafluorophosphate **32c** gave selenopyranone **28** and telluropyranone **29** in 15 and 22% isolated yields, respectively. If one assumes that deprotonation is the first step in the reactions to produce 4-methylidenechalcogenopyrans **25**,[9] then formation of the chalcogenopyranones might follow the path outlined in Scheme 6. The addition of oxygen to the methylidene carbon of **25** would generate a diradical or zwitterionic species **33**, which might collapse to dioxetanes **34**. Thermal cleavage of **34** would generate the corresponding chalcogenopyranone and formaldehyde.

Superoxide Addition to Dye 8. An alternative route to the chalcogenopyranones might involve the addition of superoxide, produced during the oxidation of tertiary alcohols with O_2, to the chalcogenopyrylium dyes. The addition of excess KO_2 to a solution of **8** in 90% MeOH gave a product mixture containing telluropyranone **29** in >95% relative yield (92% isolated yield) and trace amounts (<3%) of aldehyde **17**. Tellurophene **30(Te,Te)** was not detected in the product mixture.

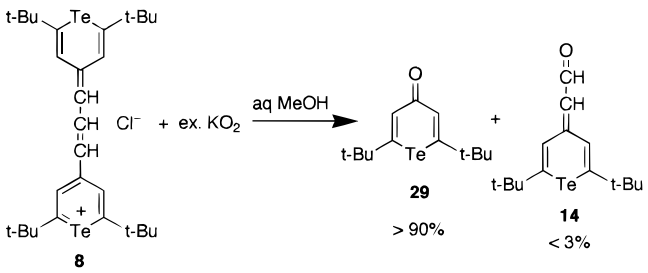
Reactions of Dye 8 with Oxygen in MeOH. The addition of O_2 to the dyes **1**−**9** prior to a hydrolytic event can be excluded as a an explanation of the differences in product mixtures between anaerobic and aerobic conditions. MeOH solutions of telluropyrylium dye **8** were stable for at least several months in deoxygenated solutions stored under an argon atmosphere. Aerated MeOH solutions of dye **8** gave a slow reaction to produce dye **4** (approximately 20% conversion after two weeks at ambient temperature) and smaller amounts of dye **1**. Products of hydrolysis from **1** and **4** were not detected in the hydrolysis studies of **8**. Telluropyranone **29**, telluropyranyl aldehyde **14**, and tellurophene **30(Te,Te)** were not detected in the aerated MeOH solutions of **8**.

(12) Kuta, J.; Koryta, J. *Coll. Czech. Chem. Commun.* **1965**, *30*, 4095−4101.

Scheme 6



Scheme 7



Summary and Conclusions

The addition of water (hydroxide) to chalcogenopyrylium dyes **1**−**9** to give intermediates **A**−**C** of Scheme 1 appears to be a reversible process. The ratio of products derived from these intermediates changes with the heteroatoms contained in the rings as well as in the presence or absence of oxygen. The heteroatoms present in the chalcogenopyrylium nuclei influence the types of products observed in hydrolysis reactions. Under anaerobic conditions, dyes containing a pyrylium nucleus (dyes **1**−**4**) give products derived from ring opening of the pyrylium ring as shown in eq 1 via intermediates **A** of Scheme 1. This process is much more rapid in these dyes than irreversible processes involving addition of hydroxide to the 4-position of the dyes or to the central carbon of the trimethine linkage (intermediates **B** and **C**, respectively, of Scheme 1).

Under anaerobic conditions for the symmetrical dyes **1**, **6**, **8**, and **9** and for the unsymmetrical dyes **5** and **7**, the ratio of products derived from intermediate **C** of Scheme 1 relative to products derived from intermediate **A** increases as the chalcogen atoms in the rings increase in atomic number (O < S < Se < Te). Hydrolysis of telluropyrylium dye **8** under anaerobic conditions gives products derived exclusively from addition of hydroxide to the central carbon of the trimethine bridge. Thiopyrylium dye **9** and selenopyrylium dyes **5**−**7** give products derived from addition of hydroxide both to the 2-position and to the central carbon of the trimethine bridge under anaerobic conditions. Addition of hydroxide to the 2-position is followed by ring-opening to the thio- or selenoketone and subsequent hydrolysis of the thio- or selenoketone to give the diketo pseudobases. The relative yields of pseudobase increase with pH, which is presumably due to increased rates of thio- or selenoketone hydrolysis. The increase in relative yield with pH also suggests that addition of water (hydroxide) to either the 2-position or the central methine carbon of the trimethine bridge is a reversible process. Oxidation of the selenohemiketal intermediates **21(X,Se)** (Scheme 2) appears to be slower than oxidation of telluro-hemiketals **31(Te,Te)** and **31(Te,Se)** (Scheme 5) and slower than ring-opening of intermediates **21(X,Se)** to the selenoketones **22(X,Se)** with subsequent hydrolysis.

Under aerobic conditions, oxidation of the intermediate alcohols **A** and/or **B** of Scheme 1 can become a competitive, irreversible step in the hydrolysis reactions (formation of chalcogenophenes **30(X,Y)** from intermediate **A**, perhaps the formation of the chalcogenopyranones **27**−**29** from intermediate **B**), which reduces the amount of products derived from intermediate **C**. The rate of oxidation relative to other hydrolysis reactions increases as the chalcogen atoms in the rings increase in atomic number (O < S < Se < Te). Oxidations of the telluro-hemiketals from dyes **7** and **8** are much more rapid than oxidations of seleno- or thio-hemiketals from dyes **5**−**7**. Increasing oxygen concentrations increase the relative yields of products derived from intermediate **A**. Ring-opening reactions of pyrylium nuclei are much more rapid than oxidation of seleno-hemiacetals and telluro-hemiacetals derived from dyes **3** and **4**, respectively. Oxidation of the telluro-hemiketal derived from dye **8** is comparable in rate to ring opening of the seleno-hemiketal and subsequent hydrolysis of the resulting seleno ketone.

The changing ratios of products from initial addition of hydroxide (water) to give intermediates **A** and **C** suggests that the hydroxide addition is reversible. The scrambling of heteroatoms in the formation of the tris(chalcogenopyranylidenemethyl)methane mixture from dye **7** is indicative that the steps leading to these products are also reversible as shown in Scheme 4. Under acidic conditions, diketones **10**−**13** regenerate the pyrylium ring, which indicates reversibility as well. At pH 8 or above, the cyclization−dehydration of the diketones may be sufficiently slow to render their formation as an irreversible step. The changes in product mixtures between aerobic and anaerobic conditions are primarily due to changes in the relative rates of the irreversible steps of the hydrolyses and not due to a kinetic partitioning of the intermediates **A**−**C** of Scheme 1.

We are currently investigating the different array of products formed under acidic conditions as well as the kinetics of hydrolysis of dyes **1**−**9** at different values of pH.

Experimental Section

General Methods. Solvents (acetonitrile, ether, ethyl acetate, methanol, dichloromethane), deuteriochloroform, magnesium sulfate, potassium superoxide, and mono-, di-, and tribasic salts of potassium phosphate were used as received from Aldrich Chemical Co. Dyes **1**−**9** were prepared according to reference 5. Preparative reactions were stirred magnetically. Concentration *in vacuo* was performed on a Büchi rotary evaporator. Nuclear magnetic resonance (NMR) spectra were recorded at 30.0 °C on a Varian Gemini-300 instrument with residual solvent signal as internal standard: $CDCl_3$ (δ 7.26 for proton, δ 77.0 for carbon). UV-visible−near-IR spectra were recorded on a Perkin-Elmer Lambda 12 spectrophotometer equipped with a circulating constant-temperature bath for the sample holder. Elemental analysis was conducted by Atlantic Microanalytical, Inc.

Preparation of Buffer Solutions for Hydrolysis Studies. Stock solutions of mono- (solution **A**, 1.50 M), di- (solution **B**, 0.5 M), and tribasic salts (solution **C**, 0.25 M) of potassium phosphate were used to prepare the buffer solutions with

nearly constant values of [K^+] (0.53 ± 0.07 M) and μ (0.75 ± 0.15). Buffer solutions of approximately pH 7.0 were prepared from 430 mL of solution **B**, 70 mL of solution **C**, and 500 mL of water ([K^+] 0.53 M, μ 0.75). Buffer solutions of approximately pH 8.0 were prepared from 500 mL of solution **B** and 500 mL of water ([K^+] 0.50 M, μ 0.75). Buffer solutions of approximately pH 9.0 were prepared from 430 mL of solution **B**, 70 mL of solution **C**, and 500 mL of water ([K^+] 0.50 M, μ 0.75). Buffer solutions of approximately pH 10.0 were prepared from 20 mL of solution **A**, 480 mL of solution **B**, and 500 mL of water ([K^+] 0.49 M, μ 0.75). Buffer solutions of approximately pH 11.0 were prepared from 200 mL of solution **A**, 300 mL of solution **B**, and 500 mL of water ([K^+] 0.45 M, μ 0.75). Buffer solutions of approximately pH 12.0 were prepared from 600 mL of solution **A** and 400 mL of water ([K^+] 0.45 M, μ 0.90). Final pH was determined by pH meter calibrated to standards at pH 8.00, 10.00, and 12.00.

General Procedure for Product Studies of Hydrolysis Reactions. A 0.10 mmol sample of dye **1**−**9** was dissolved in 2 mL of CH_3OH. The resulting solution was added dropwise via syringe to 200 mL of buffer solution at the pH values indicated in the text. For anaerobic conditions, CH_3OH was dearated by a stream of argon bubbles and phosphate buffer solutions were dearated by a stream of argon bubbles for 20 min followed by repeated evacuations and argon-purges in septum-sealed flasks. For aerated reactions, solutions were stirred magnetically while open to the air. Increased oxygen levels were realized by bubbling a slow stream of oxygen through the hydrolysis mixture during reaction. Hydrolysis reactions with telluropyrylium dyes **4**, **7**, and **8** were conducted for 0.5, 1, and 3 h, respectively, at ambient temperature and run in the dark to prevent the generation of singlet oxygen.[10,13] Hydrolysis reactions with **3** were conducted for 1.0 h. Hydrolysis reactions with dyes **1**, **6**, and **9** were conducted at ambient temperature for 15−24 h until the characteristic dye color faded from the flask. Hydrolysis reactions with dye **5** were conducted at 60 °C for 15−24 h until the characteristic dye color faded from the flask. Products were extracted with ether or CH_2Cl_2 (3 × 50 mL), and the combined extracts were washed with brine, dried over $MgSO_4$, and concentrated. The crude reaction mixtures were examined by ^{1}H NMR to give the product ratios described in the text. The product mixtures were then purified via chromatography on silica gel or basic alumina eluted initially with CH_2Cl_2 and then with increasing EtOAc as cosolvent up to 10% EtOAc in CH_2Cl_2. The pseudobases **10**−**13** were lost during chromatography being converted to some salt of dyes **1**−**4**, respectively. The dye chromophores were removed from the absorbents with MeOH. Yields are listed in the text for anaerobic and aerobic conditions following chromatographic separation. Yields of the pseudobases **10**−**13** described in the text are for mass balance purposes and represent the mass of the product mixture (assuming dye + hydroxide − chloride), which contained ≥93% pseudobase in each case. Spectral descriptions of the hydrolysis products are described below in the order of their first description in the text.

Pseudobases 10−13. For pseudobase **10**: oil, ^{1}H NMR ($CDCl_3$) δ 6.68 (d × d, 1 H, J = 12, 15 Hz), 6.44 (s, 1 H), 6.10 (d, 1 H, J = 15 Hz), 5.86 (s, 1 H), 5.58 (s, 1 H), 5.42 (d, 1 H, J = 12 Hz), 4.28 (s, 2 H), 1.28 (s, 9 H), 1.16 (s, 9 H), 1.15 (s, 9 H), 1.13 (s, 9 H); IR (film, NaCl) 1712.7, 1670.3 cm^{-1}; positive FAB, m/z 441.3329 (calcd for $C_{29}H_{44}O_3{\cdot}H^+$: 441.3369).

For pseudobase **11**: oil, ^{1}H NMR ($CDCl_3$) δ 6.82 (d × d, 1 H, J = 12, 15 Hz), 6.74 (s, 1 H), 6.42 (s, 1 H), 6.34 (s, 1 H), 6.27 (d, 1 H, J = 15 Hz), 5.96 (d, 1 H, J = 12 Hz), 4.18 (s, 2 H), 1.27 (s, 9 H), 1.23 (s, 9 H), 1.19 (s, 9 H), 1.14 (s, 9 H); IR (film, NaCl) 1708, 1660 cm^{-1}; FDMS, m/z 504.2501 (calcd for $C_{29}H_{44}O_2{}^{80}Se$: 504.2507).

For pseudobase **12**: oil, ^{1}H NMR ($CDCl_3$) δ 6.97 (d × d, 1 H, J = 12, 15 Hz), 6.82 (s, 1 H), 6.38 (s, 1 H), 6.32 (s, 1 H), 6.26 (d, 1 H, J = 15 Hz), 5.91 (d, 1 H, J = 12 Hz), 4.31 (s, 2 H), 1.27 (s, 9 H), 1.23 (s, 9 H), 1.18 (s, 9 H), 1.15 (s, 9 H); IR (film, NaCl) 1709, 1661 cm^{-1}; positive FAB, m/z 457.3126 (calcd for $C_{29}H_{44}O_2S{\cdot}H^+$: 457.3140).

For pseudobase **13**: oil, ^{1}H NMR ($CDCl_3$) δ 6.88 (d × d, 1 H, J = 12, 15 Hz), 6.78 (s, 1 H), 6.55 (s, 1 H), 6.36 (s, 1 H), 6.32 (d, 1 H, J = 15 Hz), 6.08 (d, 1 H, J = 12 Hz), 4.24 (s, 2 H), 1.26 (s, 9 H), 1.22 (s, 9 H), 1.21 (s, 9 H), 1.13 (s, 9 H); ^{13}C NMR ($CDCl_3$) δ 210.9 (C═O), 205.9 (C═O), 148.9, 141.0, 140.2, 133.2, 130.4, 129.0, 127.6, 127.5, 122.8, 120.3, 44.6, 43.9, 40.0, 39.5, 36.7 (CH_2), 31.4 (CH_3), 29.7 (CH_3), 27.0 (CH_3), 26.7 (CH_3); IR (film, NaCl) 1707, 1654 cm^{-1}; FDMS, m/z 554.2399 (calcd for $C_{29}H_{44}O_2{}^{130}Te$: 554.2404).

Aldehydes 14, 16, and 18. For aldehyde **14**:[9] ^{1}H NMR ($CDCl_3$) δ 10.21 (d, 1 H, J = 7 Hz), 8.02 (s, 1 H), 6.66 (s, 1 H), 5.87 (d, 1 H, J = 7 Hz), 1.33 (s, 9 H), 1.29 (s, 9 H); IR (film, NaCl) 1640 cm^{-1}; FDMS m/z 348 ($C_{15}H_{22}O^{130}Te$).

For aldehyde **16**:[5] ^{1}H NMR ($CDCl_3$) δ 10.00 (d, 1 H, J = 7 Hz), 7.99 (s, 1 H), 6.60 (s, 1 H), 5.68 (d, 1 H, J = 7 Hz), 1.24 (s, 9 H), 1.20 (s, 9 H); IR (film, NaCl) 1645 cm^{-1}; FDMS m/z 298 ($C_{15}H_{22}O^{80}Se$).

For aldehyde **18**:[5] ^{1}H NMR ($CDCl_3$) δ 9.85 (d, 1 H, J = 7 Hz), 7.98 (s, 1 H), 6.60 (s, 1 H), 5.52 (d, 1 H, J = 7 Hz), 1.24 (s, 9 H), 1.20 (s, 9 H); positive FAB, m/z 251 ($C_{15}H_{22}OS{\cdot}H^+$).

Tris(chalcogenopyranylidenemethyl)methanes 15, 17, 19, and 20. For tris(telluropyranylidenemethyl)methane **15**: mp 207−208 °C (lit.[9] mp, 207−208 °C); ^{1}H NMR ($CDCl_3$) δ 6.52 (s, 3 H), 6.20 (s, 3 H), 5.31 (d, 3 H, J = 9 Hz), 4.53 (q, 1 H, J = 9 Hz), 1.215 (s, 27 H), 1.18 (s, 27 H); FDMS, m/z 970 ($C_{43}H_{64}{}^{130}Te_3$).

For tris(selenopyranylidenemethyl)methane **17**: mp 195−198 °C; ^{1}H NMR ($CDCl_3$) δ 6.50 (s, 3 H), 6.16 (s, 3 H), 5.05 (d, 3 H, J = 9 Hz), 4.34 (q, 1 H, J = 9 Hz), 1.21 (s, 27 H), 1.16 (s, 27 H); FDMS, m/z 820 ($C_{43}H_{64}{}^{80}Se_3$). Anal. Calcd for $C_{43}H_{64}Se_3$: C, 63.15; H, 7.89. Found: C, 62.99; H, 7.63

For the tris(chalcogenopyranylidenemethyl) methane mixture of **15**, **17**, and **19**: FDMS, m/z 820 ($C_{43}H_{64}{}^{80}Se_3$), m/z 970 ($C_{43}H_{64}{}^{130}Te_3$), m/z 870 ($C_{43}H_{64}{}^{80}Se_2{}^{130}Te$), m/z 920 ($C_{43}H_{64}{}^{80}Se{}^{130}Te_2$) in 1:2:2:1 ratio.

For tris(thiopyranylidenemethyl)methane **20**: mp, 196−198 °C; ^{1}H NMR ($CDCl_3$) δ 6.50 (s, 3 H), 6.17 (s, 3 H), 4.75 (d, 3 H, J = 9 Hz), 4.16 (q, 1 H, J = 9 Hz), 1.22 (s, 27 H), 1.17 (s, 27 H); positive FAB, m/z 677 ($C_{43}H_{64}S_3{\cdot}H^+$). Anal. Calcd for $C_{43}H_{64}S_3$: C, 76.27; H, 9.53. Found: C, 75.99; H, 9.51.

Chalcogenopyranones 27−29. For thiopyranone **27**:[10] ^{1}H NMR ($CDCl_3$) δ 6.88 (s, 2 H), 1.34 (s, 18 H); positive FAB, m/z 225 ($C_{13}H_{20}OS{\cdot}H^+$).

For selenopyranone **28**:[10] ^{1}H NMR ($CDCl_3$) δ 6.94 (s, 2 H), 1.34 (s, 18 H); FDMS, m/z 272 ($C_{13}H_{20}O^{80}Se$).

For telluropyranone **29**:[10] ^{1}H NMR ($CDCl_3$) δ 7.02 (s, 2 H), 1.34 (s, 18 H); IR (KBr) 1595 cm^{-1}; FDMS, m/z 322 ($C_{13}H_{20}O^{130}Te$).

Chalcogenophenes 30(X,Y). For tellurophene **30(Te,Te)**:[11] oil, ^{1}H NMR ($CDCl_3$) δ 7.74 (s, 1 H), 7.09 (d × d, 1 H, J = 12, 15 Hz), 6.81 (s, 1 H), 6.58 (, 1 H, J = 15 Hz), 6.30 (s, 1 H), 6.08 (d, 1 H, J = 12 Hz), 1.38 (s, 9 H), 1.29 (s, 9 H), 1.27 (s, 9 H), 1.22 (s, 9 H); FDMS, m/z 666 ($C_{29}H_{44}O^{130}Te_2$).

For selenophene **30(Se,Se)**: oil, ^{1}H NMR ($CDCl_3$) δ 7.30 (s, 1 H), 7.07 (d × d, 1 H, J = 11, 14 Hz), 6.82 (s, 1 H), 6.53 (d, 1 H, J = 14 Hz), 6.33 (s, 1H), 6.00 (d, 1 H,J = 11 Hz), 1.37 (s, 9 H), 1.28 (s, 9 H), 1.27 (s, 9 H), 1.21 (s, 9 H); IR (film, NaCl) 1670 cm^{-1}; FDMS, m/z 566 ($C_{29}H_{42}O^{80}Se_2$). Anal. Calcd for $C_{29}H_{42}OSe_2$: C, 61.70; H, 7.50. Found: C, 62.06; H, 7.69.

For selenophene **30(Se,S)**/thiophene **30(S,Se)**: oil, ^{1}H NMR ($CDCl_3$) δ 7.28 and 7.07 (s, 1 H), 7.01 and 7.03 (d × d, 1 H, J = 12, 15 Hz), 6.68 and 6.54 (s, 1 H), 6.28 and 6.30 (d, 1 H, J = 15 Hz), 6.29 and 6.27 (s, 1 H), 5.92 and 5.93 (d, 1 H, J = 12 Hz), 1.38 (s, 9 H), 1.29 (s, 9 H), 1.27 (s, 9 H), 1.22 (s, 9 H); IR (film, NaCl) 1675 cm^{-1}; FDMS, m/z 518 ($C_{29}H_{42}OS^{80}Se$).

This mixture of products was not separable by chromatographic means.

For tellurophene **30(Te,Se)**:[11] oil, ^{1}H NMR ($CDCl_3$) δ 7.75 (s, 1 H), 7.06 (d × d, 1 H, J = 12, 15 Hz), 6.80 (s, 1 H), 6.54 (d, 1 H, J = 15 Hz), 6.31 (s, 1 H), 5.91 (d, 1 H, J = 12 Hz), 1.38 (s, 9 H), 1.26 (s, 18 H), 1.24 (s, 9 H); FDMS, m/z 616 ($C_{29}H_{44}O^{80}Se^{130}Te$).

Generation of Chalcogenopyranones 27−29 from 2,6-Di-*tert*-butyl-4-methylchalcogenopyrylium Salts 32. A

(13) Detty, M. R.; Merkel, P. B. *J. Am. Chem. Soc.* **1990**, *112*, 3845−3855.

solution of 2,6-di-*tert*-butyl-4-methylchalcogenopyrylium hexafluorophosphate[5] (0.50 mmol) in 5 mL of CH_3CN was added dropwise over a 1-h period to a stirred solution of 200 mL of 0.25 M dibasic potassium phosphate (pH 8.2) that was open to the air. The products were extracted with ether (3 × 40 mL), and the combined ether extracts were washed with brine, dried over $MgSO_4$, and concentrated. The residue was purified via chromatography on silica gel eluted with 5% EtOAc in CH_2Cl_2 to separate the corresponding thiopyranone **27** (15% isolated yield), selenopyranone **28** (15% isolated yield), or telluropyranone **29** (22% isolated yield) from other products.

Addition of KO_2 to Telluropyrylium Dye 8. Potassium superoxide (0.25 mmol) was added to a stirred solution of telluropyrylium dye **8** (0.068 g, 0.10 mmol) in 10 mL of 90% MeOH. The resulting solution was stirred 15 h at ambient temperature. The reaction mixture was diluted with 100 mL of water, and the products were extracted with CH_2Cl_2 (3 × 25 mL). The combined organic extracts were washed with brine, dried over $MgSO_4$, and concentrated. The residue was purified via chromatography on silica gel eluted with 5% EtOAc in CH_2Cl_2 to give 0.058 g (90%) of telluropyranone **29** contaminated with trace amounts of aldehyde **14**.

Acknowledgment. The authors thank the National Institute of Health (PHS 1 R01 CA69155-01A1) for financial support. The authors also thank the Eastman Kodak Company for partial support of this work through an unrestricted grant to M.R.D. The authors thank Mr. Jason Kowal (SUNY Buffalo) for technical assistance in the preparation of dyes **1**−**9** and Dr. Petr Serguievski (SUNY Buffalo) for technical assistance in aerobic products studies with dye **4**.

JO970115U