

University of Nebraska - Lincoln

DigitalCommons@University of Nebraska - Lincoln

---

Faculty Publications -- Chemistry Department

Published Research - Department of Chemistry

---

7-18-1979

**Synthesis and Characterization of Bis(Fulvalene)- Divanadium  
and the Crystal Structure of its Oxidation Product,  
Bis(Fulvalene)Bis(Acetonitrile)Divanadium(III)- (V-V)  
Bis(Hexafluorophosphate)-Acetonitrile (1/1)**

James Smart

*University of California, Berkeley, California*

Barry Pinsky

*University of California, Berkeley, California*

Michael Fredrich

*University of Nebraska - Lincoln*

Victor Day

*University of Nebraska - Lincoln*

Follow this and additional works at: <https://digitalcommons.unl.edu/chemfacpub>

 Part of the [Chemistry Commons](#)

---

Smart, James; Pinsky, Barry; Fredrich, Michael; and Day, Victor, "Synthesis and Characterization of Bis(Fulvalene)- Divanadium and the Crystal Structure of its Oxidation Product, Bis(Fulvalene)Bis(Acetonitrile)Divanadium(III)- (V-V) Bis(Hexafluorophosphate)-Acetonitrile (1/1)" (1979). *Faculty Publications -- Chemistry Department*. 23.  
<https://digitalcommons.unl.edu/chemfacpub/23>

This Article is brought to you for free and open access by the Published Research - Department of Chemistry at DigitalCommons@University of Nebraska - Lincoln. It has been accepted for inclusion in Faculty Publications -- Chemistry Department by an authorized administrator of DigitalCommons@University of Nebraska - Lincoln.

in part by National Institutes of Health Grant No. GM 23609.

**Supplementary Material Available:** Structure factor table for DL-2-( $\alpha$ -hydroxybenzyl)oxythiamin chloride hydrochloride trihydrate, anisotropic thermal parameters, and table of interring separations (6 pages). Ordering information is given on any current masthead page.

## References and Notes

- (1) In partial fulfillment of requirements for the Ph.D. degree, University of Pittsburgh.
- (2) A. Schellenberger, *Angew. Chem., Int. Ed. Engl.*, **6**, 1024 (1967).
- (3) M. Sax, P. Pulsinelli, and J. Pletcher, *J. Am. Chem. Soc.*, **96**, 155 (1974).
- (4) J. Pletcher, M. Sax, G. Blank, and M. Wood, *J. Am. Chem. Soc.*, **99**, 1396 (1977).
- (5) W. Shin, J. Pletcher, M. Sax, and G. Blank, *J. Am. Chem. Soc.*, **101**, 2462 (1979).
- (6) A. Gallo, private communication.
- (7) The DOS software for diffractometer control, data collection, and data reduction were obtained with the FACS-1 system from Picker Corp. Numerous software modifications and additions have been implemented locally.
- (8) This is equivalent to the criterion  $I \leq 3\sigma(I)$ . The terms are the same as those defined previously (see ref 20).
- (9) Programs written or modified by R. Shiono are contained in various technical reports from the Department of Crystallography, University of Pittsburgh.
- (10) G. Germain, P. Main, and M. M. Woolfson, *Acta Crystallogr., Sect. A*, **27**, 368 (1971).
- (11) D. T. Cromer and J. T. Waber, *Acta Crystallogr.*, **18**, 104 (1965).
- (12) R. F. Stewart, E. R. Davidson, and W. T. Simpson, *J. Chem. Phys.*, **42**, 3175 (1965).
- (13) "International Tables for X-ray Crystallography", Vol. III, Kynoch Press, Birmingham, England, 1968, p 214.
- (14) (a) J. Pletcher and M. Sax, *J. Am. Chem. Soc.*, **94**, 3998 (1972); (b) *Science*, **154**, 1331 (1966).
- (15) M. J. S. Dewar and H. N. Schmeising, *Tetrahedron*, **11**, 96 (1960); D. R. Lide, Jr., *ibid.*, **17**, 125 (1962).
- (16) J. Pletcher, M. Sax, S. Sengupta, J. Chu, and C. S. Yoo, *Acta Crystallogr., Sect. B*, **28**, 2928 (1972).
- (17) W. Shin, J. Pletcher, G. Blank, and M. Sax, *J. Am. Chem. Soc.*, **99**, 3491 (1977).
- (18) M. F. Richardson, K. Franklin, and D. M. Thompson, *J. Am. Chem. Soc.*, **97**, 3204 (1975).
- (19) J. Pletcher, M. Wood, G. Blank, W. Shin, and M. Sax, *Acta Crystallogr., Sect. B*, **33**, 3349 (1977).
- (20) J. Pletcher, G. Blank, M. Wood, and M. Sax, *Acta Crystallogr.*, in press.
- (21) (a) The torsion angle  $\varphi_T = C(5')-C(3,5')-N(3)-C(2)$  and  $\varphi_P = N(3)-C(3,5')-C(5')-C(4')$ . An S conformation is specified by the torsion angles ( $\varphi_T \approx \pm 100^\circ$ ,  $\varphi_P \approx \pm 150^\circ$ ). For more complete details see footnote 13 in ref 4. (b)  $\varphi_{5\alpha} = S(1)-C(5)-C(5\alpha)-C(5\beta)$  and  $\varphi_{5\beta} = C(5)-C(5\alpha)-C(5\beta)-O(5\gamma)$ .
- (22) The ORTEP program is by C. K. Johnson, Oak Ridge National Laboratory, Oak Ridge, Tenn., ORNL-3794, 1965.
- (23) C. E. Bugg, J. M. Thomas, M. Sundaralingam, and S. T. Rao, *Biopolymers*, **10**, 175 (1971).
- (24) F. Jordan, *J. Am. Chem. Soc.*, **98**, 808 (1976).

## Communications to the Editor

### Synthesis and Characterization of Bis(fulvalene)-divanadium and the Crystal Structure of Its Oxidation Product, Bis(fulvalene)bis(acetonitrile)divanadium(III)-(V-V) Bis(hexafluorophosphate)-Acetonitrile (1/1)

Sir:

Because of the current interest in the structure and reactivity of coordinatively unsaturated metallocenes<sup>1</sup> and the formally analogous metallofulvalene derivatives,<sup>2</sup> we wish to report our initial synthetic, physical, and X-ray structural studies of the bis(fulvalene)divanadium system.

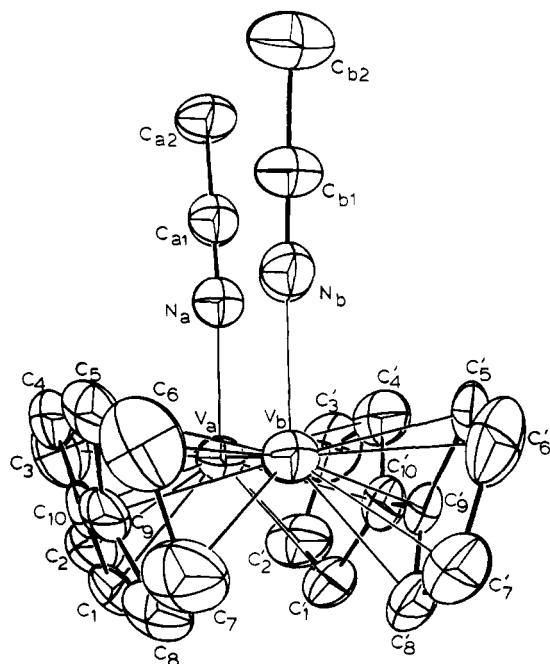
The neutral  $(C_{10}H_8)_2V_2$  (**1**) was obtained by the reaction of  $VCl_2 \cdot 2THF^3$  with 1 equiv of fulvalene dianion<sup>2d</sup> in refluxing THF. The dark purple air-sensitive product was isolated and purified by repeated sublimation under high vacuum at 230 °C.<sup>4</sup> The solubility of **1** in polar and nonpolar solvents is very low. The mass spectrum<sup>5</sup> and infrared spectrum<sup>6</sup> of **1** are similar to those for the neutral bis(fulvalene)dimetal derivatives of Ni,<sup>6a</sup> Co,<sup>6b</sup> Fe,<sup>6c</sup> and Cr.<sup>6b</sup> Magnetic susceptibility measurements on solid samples indicate that **1** is diamagnetic from 4.2 to 100 K. This is consistent with the observed diamagnetism of both the dicationic and neutral derivatives of all bis(fulvalene)dimetal complexes studied to date, from vanadium, with 28<sup>6b</sup> and 30 valence electrons, respectively, to nickel, with 38 and 40<sup>6a</sup> valence electrons. The complete magnetic coupling found in **1**, compared to the "parent" vanadocene with an open-shell 15-electron structure and three unpaired electrons, can be rationalized by either a direct metal-metal interaction (bond) or by ligand-propagated exchange. Although X-ray crystallographic data for neutral  $(C_{10}H_8)_2Ni_2$  clearly indicate the presence of a ligand-propagated exchange,<sup>7</sup> an assessment of the relative contributions from each exchange mechanism for electron-deficient early transition metal derivatives must await similar detailed structural information.

The oxidation of **1** with either 1 or 2 equiv of ferrocenium hexafluorophosphate per dinuclear vanadium complex in dry oxygen-free acetonitrile yields only a two-electron product,  $[(\eta^5-C_{10}H_8)_2(CH_3CN)_2V_2(III)(V-V)^{2+}][PF_6^-]_2 \cdot CH_3CN$  (**2**), that was isolated as brown microcrystals by the slow

addition of toluene.<sup>8</sup> Magnetic susceptibility measurements in acetonitrile at 310 K by the Evans NMR method<sup>9</sup> indicate that **2** is paramagnetic with  $\mu_{eff} = 2.9$  BM per dinuclear vanadium complex. Measurements on solid samples from 4 to 80 K indicate a  $\mu_{eff} = 3.0$  BM. These results establish the presence of two unpaired electrons for the dinuclear metal complex. The infrared spectrum of **2** exhibits terminal nitrile stretches at 2320 and 2290  $cm^{-1}$ .

Hygroscopic and air-sensitive single crystals of the acetonitrile solvate **2**, obtained by recrystallization from acetonitrile/benzene, are orthorhombic and noncentrosymmetric, space group  $Cmc2_1$  ( $C_{2v}$ ,<sup>12</sup> No. 36), with  $a = 7.771$  (1) Å,  $b = 20.556$  (3) Å,  $c = 18.324$  (3) Å, and  $Z = 4$  [ $(C_{10}H_8)_2V_2 \cdot (NCCCH_3)_2$ ][ $PF_6$ ] $_2 \cdot CH_3CN$  formula units). The various statistical indicators calculated with normalized structure factors, as well as all stages of the structure solution and refinement, were in agreement with the choice of a noncentrosymmetric space group. Diffracted intensities were measured for 2193 independent reflections having  $2\theta_{MoK\alpha} < 58.7^\circ$  on a computer-controlled Syntex P<sub>T</sub> autodiffractometer using graphite-monochromated Mo  $K\alpha$  radiation and full ( $1^\circ$  wide)  $\omega$  scans. The structural parameters<sup>10</sup> have been refined to convergence [ $R = 0.045$  for 949 independent reflections having  $2\theta_{MoK\alpha} < 43^\circ$  and  $I > 3\sigma(I)$ ] in cycles of unit-weighted, full-matrix, least-squares refinement which employed anisotropic thermal parameters for all nonhydrogen atoms.

The structural analysis reveals that the crystal is composed of bis(fulvalene)bis(acetonitrile)divanadium(III)(V-V) dications (Figure 1), hexafluorophosphate anions, and acetonitrile molecules of crystallization. Although each  $[(\eta^5-C_{10}H_8)_2(CH_3CN)_2V_2]^{2+}$  unit is required to possess only crystallographic  $C_s$ - $m$  symmetry (with the two vanadium atoms and the nonhydrogen atoms of their coordinated acetonitrile ligands lying in the mirror plane), the dication as a whole approximates rather closely idealized  $C_{2v}$  site symmetry with the pseudo- $C_2$  axis passing through the midpoints of the  $C_9-C_{10}'$  and  $V_a-V_b$  vectors of Figure 1. Bond lengths and angles for chemically equivalent groupings, averaged in accord with approximate  $C_{2v}$  molecular symmetry, include:  $V_a-V_b$ , 3.329 (4) Å; V-N, 2.09 (1,2,2,2) Å;<sup>11</sup> V-C, 2.28 (1,2,3,10)



**Figure 1.** Perspective ORTEP drawing of the nonhydrogen atoms for the bis(fulvalene)bis(acetonitrile)divanadium(III) dication viewed approximately  $10^\circ$  off the crystallographic mirror plane which contains  $V_a$ ,  $V_b$ , and their coordinated acetonitrile ligands. All atoms are represented by thermal vibration ellipsoids drawn to encompass 50% of the electron density. Atoms  $V_a$ ,  $N_a$ ,  $C_{a1}$ ,  $C_{a2}$ , and fulvalene atoms  $C_1$ – $C_4$  and  $C_{10}$  are related to the corresponding  $V_b$ ,  $N_b$ ,  $C_{b1}$ ,  $C_{b2}$ , and fulvalene atoms  $C_5$ – $C_8$  and  $C_9$ , by a pseudo-mirror plane. Atoms labeled with a prime (') are related to those without a prime by the crystallographic mirror plane.

$\text{\AA}$ ;  $^{11}$  C–C (intra-ring), 1.44 (2,2,5,10)  $\text{\AA}$ ;  $C_9$ – $C_{10}$ , 1.45 (2)  $\text{\AA}$ ;  $N_a$ – $C_{a1}$ , 1.13 (2,2,2,2)  $\text{\AA}$ ;  $C_{a1}$ – $C_{a2}$ , 1.45 (3,1,1,2)  $\text{\AA}$ ; V–V–N, 89.1 (4,9,9,2) $^\circ$ ;  $^{11}$  V– $N_a$ – $C_{a1}$ , 171 (1,2,2,2) $^\circ$ ;  $^{11}$   $N_a$ – $C_{a1}$ – $C_{a2}$ , 178 (2,1,1,2) $^\circ$ ; C–C–C (intra-ring), 108 (1,1,3,10) $^\circ$ ; and C– $C_9$ – $C_{10}$ , 125 (1,1,2,4) $^\circ$ .

Although each set of five carbon atoms which comprise the two rings of a fulvalene ligand are individually coplanar to within 0.007  $\text{\AA}$ , the entire ligand is folded with the mean planes for the two planar five-membered rings intersecting in a dihedral angle of  $13.6^\circ$ . The nature of this folding is such that the average  $C_1$ – $C_1'$ ,  $C_2$ – $C_2'$ ,  $C_7$ – $C_7'$ , and  $C_8$ – $C_8'$  separation for both halves of the dication is 2.98 (3,3,4,4)  $\text{\AA}$ , while the average  $C_3$ – $C_3'$ ,  $C_{10}$ – $C_{10}'$ ,  $C_6$ – $C_6'$ , and  $C_9$ – $C_9'$  separation is 3.89 (3,2,3,4)  $\text{\AA}$ ; the average  $C_4$ – $C_4'$  and  $C_5$ – $C_5'$  separation is 4.46 (2, 1,1,2)  $\text{\AA}$ . This particular type of distortion from planarity for the fulvalene ligand appears to be induced by the stereochemical preference of each vanadium atom for a pseudotetrahedral coordination similar to that observed for analogous  $(\eta^5\text{-C}_5\text{H}_5)_2\text{MX}_2$  species<sup>12</sup> as well as related monofulvalene complexes of titanium<sup>2a,b</sup> and molybdenum which have additional bridging atoms as well as metal–metal bonding. In the present case, one coordination site of each vanadium would be occupied by the metal–metal vector and the other site by a coordinated acetonitrile ligand. The mean planes of the two five-membered rings which are  $\eta^5$ -bonded to a given vanadium atom of the dication intersect in an average dihedral angle of  $140.8$  ( $-9,9,2$ ) $^\circ$ . Although the 3.329 (4)  $\text{\AA}$  V–V separation in **2** is significantly longer than the  $\sim 2.6$   $\text{\AA}$  value generally expected for a single-order metal–metal bond involving first transition series metals [a V–V bond length of 2.462 (2)  $\text{\AA}$  has, in fact, been observed<sup>13</sup> in  $(\eta^5\text{-C}_5\text{H}_5)_2\text{V}_2(\text{CO})_5$ ], it is significantly shorter than the 3.984 (4)  $\text{\AA}$  Fe–Fe separation found in bis(fulvalene)diiron<sup>14</sup> and the 4.163 (6)  $\text{\AA}$  Ni–Ni separation in bis(fulvalene)nickel.<sup>7</sup> The observed structure for the dication presumably represents the best compromise between a shorter and more normal metal–metal

bond and planar fulvalene ligands. Although the steric factors responsible for metal–metal bond elongation in the dication are entirely different, the observed V–V separation is quite similar to the formally single-order metal–metal bonds in the following “sterically-crowded” dinuclear complexes:  $[(\eta^5\text{-C}_5\text{H}_5)(\text{CO})_2(\text{P}(\text{OCH}_3)_3)\text{Cr}]_2$ , 3.343 (3)  $\text{\AA}$  Cr–Cr;<sup>15</sup>  $[(\eta^5\text{-C}_5\text{H}_5)(\text{CO})_3\text{Cr}]_2$ , 3.281 (1)  $\text{\AA}$  Cr–Cr;<sup>16</sup> and  $[(\eta^3\text{-C}_3\text{H}_5)(\text{CO})_3\text{Fe}]_2$ , 3.138 (3)  $\text{\AA}$  Fe–Fe.<sup>17</sup>

Thus the structural data are consistent with a significantly elongated single-order metal–metal bond in the dication which is undoubtedly due to the constraints of the bridging ligands. Such a bond would produce a seventeen-electron valence-shell electronic configuration for each vanadium atom, in agreement with the magnetic susceptibility data. The presence of a “stretched” (and presumably weakened) metal–metal bond, as well as two electron-deficient metal centers, would seem to indicate an unusually rich chemistry for this dication. The cis disposition of ligands with respect to the metal–metal axis in the bent metallofulvalene complex<sup>18</sup> suggests that reactions of small molecules at both metal centers could take place in either a concerted or sequential manner. These features in both the planar and bent derivatives may lead to new kinds of stoichiometric and catalytic transformations, which are quite different from those of the “parent” metallocenes.

**Acknowledgment** is made to the Petroleum Research Fund, administered by the American Chemical Society, and the U.S. Energy Research and Development Administration for support of this research. We also thank the University of Nebraska Computing Center for a generous allocation of computer time.

## References and Notes

- (1) (a) J. J. Manriquez and J. E. Bercaw, *J. Am. Chem. Soc.*, **96**, 6229 (1974); (b) F. Calderazzo, G. Fachinetti, and F. Floriani, *ibid.*, **96**, 3695 (1974); (c) G. Fachinetti, S. Del Nero, and C. Floriani, *J. Chem. Soc., Dalton Trans.*, 1046 (1976); (d) R. B. Francia, M. L. H. Green, T. Luong-thi, and G. A. Moser, *ibid.*, 1339 (1976).
- (2) (a) L. J. Guggenberger and F. N. Tebbe, *J. Am. Chem. Soc.*, **98**, 4137 (1976); (b) G. J. Oltorf, *J. Organomet. Chem.*, **128**, 367 (1977); (c) N. J. Cooper and M. L. H. Green, *Chem. Commun.*, 145 (1977); (d) J. C. Smart and C. J. Curtis, *Inorg. Chem.*, **16**, 1788 (1977); (e) J. C. Smart and C. J. Curtis, *J. Am. Chem. Soc.*, **99**, 3518 (1977); (f) J. C. Smart and C. J. Curtis, *Inorg. Chem.*, **17**, 3290 (1978).
- (3) F. M. Kohler and W. Prossdorf, *Z. Naturforsch.*, **32b**, 1026 (1977).
- (4) Anal. Calcd for  $\text{C}_{20}\text{H}_{16}\text{V}_2$ : C, 67.06; H, 4.50; V, 28.4. Found: C, 67.31; H, 4.64; V, 27.8.
- (5) Mass spectrum (70 eV),  $m/e$ : 358 ( $\text{C}_{10}\text{H}_8$ ) $^2\text{V}_2^+$ ; 179, ( $\text{C}_{10}\text{H}_8$ ) $\text{V}^+$ ; 128, ( $\text{C}_{10}\text{H}_8$ ) $^+$ ; 102,  $\text{V}_2^+$ .
- (6) (a) J. C. Smart and B. L. Pinsky, *J. Am. Chem. Soc.*, **99**, 956 (1977); (b) J. C. Smart and B. L. Pinsky, unpublished results; (c) K. LeVanda, K. Bechgaard, D. O. Cowan, V. T. Mueller-Westerhoff, P. Eilbracht, G. A. Candela, and R. L. Collins, *J. Am. Chem. Soc.*, **98**, 3181 (1976).
- (7) J. C. Smart, P. R. Sharp, B. L. Pinsky, and K. N. Raymond, unpublished results.
- (8) Repeated attempts to obtain reproducible elemental analyses on recrystallized samples were unsuccessful.
- (9) D. F. Evans, *J. Chem. Soc.*, 2003 (1959).
- (10) The structure was solved using the heavy atom technique. Further refinement is underway using the more complete ( $2\theta_{\text{MOR}} < 58.7^\circ$ ) data set and a model which incorporates anisotropic thermal parameters for all nonhydrogen atoms and isotropic thermal parameters for all locatable hydrogen atoms.
- (11) The first number in parentheses following an averaged value of a bond length or angle is the root-mean-square estimated standard deviation of an individual datum. The second and third numbers, when given, are the average and maximum deviations from the averaged value, respectively. The fourth number represents the number of individual measurements which are included in the average value.
- (12) J. L. Petersen, D. L. Lichtenberger, R. F. Fenske, and L. F. Dahl, *J. Am. Chem. Soc.*, **97**, 6433 (1975).
- (13) (a) F. A. Cotton, B. A. Frenz, and L. Kruczynski, *J. Am. Chem. Soc.*, **95**, 951 (1973); (b) F. A. Cotton, *Prog. Inorg. Chem.*, **21**, 1 (1975).
- (14) M. R. Churchill, J. Wormald, *Inorg. Chem.*, **8**, 1970 (1969).
- (15) L. Y. Goh, M. J. D'Aniello, Jr., S. Slater, E. L. Muettteries, I. Tavanaiepour, M. I. Chang, M. F. Fredrich, and V. W. Day, *Inorg. Chem.*, **18**, 192 (1979).
- (16) R. D. Adams, D. E. Collins, and F. A. Cotton, *J. Am. Chem. Soc.*, **96**, 749 (1974).
- (17) C. F. Putnik, J. J. Welter, G. D. Stucky, M. J. D'Aniello, Jr., B. A. Sosinsky, J. F. Kirner, and E. L. Muettteries, *J. Am. Chem. Soc.*, **100**, 4107 (1978).
- (18) An inspection of molecular models indicates that a trans isomer is possible by twisting the two five-membered rings of the bridging fulvalene ligands

from the approximately coplanar disposition found in the *cis* isomer, and significantly lengthening the metal-metal distance. This suggests that metal-metal bonding may dictate the conformation in bent bis(fulvalene)-dimetal complexes apart from any possible electronic stabilization from coplanar fulvalene ligands.

- (19) Address correspondence to author at Solar Energy Research Institute, 1536 Cole Blvd., Golden, Colorado 80401.  
 (20) Camille and Henry Dreyfus Teacher-Scholar.

James C. Smart,\*<sup>19</sup> Barry L. Pinsky

Department of Chemistry and Materials and Molecular  
 Research Division of the Lawrence Berkeley Laboratory  
 University of California, Berkeley, California 94720

Michael F. Fredrich, Victor W. Day\*<sup>20</sup>

Department of Chemistry, University of Nebraska,  
 Lincoln, Nebraska 68588  
 Received August 4, 1978

### On the Photoassisted Decomposition of Water at the Gas-Solid Interface on TiO<sub>2</sub>

Sir:

The catalytic nature of the now well-documented photoassisted decomposition of water in photoelectrochemical cells seems to be an established fact, at least on several stable anode materials such as TiO<sub>2</sub> or the alkaline-earth titanates.<sup>1,2</sup> The amount of gaseous products produced greatly exceeds that which might come from the decomposition (if any) of the surface layers of the electrode. High quantum efficiencies can be achieved and no poisoning of the reaction seems to occur, even after long reaction times.

On the other hand, the catalytic nature of the photoassisted decomposition of water at the gas-solid (GS) interface on simple catalysts, such as pure or doped TiO<sub>2</sub>, as reported by Schrauzer and Guth,<sup>3</sup> has yet to be established. The efficiency was found much lower than in the photoelectrochemical devices and the reaction actually stopped after a few hours. These authors suggested that this may have been caused by catalysis of the reverse reaction  $H_2 + \frac{1}{2}O_2 \rightarrow H_2O$ . This could indeed have been responsible because they used small static reactors (200 mg of catalyst in 38-mL capacity vessels).

We have, therefore, studied the photodecomposition of H<sub>2</sub>O over TiO<sub>2</sub> in a flow system in order to remove the reaction products from the catalyst completely. Helium, purified by passage over charcoal at liquid nitrogen temperature, was saturated with H<sub>2</sub>O at room temperature and flowed over the catalyst (50 cm<sup>3</sup> (NTP)/min) for periods up to 6 h. The catalyst (500 mg of anatase; 11.2 m<sup>2</sup> g) was spread uniformly on a quartz optical plate of area 5 cm<sup>2</sup> which made up the bottom of a flask which was joined by a standard taper joint to a vacuum-tight flow system. The TiO<sub>2</sub> could be illuminated from below with white light from a 1000-W xenon lamp during the test periods. The exhaust flow was first dried by passing through a liquid N<sub>2</sub> trap and any H<sub>2</sub> or O<sub>2</sub> was subsequently trapped downstream on activated 5A molecular sieve at this temperature. The trapped gases could be released and analyzed by mass spectrometry. The anatase was pretreated *in situ* at 1000 °C in flowing O<sub>2</sub> for 1 h (and consequently partially converted into rutile); it was cooled to 25 °C in wet He. This treatment had been recommended by Schrauzer and Guth as the most efficient for their purposes. Only traces of H<sub>2</sub> were detected, even after 6 h of running in UV light. The O<sub>2</sub> could not be detected unambiguously because of the spectrometer background at *m/e* 32, but certainly a substantial amount (several monolayers) could not have been missed.

We also have studied the hydrogen oxidation reaction over TiO<sub>2</sub>, BaTiO<sub>3</sub>, and SrTiO<sub>3</sub> in a static recirculation system.<sup>4</sup> The thermal reaction rate was found to be too slow at 25 °C

by at least one order of magnitude ( $<10^{-7}$  mol g<sup>-1</sup> h<sup>-1</sup>) to support the assumption that an equilibrium was reached in the experiments of Schrauzer and Guth, i.e., with hydrogen and oxygen partial pressures of the order of, or  $<1$  Torr and saturating partial pressures of water. Moreover, no rate enhancement by light was found on any of these materials from 400 °C down to room temperature, although enhancement was found for CO oxidation under similar conditions with these systems.

These observations cast serious doubt about the catalytic nature of the process discovered by Schrauzer and Guth. From the particle size given for the TiO<sub>2</sub> sample which they used (2 μ), the specific surface area of the powder may be estimated as  $\sim 1$  m<sup>2</sup> g<sup>-1</sup>. Thus, the maximum amounts of H<sub>2</sub> and O<sub>2</sub> observed ( $5.0 \times 10^{18}$  and  $2.5 \times 10^{18}$  molecule g<sup>-1</sup>, respectively) were of the same order as that expected for the photodecomposition of the hydroxylated surface layer<sup>5</sup> of the material ( $10^{19}$  OH m<sup>-2</sup>).

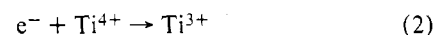
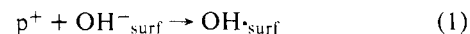
Schrauzer and Guth also showed that hydrogen evolution was inhibited by N<sub>2</sub> in the gas phase and that NH<sub>3</sub> and N<sub>2</sub>H<sub>2</sub> were produced instead of H<sub>2</sub>, and in higher yields, especially on the iron-doped samples. Assuming again a specific surface area of the order of 1 m<sup>2</sup> g<sup>-1</sup>, their highest yield would correspond to about seven monolayers of OH groups. A true surface area determination will be necessary, however, to make these considerations quantitative.

Another thermodynamically "uphill" reaction, namely the reaction of H<sub>2</sub>O and CO<sub>2</sub> to form CH<sub>4</sub>, has recently been shown to be photoassisted on a SrTiO<sub>3</sub>-Pt sandwich.<sup>6</sup> Remarkably, in this case also, the reaction is poisoned when an equivalent monolayer of methane has been produced.

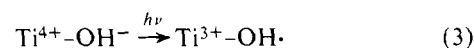
In contrast to these low yields, the photoassisted decomposition of water at the liquid-solid (LS) interface in TiO<sub>2</sub>-Pt electrochemical cells occurs with typical rates of  $\sim 3 \times 10^{19}$  H<sub>2</sub>O molecules decomposed/h on a TiO<sub>2</sub> single-crystal electrode of area  $\sim 1$  cm<sup>2</sup>.<sup>1,2</sup> This corresponds to a turnover number for each OH group on the electrode surface of the order of  $6 \times 10^4$ /h, i.e., more than four orders of magnitude higher than at the GS interface.

This large difference in turnover numbers deserves special comment. A fundamental difference between the LS and GS systems is that in the former O<sub>2</sub> and H<sub>2</sub> are produced separately at the oxide anode and at the metallic cathode, respectively, whereas in the latter both are released from the oxide surface. In both types of experiments, however, the primary process going on upon absorption of light in the surface layers may be expected to be the same, i.e., generation of an electron-hole pair, followed by trapping of some of the free carriers.

The following chemistry is written, not because we have firm conviction that it is unique and entirely correct, but rather because it affords a rationale which provides interesting food for thought. For instance, the carriers may be trapped by



Both the participation of surface OH<sup>-</sup> groups as hole traps and the identification of Ti<sup>3+</sup> ions in various environments as donor centers conferring n-type conductivity have been widely proposed. Band to band transition and charge trapping according to eq 1 and 2 could be described together in an equivalent manner.



The right-hand member of this equation provides an adequate center for further reaction or for electron-hole recombination.

In the photoelectrochemical (LS) devices, conduction