

side arms (stacking with *p*-nitrophenyl moiety). The stability constant  $K_s = 1609 \text{ M}^{-1}$  ( $\pm 12\%$ ) was determined by NMR titration of **3** in  $\text{CDCl}_3$  with triethylammonium *p*-nitrobenzoate.<sup>11,12</sup>

Similarly, sodium *p*-methoxybenzoate and sodium phenylacetate were extracted by **3**, and NH guanidinium protons shifted downfield, whereas aromatic naphthoyl protons shifted upfield. However, the overall effect was somewhat lower than in the *p*-nitrobenzoate case. For example, the naphthoyl  $\text{H}_1$  proton shifted only 0.27 and 0.26 ppm in the *p*-methoxybenzoate and the phenylacetate complexes, respectively.

The chirality of **3** should force any substrate to bind in a dissymmetric environment, allowing the enantioselective recognition of chiral carboxylic acids. Extraction experiments of sodium (*S*)-mandelate and (*S*)-naproxenate [(+)-6-methoxy- $\alpha$ -methyl-2-naphthaleneacetate] with both enantiomers **3-SS** and **3-RR** afforded the corresponding diastereomeric salts. Chemical shifts for these complexes were quite similar as those for the achiral guests mentioned above, but small differences in both diastereomeric salts of each guest were observed. For instance, the naphthoyl  $\text{H}_1$  protons of the **3-SS** host showed upfield shifts of 0.26 (mandelate) and 0.27 ppm (naproxenate), but the shifts were 0.30 and 0.32 ppm, respectively, when the **3-RR** host was employed. It was also noteworthy that in the naproxen complexes, the proton at the chiral carbon center of guest shifted upfield quite differently in both species: 0.11 ppm for the **3-SS** host but only 0.05 for the **3-RR** one.<sup>13</sup>

Free amino acids in zwitterionic form (i.e., valine, phenylalanine, tryptophan) were not extracted from aqueous solutions by **3**, hence *N*-acetyl and *N*-tert-butoxycarbonyl derivatives of sodium tryptophan were examined, since they contained two recognition functions (the carboxylate and the well-known  $\pi$ -donor indole ring) and a bulk substituent to interact sterically with the host aromatic side arm not involved in the stacking. Indeed, extraction of an excess of the racemic salts with **3-SS** afforded two diastereomeric salts in each case, with diastereomeric excesses (de) of ca. 17% for the L-tryptophan derivative.<sup>14</sup> For the *N*-acetyl derivative, a 1.07 ppm downfield shift was observed for the guanidinium NH protons, whereas naphthoyl protons shifted upfield (0.22 ppm for  $\text{H}_1$ ). Both diastereomeric complexes became evident from the well-differentiated downfield shifted signals of the guest: NH (0.16 and 0.19 ppm) and methyl (0.21 and 0.32 ppm). NMR titration of the triethylammonium salts of *N*-acetyltryptophan in  $\text{CDCl}_3$  gave  $K_s = 1051$  ( $\pm 19.3\%$ ) and  $534$  ( $\pm 15.6\%$ )  $\text{M}^{-1}$  for the L- and D-enantiomers, respectively. A similar de was obtained when the sodium salt of D-*N*-acetyltryptophan was extracted with the enantiomeric receptor, **3-RR**. This represents, to our knowledge, the first example of enantioselective recognition of anionic species by an abiotic receptor. Studies toward the design of more selective receptors, based on three-point binding hosts (derived from **2**), are underway.

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ersity of Tokyo, Japan, for the calculation of stability constants from NMR titration data.

**Supplementary Material Available:** NMR spectroscopic data for **3** and its complexes (6 pages). Ordering information is given on any current masthead page.

### Synthesis and Structure of the First Example of a Four-Electron Donor, Side-On Bridging Thiocarbonyl Ligand

Ruth Ann Doyle, Lee M. Daniels,<sup>†</sup> and Robert J. Angelici\*

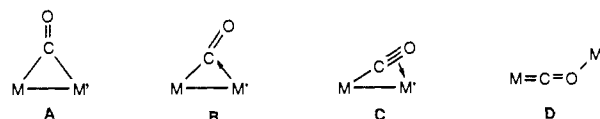
Department of Chemistry, Iowa State University  
Ames, Iowa 50011

F. Gordon A. Stone

Department of Inorganic Chemistry  
The University of Bristol  
Bristol BS8 1TS, United Kingdom

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The similarity of carbon monosulfide (CS) to CO has stimulated much interest in the synthesis and reactivity of CS complexes.<sup>1</sup> There are four types of CO bridging ligand:<sup>2</sup> carbon bridging (A), semibridging (B), in which a filled orbital on  $\text{M}'$  donates into



the empty  $\pi^*$  orbital of the CO ligand, side-on bonding (C), involving donation from the filled  $\pi$ -orbital of the CO ligand into an empty orbital on  $\text{M}'$ , and end-on (D). Unlike CO, CS has not been found or suggested to be a side-on bridging ligand (type C) in any metal complexes. The C-S group is known as a carbon-bridging ligand (e.g.,  $\text{Cp}_2\text{Fe}_2(\text{CO})_2(\mu\text{-CO})(\mu\text{-CS})$ ),<sup>3</sup>  $\text{MnPt}(\mu\text{-CS})(\text{CO})_2(\text{PMePh}_2)_2\text{Cp}$ ),<sup>4</sup> as an end-to-end bridging ligand (e.g.,  $(\text{dppe})_2(\text{CO})\text{W}-\text{C}\equiv\text{S}-\text{W}(\text{CO})_5$ ,<sup>5</sup> ( $\eta^6\text{-C}_6\text{H}_5\text{Me}$ )( $\text{CO})_2\text{Cr}-\text{C}\equiv\text{S}-\text{Cr}(\text{CO})_5$ ),<sup>6</sup> and as a semibridging ligand (e.g.,  $[\text{HB}(\text{pz})_3](\text{CO})\text{W}(\mu\text{-CO})(\mu\text{-CS})\text{Au}(\text{PR}_3)$ ,  $\text{R} = \text{Me}, \text{Ph}$ ).<sup>7</sup> In all of these types of complexes, the CS ligand has a greater preference for the bridging position than CO. In this communication, we describe the synthesis and structure of  $[\text{HB}(\text{pz})_3](\text{CO})_2\text{W}(\mu\text{-CS})\text{Mo}(\text{CO})_2(\text{In})$  (**1**;  $\text{In} = \eta^5\text{-C}_9\text{H}_7^-$ , indenyl;  $\text{HB}(\text{pz})_3^-$ , hydrotris(1-pyrazolyl)borate), the first example of a complex containing a side-on bridging CS ligand. In this type of bridging situation, the CS ligand also forms a more stable complex than CO.

Addition of 1 equiv of  $[(\text{In})\text{Mo}(\text{CO})_2(\text{MeCN})_2]\text{BF}_4$  to a THF solution of  $\text{Bu}_4\text{N}[\{\text{HB}(\text{pz})_3\}(\text{CO})_2\text{W}(\text{CS})]$ <sup>9</sup> (0.553 mmol) at 25 °C produces a brown solution of **1** in 30 min. After the solvent is removed in vacuo, the resulting brown residue is recrystallized several times from THF/ $\text{Et}_2\text{O}$ . A final recrystallization from

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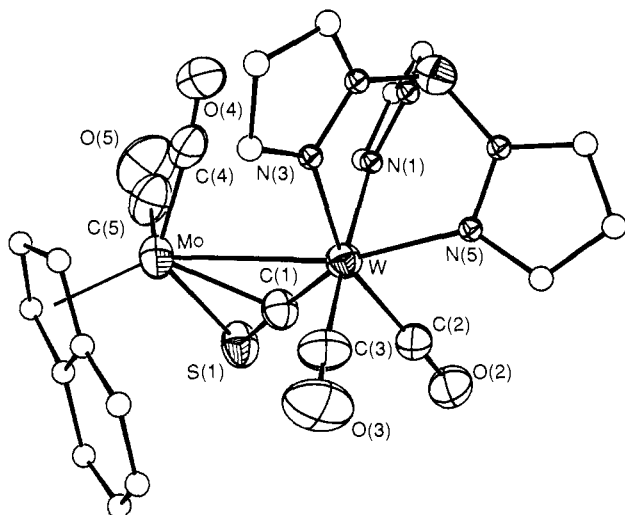
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(12) Due to the presence of chloride and triethylammonium ions in the solution, changes in the NMR spectra of this 1:1 mixture were lower than those observed in the extraction experiment. Chemical shifts were also found to be strongly dependent on the nature of the counterions. For example, a very large downfield shift (3.24 ppm) was observed for the guanidyl protons in the 1:1 mixture of the  $\text{Ph}_4\text{B}^-$  salt of **3** and  $\text{Bu}_4\text{N}^+$  *p*-nitrobenzoate. Therefore, stability constants for these ion pairs could be influenced by the nature of the counterions or by the presence of other salts in the solution.

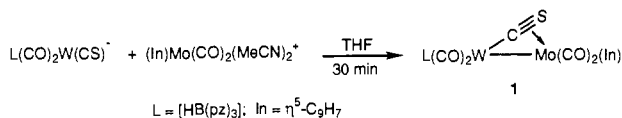
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**Figure 1.** ORTEP plot of  $[\text{HB}(\text{pz})_3](\text{CO})_2\text{W}(\mu\text{-CS})\text{Mo}(\text{CO})_2(\text{In})$ , **1**. Selected bond distances (Å) and angles (deg) are as follows: W–Mo = 3.3102 (4), W–C(1) = 1.895 (5), C(1)–S(1) = 1.640 (6), W–N(1) = 2.194 (4), W–N(3) = 2.205 (4), W–N(5) = 2.229 (4), W–C(2) = 2.001 (5), W–C(3) = 1.969 (5), Mo–C(1) = 2.229 (4), Mo–S(1) = 2.511 (2), Mo–C(4) = 1.956 (6), Mo–C(5) = 1.917 (7), W–C(1)–S(1) = 170.8 (3), C(1)–W–Mo = 40.2 (1), Mo–W–N(5) = 165.4 (1).

$\text{CH}_2\text{Cl}_2/\text{hexanes}$  at  $-20^\circ\text{C}$  gives **1** as a brown crystalline solid in 64% yield. The compound is characterized by elemental analysis, IR,  $^1\text{H}$  and  $^{13}\text{C}\{\text{H}\}$  NMR, and mass spectra.<sup>10</sup>



An X-ray structure determination<sup>13</sup> of a red-brown single crystal of **1** reveals a side-on bonded bridging CS ligand which is carbon-bonded to tungsten and  $\pi$ -donating to molybdenum as shown in Figure 1. The Mo–C(1) bond distance (2.229 (4) Å) is within experimental error of the Mo–C distance (2.237 (7) Å) in the side-on bonded isonitrile complex  $[\text{Mo}_2(\mu\text{-}\eta^2\text{-}(\text{CN-}t\text{-Bu}))(\text{CO})_4\text{Cp}_2]$ .<sup>14</sup> Moreover, it is  $\sim 0.1$  Å shorter than the Mo–C distances to the side-on bridging CO's in  $[\text{MoW}_2(\mu\text{-C}(\text{C}_6\text{H}_4\text{Me-4}))_2(\mu\text{-CO})_2(\text{CO})_4\text{Cp}_2]$  (2.355 (12) and 2.348 (14) Å).<sup>15</sup> The Mo–S(1) distance (2.511 (2) Å) is clearly bonding and

(10)  $[\text{HB}(\text{pz})_3](\text{CO})_2\text{W}(\mu\text{-CS})\text{Mo}(\text{CO})_2(\text{In})$ , **1**: IR (THF)  $\nu(\text{CO})$  1984 m, 1938 vs, 1893 m, 1862  $\text{cm}^{-1}$ ;  $\nu(\text{CS})$  is not observed;  $^1\text{H}$  NMR ( $\text{CD}_2\text{Cl}_2$ )  $\delta$  7.72 (d,  $J = 2.2$ , H3 and H5 of pz); 7.19, 7.06 and 6.77 (m, H4-7 of In); 6.47, 5.91 (m, H1 and H3 of In); 6.28 (s, H4 of pz); 5.56 (t,  $J = 2.8$ , H2 of In). The assignments for In and HB(pz)<sub>3</sub> are based on those for (In)Rh(C<sub>2</sub>H<sub>4</sub>)<sub>2</sub><sup>11</sup> and  $[\text{HB}(\text{pz})_3](\text{CO})_2\text{W}\equiv\text{CMe}$ ,<sup>12</sup> respectively.  $^{13}\text{C}\{\text{H}\}$  NMR ( $\text{C}_2\text{D}_2\text{Cl}_2$ )  $\delta$  285.8 (CS); 243.2, 242.8, 223.7, 221.5 (CO); 145.8 (C3 of pz); 136.4 (C5 of pz); 106.5 (C4 of pz); 127.2, 126.6, 124.6, 124.4, 119.1, 117.8, 93.9, 82.8, 78.5 (In); EIMS (70 eV)  $m/e$  764 ( $\text{M}^+$ ), 708 ( $\text{M}^+ - 2\text{CO}$ ), 680 ( $\text{M}^+ - 3\text{CO}$ ). Anal. Calcd for  $\text{C}_{23}\text{H}_{17}\text{BMoN}_5\text{O}_4\text{S}$ : C, 36.15; H, 2.24; N, 11.00. Found: C, 36.10; H, 2.33; N, 10.90.

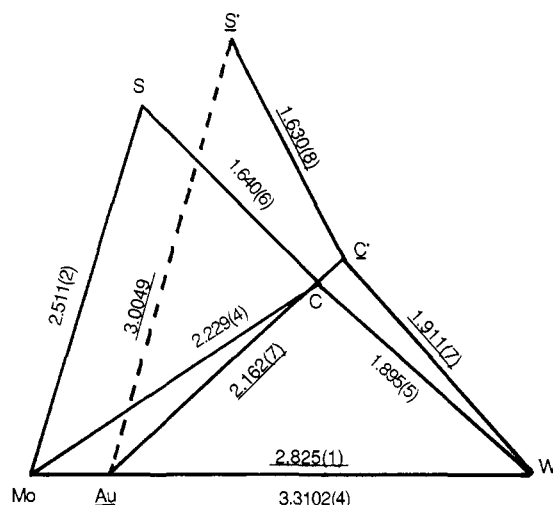
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**Figure 2.** Comparison of bond distances (Å) and angles (deg) in the side-on bonded CS in **1** with the semibridging CS in  $[\text{HB}(\text{pz})_3](\text{CO})\text{W}(\mu\text{-CO})(\mu\text{-CS})\text{Au}(\text{PPh}_3)$ . Selected bond angles are as follows: C–W–Mo = 40.2 (1), C'–W–Au = 49.9 (2), W–C–S = 170.8 (3), W–C'–S' = 165.9 (5).

compares well with other Mo–S bond distances in such diverse compounds as  $\text{Mo}(\text{CO})_3(\text{phen})(\eta^2\text{-SO}_2)$  (2.532 (3) Å),<sup>16</sup>  $\text{Et}_4\text{N}[\text{W}_2(\text{CO})_{10}(\mu\text{-SC}_6\text{Cl}_5)]$  (2.568 (4) Å),<sup>17</sup> and  $[\text{Na}(18\text{-crown-6})][\text{W}(\text{CO})_5(\text{SH})]$  (2.567 (5) Å).<sup>18</sup> The W–C(1) distance (1.895 (5) Å) is similar to the W–CS bond distances in the semibridging CS complex  $[\text{HB}(\text{pz})_3](\text{CO})_2\text{W}(\mu\text{-CS})\text{Au}(\text{PPh}_3)$  (1.911 (7) Å)<sup>7</sup> and the terminal CS complex *trans*- $[\text{W}(\text{CO})_4(\text{CS})(\text{CNCy})]$  (1.944 (19) Å).<sup>19</sup> The C(1)–S(1) distance (1.640 (6) Å) is  $\sim 0.1$  Å longer than the C–S distances in the terminal thiocarbonyl complexes  $[(\eta^5\text{-C}_5\text{H}_4\text{Me})\text{Mn}(\text{CS})(\text{NO})\text{I}]$  (1.513 (6) Å),<sup>20</sup> *trans*- $[\text{RhCl}(\text{CS})(\text{PPh}_3)_2]$  (1.54 (1) Å),<sup>21</sup> and *trans*- $[\text{W}(\text{CO})_4(\text{CS})(\text{CNCy})]$  (1.56 (2) Å).<sup>19</sup> This bond lengthening may be attributed to the donation of electron density from a CS  $\pi$ -bonding orbital to an empty orbital on molybdenum. The W–Mo bond distance (3.3102 (4) Å) is  $\sim 0.1$  Å longer than the M–M bond distances in  $[\text{CpM}(\text{CO})_3]_2$  (M = Mo, W; 3.235 (1) and 3.222 (1) Å, respectively)<sup>22</sup> and  $[\text{Mo}_2(\mu\text{-}\eta^2\text{-}(\text{CN-}t\text{-Bu}))(\text{CO})_4\text{Cp}_2]$  (3.2152 (10) Å).<sup>14</sup> A similar lengthening of the W–Au bond was observed in the semibridging CS complex  $[\text{HB}(\text{pz})_3](\text{CO})\text{W}(\mu\text{-CO})(\mu\text{-CS})\text{Au}(\text{PPh}_3)$  (2.824 (4) Å)<sup>7</sup> as compared with that in the semibridging CO complex  $\text{Cp}(\text{CO})\text{W}(\mu\text{-CO})_2\text{Au}(\text{PPh}_3)$  (2.698 (3) Å).<sup>15</sup>

To compare the bond distances and angles of the side-on bonded CS ligand in **1** with those of the semibridging CS complex  $[\text{HB}(\text{pz})_3](\text{CO})\text{W}(\mu\text{-CO})(\mu\text{-CS})\text{Au}(\text{PPh}_3)$ ,<sup>7</sup> these data are summarized in Figure 2. In both complexes, the bridging CS carbon is bonded to both metals, although more strongly to the W atom. On the other hand, the S in the semibridging CS does not bond to either metal, but the side-on CS sulfur is within normal bonding distance of the Mo. It is the bonding of the S atom which clearly distinguishes these two types of bridging CS ligands.

The side-on carbonyl analogue of **1**,  $[\text{HB}(\text{pz})_3](\text{CO})_2\text{W}(\mu\text{-CO})\text{Mo}(\text{CO})_2(\text{In})$ , was observed by IR spectroscopy ( $\nu(\text{CO})$  1957 m, 1884 s, 1827 s, 1815 sh, 1630 vw (br)  $\text{cm}^{-1}$ ) when a  $\text{CH}_2\text{Cl}_2$  solution of  $\text{Et}_4\text{N}[\text{HB}(\text{pz})_3]\text{W}(\text{CO})_3$ <sup>23</sup> was treated with  $[(\text{In})$

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Mo(CO)<sub>2</sub>(MeCN)<sub>2</sub>]BF<sub>4</sub>.<sup>8</sup> Attempts to grow single crystals of the complex were unsuccessful because it decomposed in solution in ~8 h. This result suggests that CO is a less stable side-on bridging ligand than CS. Also the fact that complex **1** contains a side-on bonded CS rather than CO indicates that CS has a greater preference for a side-on bridging site than CO. Thus, in all four types of bridging situations (A, B, C, and D), the CS is favored over CO as the bridging ligand.

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**Supplementary Material Available:** Tables of crystal data, positional and thermal parameters, complete bond angles and distances, coordinates (calculated) for hydrogen atoms, least-squares planes, and root-mean-square amplitudes of thermal vibration (16 pages); table of observed and calculated structure factors (26 pages). Ordering information is given on any current masthead page.

### Probes Which Reflect the Distance between the Retinal Chromophore and Membrane Surface in Bacteriorhodopsin (bR). Direction of Retinal 9-Methyl in bR

Myung Hwan Park, Toshihiro Yamamoto, and Koji Nakanishi\*

Department of Chemistry, Columbia University  
New York, New York 10027

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Bacteriorhodopsin (bR),<sup>1</sup> the purple membrane contained in *Halobacterium halobium*, consists of 248 amino acids comprising seven  $\alpha$ -helices and functions as a light-driven proton pump.<sup>2</sup> Its all-trans-retinal chromophore is linked through a protonated Schiff base to the  $\epsilon$ -amino group of Lys-216.<sup>3</sup> Despite the importance of the bR tertiary structure and location of the chromophore within the binding site in clarifying its mode of action, these are still unsettled problems although several three-dimensional models have been proposed on the basis of the amino acid sequence,<sup>4</sup> diffraction data,<sup>5</sup> susceptibilities of certain regions to proteolysis,<sup>6</sup> spectroscopy,<sup>7</sup> fluorescence energy transfer,<sup>8</sup> neutron diffraction,<sup>9</sup>

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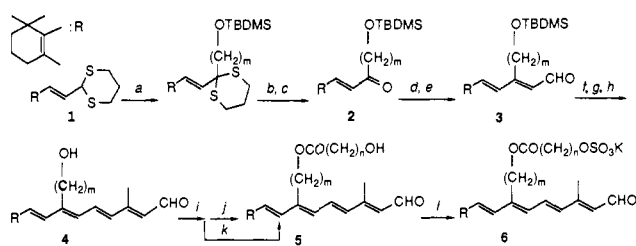
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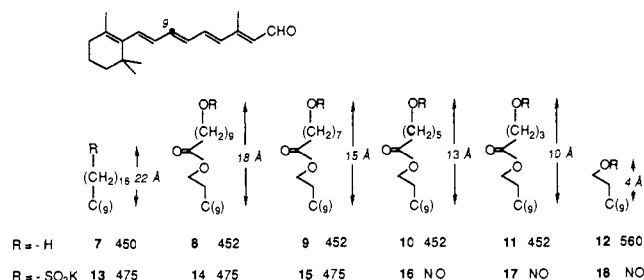
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### Scheme I



<sup>a</sup> (a) *n*-BuLi/I(CH<sub>2</sub>)<sub>*m*</sub>OTBDMS/THF, -78 °C, 44%; (b) HgCl<sub>2</sub>-HgO/95% MeOH reflux, 78%; (c) TBDMSCl/Et<sub>3</sub>N/CH<sub>2</sub>Cl<sub>2</sub>, quantitative; (d) (EtO)<sub>2</sub>POCH<sub>2</sub>CN/NaH/THF, 92%; (e) Dibal/Et<sub>2</sub>O, -78 °C, 64%, flash chromatography; (f) (EtO)<sub>2</sub>POCH<sub>2</sub>C(CH<sub>3</sub>)=CHCN/NaH/THF, 73%; (g) Dibal/Et<sub>2</sub>O, -78 °C, 30%, HPLC (Li-Chrosorb, 30% EtOAc in hexane); (h) *n*-Bu<sub>4</sub>NF/THF, 97%; (i) TBDMS-O-(CH<sub>2</sub>)<sub>*n*</sub>-COOH/DCC/DMAP/CH<sub>2</sub>Cl<sub>2</sub>, quantitative; (j) *n*-Bu<sub>4</sub>NF/THF when *n* = 9; (k) C<sub>5</sub>H<sub>5</sub>N + *n*-Bu<sub>4</sub>NF/THF, when *n* = 3 or 5 or 7, HPLC as in *h*; (l) SO<sub>3</sub>-C<sub>5</sub>H<sub>5</sub>N/C<sub>5</sub>H<sub>5</sub>N, aqueous KCl, combined yields for steps *i*, *j*, *k* and *l* are ca. 35%.

**Chart I.** Absorption Maxima of Pigment Analogues Formed from Retinal Analogues Containing Indicated Chains at C-9<sup>a</sup>



<sup>a</sup> Approximate C-9 side-chain distances are shown in italics. Pigments were reconstituted from bleached bR-opsin and retinal analogues in 10 mM HEPES buffer, pH 7.0, 25 °C, dark.

photoaffinity labeling,<sup>10</sup> and point-mutation techniques.<sup>11</sup>

In the following we show that 9-substituted retinal analogues with terminal sulfate groups behave as probes reflecting the distance between the chromophore and the membrane surface. Namely, retinal sulfates with sufficiently long spacers bind to give functional pigments, while those with short chains do not bind, presumably because the electrostatic affinity between the sulfate anions and positive charges on the membrane surface prevent the retinal to reach the binding site. Hydroxyalkyl ketone **2**, prepared from dithiane **1**<sup>12</sup> was converted into 9-hydroxyalkylretinal **4** through Emmons reaction, dibal reduction, deprotection, and chromatographic separation of isomers. Retinal **4** was converted into **6** by esterification, deprotection, and sulfonation<sup>13</sup> (Scheme I<sup>14</sup>).

Incubation in HEPES buffer, pH 7.0, in the dark, of bleached bR-opsin<sup>15</sup> with retinals **7-12** having terminal hydroxyl groups, resulted in smooth formation of pigments (Chart I). Retinal sulfates **13** and **14** also immediately formed pigments,<sup>16</sup> while

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