inlet tube, reflux condenser, and magnetic stir bar was charged with 100 mL of dry methylene chloride, 2.0 g (8.42 mmol) of **12**, and 200 mg of 5% palladium on carbon. The system was purged with hydrogen and stirred at room temperature until 189 mL (8.42 mmol, 1 equiv) of hydrogen was used (4.5 h). Filtration through silica gel followed by removal of the solvent afforded 1.68 g (83% yield) of **11**, which had spectral properties identical with those of the sample of **11** obtained from **7**. Additional purification by HPLC on silica gel using 1% ethyl acetate–99% hexane gave a sample; mp 36–37 °C.

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Registry No. **5**, 36611-93-5; **6**, 285-67-6; **7**, 286-20-4; **8**, 6705-51-7; **9**, 105162-55-8; **10**, 105162-56-9; **11**, 105162-57-0; **12**, 105162-58-1; **13**, 1713-33-3; **14**, 105162-59-2; **15**, 20152-33-4; **17**, 83152-89-0; **19**, 105162-60-5; $(CH_3)_3CSi(CH_3)_2CN$, 56522-24-8; ZnI_2, 10139-47-6; $(CH_3)_3CSi(CH_3)_2Cl$, 18162-48-6; $(CH_3)_3CSi(CH_2)_2OTf$, 69739-34-0; $(CH_3)_3SiCN$, 7677-24-9.

Use of ^{33}S Chemical Shifts To Determine pK_a's of Arenesulfonic Acids

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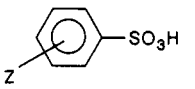
The ^{33}S chemical shifts of several arenesulfonic acids were recently determined in 1–3 M aqueous solution where they are completely ionized.[2] It was observed that substitution on the aromatic ring led to a change in the ^{33}S chemical shift of the sulfonate sulfur. In a general sense the chemical shift is related to the electron density on the probe nucleus, other things being equal. If the ^{33}S chemical shift is related to the electron density on sulfur, then it is also related to the electron distribution in the sulfonate ion. The pK_a of an arenesulfonic acid should also be directly influenced by the electron distribution in the sulfonate ion conjugate base, and therefore we investigated whether ^{33}S chemical shifts could be utilized in some manner for the determination of the pK_a's of arenesulfonic acids.

Currently it is necessary to carry out pK_a determinations of sulfonic acids in concentrated sulfuric acid solution where appreciable amounts of both the free sulfonic acid and its conjugate base are present. The concentrations are determined by either UV or ^1H NMR methods in solutions of varying Hammett acidity (H_0). The pK_a is obtained by extrapolation of these plots to dilute solution.[3] As a consequence of these experimental difficulties, not a large number of these values have been reported. Measurement of ^{33}S chemical shifts would be a vast improvement over current methods if pK_a values could be derived from them.

We report that substituent effects on the ^{33}S chemical shifts of arenesulfonates are accurately described by a dual-substituent parameter (DSP) treatment and that ^{33}S chemical shifts of arenesulfonates are linearly related to pK_a's of the sulfonic acids. In addition we report a simple method for the preparation of pure samples of arenesulfonic acids.

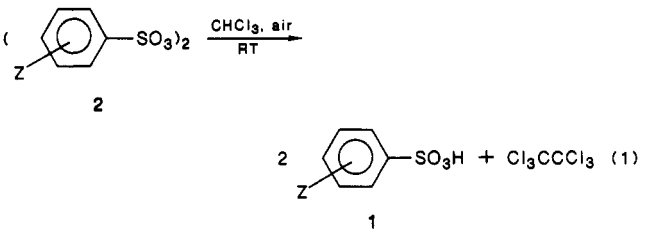
Results and Discussion

The series of arenesulfonic acids **1a–g** was utilized in this study as the free acid dissolved in water. Concentrations



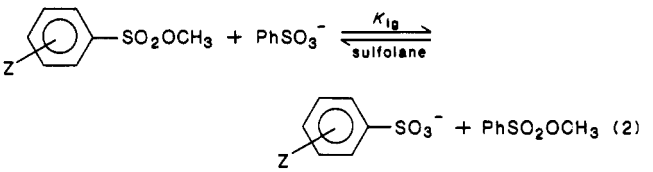
1a, Z = H
b, Z = *m*-CH_3
c, Z = *p*-CH_3
d, Z = *p*-Br
e, Z = *m*-CF_3
f, Z = *m*-NO_2
g, Z = *p*-NO_2

were normally about 2.4 M. Experiments with both methanesulfonic acid and benzenesulfonic acid showed that over the concentration ranges used in this study (2.0–2.7 M) changes in ^{33}S chemical shifts were within the experimental error. Acids **1a–c** were available commercially. Acids **1d–g** were prepared in generally high yields by decomposition of the corresponding bis(arenesulfonyl peroxide) (**2**) in chloroform (eq 1).



2 **1**

Table I contains the chemical shift data, measured relative to an external 4.0 M ammonium sulfate reference, for this series of acids as well as pK_a values, which were measured by Cerfontain[3] or extrapolated by us.[4] Included in Table I are pK_{lg} values, which are derived from the equilibrium constants for methyl transfer between a substituted methyl arenesulfonate and benzenesulfonate in sulfolane solution[5,6] (eq 2).



A Hammett plot of δ (^{33}S) vs. σ followed the relationship of eq 3. A linear relationship of $\delta(^{33}S)$ and σ was reported earlier for a limited set of arenesulfonic acids.[7] The fit was greatly improved by using a dual-substituent parameter fit to σ_I and σ_R (eq 4 and 5).[8] A plot of the chemical shifts calculated from eq 4 and 5 vs. the observed values gives excellent agreement (r = 0.997), and the slope of this

$$\delta(^{33}S) = -8.75\sigma - 11.89 \quad (r = 0.986) \qquad (3)$$

$$\delta(^{33}S_m) = -6.39\sigma_I - 10.08\sigma_R - 11.98 \quad (r = 0.997) \qquad (4)$$

$$\delta(^{33}S_p) = -7.37\sigma_I - 11.6\sigma_R - 12.43 \quad (r = 0.994) \qquad (5)$$

(1) (a) Loyola University of Chicago. (b) New Mexico State University.
(2) Crumrine, D. S.; Gillece-Castro, B. *J. Org. Chem.* **1985**, *50*, 4408.
(3) (a) Koeberg-Telder, A.; Cerfontain, H. *J. Chem. Soc., Perkins Trans. 2*, **1975**, 226. (b) Cerfontain, H.; Schnitger, B. S. *Recl. Trav. Chim. Pays-Bas* **1972**, *91*, 199.
(4) Hoffman, R. V.; Belfoure, E. L. *J. Am. Chem. Soc.* **1982**, *104*, 2183.
(5) Lewis, E. S.; Hu, D. D. *J. Am. Chem. Soc.* **1984**, *106*, 3292.
(6) Hoffman, R. V.; Shankweiler, J. M. *J. Am. Chem. Soc.* **1986**, *108*, 5536.
(7) Hinton, J. F.; Buster, D. *J. Magn. Reson.* **1984**, *57*, 494.
(8) Values taken from: Hine, J. *Structural Effects On Equilibria in Organic Chemistry*; Wiley-Interscience: New York, 1975.

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Table I. ^{33}S Chemical Shift Data for Arenesulfonic Acids ($ZC_6H_4SO_3H$)

Z	$\delta(^{33}S)^a$	$\delta(^{33}S)$ (calcd)^b	pK_a	pK_{lg}
H	-12.0	-12.21	-6.65	0
m-CH_3	-10.7	-10.61	-6.56	0.14
p-CH_3	-11.3	-10.85	-6.62	0.46
p-Br	-13.3	-13.45	-6.72	-0.74
m-CF_3	-15.3	-15.66	-6.93	-1.33
m-NO_2	-17.9	-17.97	-7.1	-2.15
p-NO_2	-19.1	-18.97	-7.15	-2.36

[a] Chemical shifts determined in 2.0–2.7 M aqueous solution relative to 4.0 M external ammonium sulfate reference. Errors are, in general, ±0.3 ppm. [b] These are values calculated from the DSP fits of eq 4 and 5.

plot (0.978) is within experimental error of 1.00.

The marked improvement for the DSP fit indicates that there is a significant resonance interaction between the aromatic ring and the sulfonate sulfur, probably of the d–p π type, and the DSP treatment better accounts for this interaction. This resonance interaction between the aromatic ring and the sulfonate group was also used to explain the higher ^{33}S chemical shifts of aromatic sulfonic acids vs. aliphatic sulfonic acids,[9] and resonance interaction between the aromatic ring and carbon was used to explain the higher field ^{13}C signals of aromatic carboxylic acids vs. aliphatic ones.[9] It was initially surprising, however, that electron-withdrawing substituents on the aromatic ring caused an upfield shift in the ^{33}S signal, although the same effect has been reported for several other systems including benzoic acids,[10] benzoate anions,[10] acetophenones,[11] and phenylphosphonic acids.[12]

Two different explanations have been advanced to account for these effects. The dominance of the paramagnetic term in the shielding equation for atoms that have p orbitals would predict this behavior[13] and has been invoked previously.[7]

Alternatively it has been proposed that resonance interaction with the aromatic ring could increase d–p π polarization, or back-bonding, from the oxygen atoms to the central sulfur, carbon,[10] or phosphorus[12] atom. Thus, the net effect of resonance interaction between electron-withdrawing aromatic rings and the sulfur center of sulfonic acids is to shift electron density on the attached oxygens toward the sulfur and hence increase the electron density in the vicinity of the sulfur nucleus. This latter proposal has been recently discussed for the case of phosphorus.[14] While the present data do not allow a resolution of these issues, most important for our purposes is that ^{33}S chemical shifts are well described by the DSP treatment.

Changes in ^{33}S chemical shift of arenesulfonates are related to the pK_a's of the arenesulfonic acids as shown in Figure 1. They fit the linear relationship of eq 6. The excellent correlation provides a very direct way to determine the pK_a's of arenesulfonic acids in aqueous solution by simply inserting the ^{33}S chemical shift into eq 6. It should be noted that this method is only applicable to

$$pK_a = 0.0725\delta(^{33}S) - 5.787 \quad (r = 0.996) \qquad (6)$$

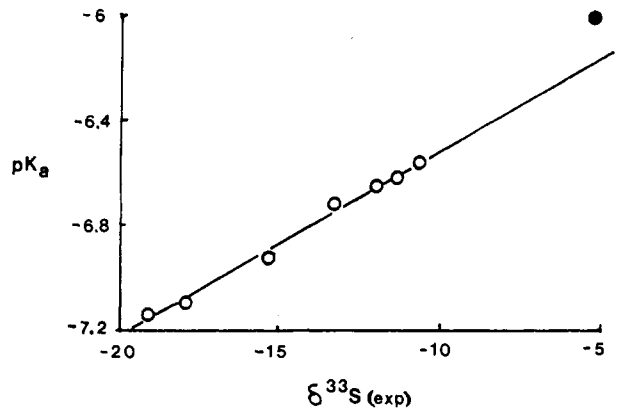

Figure 1. ^{33}S chemical shifts of arenesulfonic acids in water vs. the pK_a's of these acids. The solid point is for methanesulfonic acid and is not included in the linear correlation.

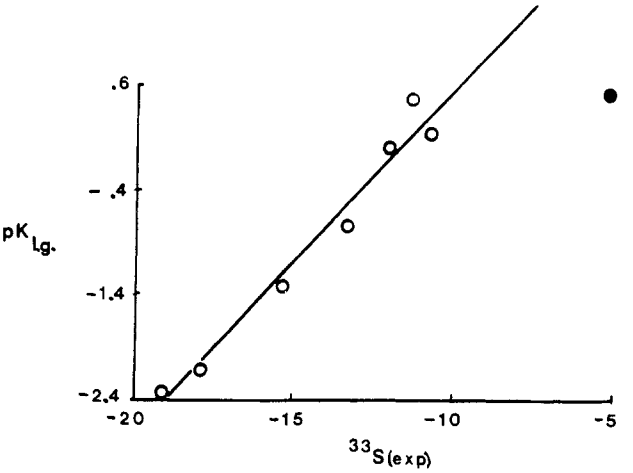

Figure 2. ^{33}S chemical shifts of arenesulfonic acids in water vs. pK_{lg} determined for eq 2. The solid point is for methanesulfonic acid and is not included in the linear correlation.

aromatic sulfonic acids. Figure 1 shows a point for methanesulfonic acid that falls off the curve of the aromatic examples (and is not included in the correlation). Obviously factors other than electron density influence the chemical shift. The results suggest, however, that similar correlations could be developed for related families of compounds such as alkanesulfonic acids and alkyl sulfates.

With the expectation that eq 4 and 5 hold generally for meta and para substituents, it is possible to directly calculate the pK_a of any arenesulfonic acid. For a given substituent the ^{33}S chemical shift can be calculated from eq 4 and 5, and then eq 6 can be used to calculate the pK_a. The accuracy of the pK_a is limited to the data fit (which is quite good) and to the generality of substituent behavior.

A second parameter of interest for arenesulfonates is pK_{lg}, which is the equilibrium constant for methyl transfers between arenesulfonates (eq 2).[5,6] This parameter is quite useful in Brønsted-type plots that can be used for transition-state mapping of reactions in which the arenesulfonate group acts as a leaving group.[6] Known values of pK_{lg} are plotted vs. $\delta(^{33}S)$ in Figure 2 and follow the relationship of eq 7.

$$pK_{lg} = 0.337\delta(^{33}S) + 3.94 \quad (r = 0.984) \qquad (7)$$

As with the case of pK_a, these results provide a simple method to obtain this parameter easily. The point for methanesulfonate lies far off the line and was not included in the correlation.

Experimental Section

All spectra were obtained on a Varian 24K FT-80 spectrometer

(9) Levy, G. C.; Nelson, B. L. *Carbon 13 Nuclear Magnetic Resonance for Organic Chemists*; Wiley-Interscience: New York, 1972; p 117.
(10) Kosugi, Y.; Furuya, Y. *Tetrahedron* **1980**, *36*, 2741.
(11) Bromilow, J.; Brownlee, R. T. C.; Craik, D. J.; Fiske, P. R.; Rowe, J. E.; Sadek, M. *J. Chem. Soc., Perkin Trans. 2* **1981**, 753.
(12) Mitsch, C. C.; Freedman, L. L.; Moreland, C. G. *J. Magn. Reson.* **1970**, *3*, 446.
(13) Craik, D. J. *Annual Reports of NMR Spectroscopy*; Webb, G. A., Ed.; Academic: New York, 1983; Vol. 15, p 1.
(14) Gorenstein, D. G. *Phosphorous 31 NMR*; Gorenstein, D. G., Ed.; Academic: New York, 1984; pp 23–27.

at 36 ± 1 °C as previously described.[2] The sulfonic acids were all in the acid form dissolved in deionized water with no added counterion or buffer. All reported chemical shifts are the average of at least two determinations. Sulfonic acids **1a–c** were obtained commercially.

***p*-Nitrobenzenesulfonic Acid.** A solution of *p*-nitrobenzenesulfonyl peroxide[15] (2.0 g, 5 mmol) in chloroform (150 mL) was stirred at room temperature for 1 week. Iodometric titration was used to monitor the disappearance of the peroxide. A white precipitate of *p*-nitrobenzenesulfonic acid [1.46 g (72%)] was removed by filtration and recrystallized from diethyl ether–benzene; mp 108–110 °C. A sample of the acid was converted to the *S*-benzylisothiuronium derivative, mp 199–200 °C (lit.[16] mp 200–202 °C).

***m*-Nitrobenzenesulfonic Acid.** A solution of *m*-nitrobenzenesulfonyl peroxide[15] (0.82 g, 2 mmol) in chloroform (40 mL) was stirred at room temperature for 1 week. The resulting yellow solution was extracted with water (3 × 25 mL), and the water was removed under vacuum. The resulting gray crystals [0.78 g (95%)] were recrystallized from ether–benzene; mp 67–70 °C. A sample of the acid was converted to the *S*-benzylisothiuronium derivative, mp 145–146 °C (lit.[15] mp 145–146 °C).

***p*-Bromobenzenesulfonic Acid.** A solution of *p*-bromobenzenesulfonyl peroxide (1.2 g, 2.5 mmol)[17] in chloroform (100 mL) was stirred for 3 days at room temperature. The orange solution was extracted with water (3 × 25 mL), and the water was removed in vacuo. The resulting yellow crystals [0.9 g (76%)] were recrystallized from ether–benzene; mp 89–90 °C (lit.[18] mp 88 °C).

***m*-(Trifluoromethyl)benzenesulfonic Acid.** A solution of *m*-(trifluoromethyl)benzenesulfonyl peroxide[19] (4 g, 9 mmol) in chloroform was stirred at room temperature for 3 weeks. The acid formed a second layer that was separated from the chloroform solution, dissolved in water, and filtered. The water was removed in vacuo to give white crystals: 1.5 g (37%); mp 42–44 °C. A sample of the acid was converted to the *S*-benzylisothiuronium derivative, mp 137–138 °C (lit.[19] mp 138–139 °C).

Acknowledgment. The work at New Mexico State was supported by the National Science Foundation whom we thank. Computer-fitting routines were performed on the Prophet computer system supported at New Mexico State by the National Institutes of Health.

Registry No. $PhSO_3H$, 98-11-3; Me-*m*-$C_6H_4SO_3H$, 617-97-0; Me-*p*-$C_6H_4SO_3H$, 104-15-4; Br-*p*-$C_6H_4SO_3H$, 138-36-3; F_3C-*m*-$C_6H_4SO_3H$, 1643-69-2; O_2N-*m*-$C_6H_4SO_3H$, 98-47-5; O_2N-*p*-$C_6H_4SO_3H$, 138-42-1; Me-*m*-$C_6H_4SO_3^-$, 104994-83-4; Me-*p*-$C_6H_4SO_3^-$, 16722-51-3; Br-*p*-$C_6H_4SO_3^-$, 45900-71-8; F_3C-*m*-$C_6H_4SO_3^-$, 104994-84-5; O_2N-*m*-$C_6H_4SO_3^-$, 30904-40-6; O_2N-*p*-$C_6H_4SO_3^-$, 30904-42-8.

(15) Dannley, R. L.; Corbett, G. E. *J. Org. Chem.* **1966**, *31*, 153.
(16) Dannley, R. L.; Hoffman, R. V. *J. Org. Chem.* **1975**, *40*, 2426.
(17) Bolte, J.; Kergomard, A.; Vincent, S. *Tetrahedron Lett.* **1965**, 1529.
(18) Garrick, A. *Z. Chem.* **1869**, 549.
(19) Dannley, R. L.; Tornstrom, P. K. *J. Org. Chem.* **1975**, *40*, 2278.

Experimental Method for the Determination of Cation Binding Constants in Methanol Using Ion-Selective Electrode Methods

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The high level of interest in podands,[1] crown ethers,[2] lariat ethers,[3] cryptands,[4] cavitands,[5] and related species is apparent from the extensive literature in this field that has appeared during the past few years. An important reason for the extensive synthetic effort[6] witnessed recently is the ability of these species to complex cations and molecules. The syntheses of cation binders were followed almost immediately by methods for measuring the cation binding affinities of the various species.

In the earliest work in this area, cation binding affinities were assessed by extraction methods. In these experiments, the salt of a colored organic acid (like picric acid[7]) is dissolved in water and an immiscible organic solvent ($CHCl_3$, CH_2Cl_2) is added. When the two phases are shaken, no extraction occurs because the salt is insoluble in the organic phase. When a lipophilic cation binder is added, the cation is complexed and conducted into the organic phase. The colored anion follows, and the extent of extraction can be assessed colorimetrically or by atomic absorption. Such methods are certainly reliable, but several variables must be controlled in each individual experiment. For example, the same solvent pair, ionic strengths, salt concentrations, temperatures, solvent volumes, etc., must all be kept identical for results to be directly comparable. An example of the problem is found in recent papers by several prominent workers in this field: the solvent systems used have been chloroform–water,[8,9] dichloromethane–water,[10] 1,2-dichloroethane–water,[11] and *o*-dichlorobenzene–butanol.[12]

The extensive work and compilations of Izatt, Christensen, and their co-workers[13] have made homogeneous cation binding constants of considerable value. Frensdorff[14] reported an important method for assessing homogeneous cation binding affinities more than 15 years ago, and this method has been the mainstay of our own group. Following a number of inquiries concerning the experimental details of our method for measuring cation binding affinities using the Frensdorff approach, we set forth this information here.

Experimental Section

Reagents. Reagent-grade methanol was distilled from magnesium turnings through a 20-cm Vigreux column. Either ClO_4^- or Cl^- salts were used. $NaClO_4$, $KClO_4$, NaCl, and KCl were the purest available from Aldrich Chemical Co., recrystallized from water, and dried in a vacuum oven [60 °C (0.05 torr)] for 2 days. NH_4Cl was used as received from Aldrich.

Apparatus. Potentials to within ±0.1 mV were measured on an Orion Model 701A voltmeter. Sodium activity was determined by a sodium ion selective electrode (ISE, Corning Model No.

(1) Voegtle, F.; Weber, E. *Angew. Chem., Int. Ed. Engl.* **1979**, *18*, 753.
(2) Voegtle, F.; Weber, E. *Host Guest Complex Chemistry*; Springer Verlag: Weinheim, 1985.
(3) (a) Dishong, D. M; Diamond, C. J.; Cinoman, M. I.; Gokel, G. W. *J. Am. Chem. Soc.* **1983**, *105*, 586. (b) Schultz, R. A.; White, B. D.; Dishong, D. M.; Arnold, K. A.; Gokel, G. W. *J. Am. Chem. Soc.* **1985**, *107*, 6659.
(4) Lehn, J.-M. *Science (Washington, D.C.)* **1985**, *227*, 849.
(5) (a) Cram, D. J. *Science (Washington, D.C.)* **1983**, *219*, 1177. (b) Cram, D. J.; Trueblood, K. N. In *Host Guest Complex Chemistry: Macrocycles*; Voegtle, F., Weber, E., Eds.; Springer Verlag: Weinheim, 1985; pp 125–188.
(6) Gokel, G. W.; Korzeniowski, S. H. *Macrocyclic Polyether Syntheses*; Springer Verlag: Weinheim, 1982.
(7) Pedersen, C. J. *J. Am. Chem. Soc.* **1967**, *89*, 7017.
(8) Strzelbicki, J.; Bartsch, R. A. *Anal. Chem.* **1981**, *53*, 1894.
(9) Pacey, G. E.; Wu, Y. P.; Bubnis, B. P. *Analyst* **1981**, *106*, 636.
(10) Kawakami, Y.; Sugiura, T.; Yamashita, Y. *Bull. Chem. Soc. Jpn.* **1978**, *51*, 3053.
(11) Bartsch, R. A.; Czech, B. P.; Kang, S. I.; Stewart, L. E.; Walkowiak, W.; Charewicz, W. A.; Heo, G. S.; Son, B. *J. Am. Chem. Soc.* **1985**, *107*, 4997.
(12) (a) Shinkai, S.; Nakaji, T.; Ogawa, T.; Shigematsu, K.; Manabe, O. *J. Am. Chem. Soc.* **1981**, *103*, 111. (b) Shinkai, S.; Minami, T.; Kusano, Y.; Manabe, O.; *Tetrahedron Lett.* **1982**, 2584.
(13) Izatt, R. M.; Bradshaw, J. S.; Nielson, S. A.; Lamb, J. D.; Christensen, J. J. *Chem. Rev.* **1985**, *85*, 271.
(14) Frensdorff, H. K. *J. Am. Chem. Soc.* **1971**, *93*, 600.

0022-3263/86/1951-5015$01.50/0