

## NMR Chemical Shifts of Trace Impurities: Common Laboratory Solvents, Organics, and Gases in Deuterated Solvents Relevant to the Organometallic Chemist

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Tables of <sup>1</sup>H and <sup>13</sup>C NMR chemical shifts have been compiled for common organic compounds often used as reagents or found as products or contaminants in deuterated organic solvents. Building upon the work of Gottlieb, Kotlyar, and Nudelman in the *Journal of Organic Chemistry*, signals for common impurities are now reported in additional NMR solvents (tetrahydrofuran-*d*<sub>8</sub>, toluene-*d*<sub>8</sub>, dichloromethane-*d*<sub>2</sub>, chlorobenzene-*d*<sub>5</sub>, and 2,2,2-trifluoroethanol-*d*<sub>3</sub>) which are frequently used in organometallic laboratories. Chemical shifts for other organics which are often used as reagents or internal standards or are found as products in organometallic chemistry are also reported for all the listed solvents.

Hanging above the desk of most every chemist whose work relies heavily on using NMR spectroscopy<sup>1</sup> is *NMR Chemical Shifts of Common Laboratory Solvents as Trace Impurities* by Gottlieb, Kotlyar, and Nudelman.<sup>2</sup> By compiling the chemical shifts of a large number of contaminants commonly encountered in synthetic chemistry, the publication has become an essential reference, allowing for easy identification of known impurities in a variety of deuterated organic solvents. However, despite the utility of Gottlieb et al.'s work,<sup>3</sup> the chemical shifts of impurities in a number of NMR solvents often used by organometallic chemists were not included. Tetrahydrofuran-*d*<sub>8</sub> (THF-*d*<sub>8</sub>), toluene-*d*<sub>8</sub>, dichloromethane-*d*<sub>2</sub> (CD<sub>2</sub>Cl<sub>2</sub>), chlorobenzene-*d*<sub>5</sub> (C<sub>6</sub>D<sub>5</sub>Cl), and 2,2,2-trifluoroethanol-*d*<sub>3</sub> (TFE-*d*<sub>3</sub>) are commonplace in laboratories practicing inorganic syntheses. Therefore, we have expanded the spectral data compilation with the inclusion of chemical shifts of common impurities recorded in the deuterated solvents heavily employed in our organometallic laboratories. The chemical shifts of various gases (hydrogen, methane, ethane, propane,

ethylene, propylene, and carbon dioxide) often encountered as reagents or products in organometallic reactions, along with organic compounds relevant to organometallic chemists (allyl acetate, benzaldehyde, carbon disulfide, carbon tetrachloride, 18-crown-6, cyclohexanone, diallyl carbonate, dimethyl carbonate, dimethyl malonate, furan, Apiezon H grease, hexamethylbenzene, hexamethyldisiloxane, imidazole, pyrrole, and pyrrolidine), have also been added to this expanded list.

### Experimental Section

All deuterated solvents were obtained commercially through Cambridge Isotope Laboratories, Inc. NMR spectra were recorded at 298 K using 300, 500, or 600 MHz spectrometers (<sup>13</sup>C{<sup>1</sup>H} NMR frequencies of 75.5, 126, or 151 MHz, respectively). Adopting the previously reported strategy,<sup>2</sup> standard solutions of mixtures of specific impurities were used to reduce the number of necessary individual NMR experiments. The combinations of organic compounds were chosen in a way in which intermolecular interactions and resonance convolution would be minimized. Unless otherwise stated, the standard solutions were prepared with qualitatively equal molar amounts of the following compounds: (solution 1) acetone, dimethylformamide, ethanol, toluene; (solution 2) benzene, dimethyl sulfide, ethyl acetate, methanol; (solution 3) acetic acid, chloroform, diethyl ether, 2-propanol, tetrahydrofuran; (solution 4) acetonitrile, dichloromethane, 1,4-dioxane, *n*-hexane, hexamethylphosphoramide (HMPA); (solution 5) 1,2-dichloroethane, *n*-pentane, pyridine, hexamethylbenzene; (solution 6) *tert*-butyl alcohol, 2,6-di-*tert*-butyl-4-methylphenol (BHT), cyclohexane,

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(1) For general information on <sup>1</sup>H and <sup>13</sup>C{<sup>1</sup>H} NMR spectroscopy, see: Balci, M. *Basic <sup>1</sup>H- and <sup>13</sup>C-NMR Spectroscopy*; Elsevier: Amsterdam, 2005.

(2) Gottlieb, H. E.; Kotlyar, V.; Nudelman, A. *J. Org. Chem.* **1997**, *62*, 7512.

(3) According to ACS Publications as of December 2009 (<http://pubs.acs.org/>), Gottlieb et al.'s publication<sup>2</sup> is the most downloaded *Journal of Organic Chemistry* article over the preceding 12 months.

## NMR Chemical Shifts of Common Laboratory Solvents as Trace Impurities

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In the course of the routine use of NMR as an aid for organic chemistry, a day-to-day problem is the identification of signals deriving from common contaminants (water, solvents, stabilizers, oils) in less-than-analytically-pure samples. This data may be available in the literature, but the time involved in searching for it may be considerable. Another issue is the concentration dependence of chemical shifts (especially  $^1\text{H}$ ); results obtained two or three decades ago usually refer to much more concentrated samples, and run at lower magnetic fields, than today's practice.

We therefore decided to collect  $^1\text{H}$  and  $^{13}\text{C}$  chemical shifts of what are, in our experience, the most popular "extra peaks" in a variety of commonly used NMR solvents, in the hope that this will be of assistance to the practicing chemist.

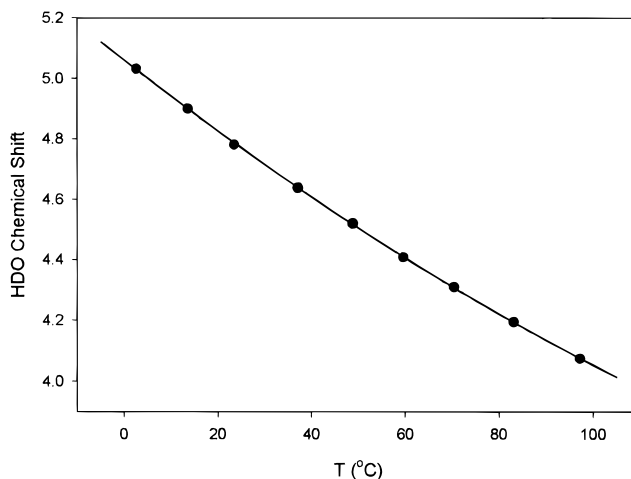
### Experimental Section

NMR spectra were taken in a Bruker DPX-300 instrument (300.1 and 75.5 MHz for  $^1\text{H}$  and  $^{13}\text{C}$ , respectively). Unless otherwise indicated, all were run at room temperature ( $24 \pm 1$  °C). For the experiments in the last section of this paper, probe temperatures were measured with a calibrated Eurotherm 840/T digital thermometer, connected to a thermocouple which was introduced into an NMR tube filled with mineral oil to approximately the same level as a typical sample. At each temperature, the  $\text{D}_2\text{O}$  samples were left to equilibrate for at least 10 min before the data were collected.

In order to avoid having to obtain hundreds of spectra, we prepared seven stock solutions containing approximately equal amounts of several of our entries, chosen in such a way as to prevent intermolecular interactions and possible ambiguities in assignment. Solution 1: acetone, *tert*-butyl methyl ether, dimethylformamide, ethanol, toluene. Solution 2: benzene, dimethyl sulfoxide, ethyl acetate, methanol. Solution 3: acetic acid, chloroform, diethyl ether, 2-propanol, tetrahydrofuran. Solution 4: acetonitrile, dichloromethane, dioxane, *n*-hexane, HMPA. Solution 5: 1,2-dichloroethane, ethyl methyl ketone, *n*-pentane, pyridine. Solution 6: *tert*-butyl alcohol, BHT, cyclohexane, 1,2-dimethoxyethane, nitromethane, silicone grease, triethylamine. Solution 7: diglyme, dimethylacetamide, ethylene glycol, "grease" (engine oil). For  $\text{D}_2\text{O}$ . Solution 1: acetone, *tert*-butyl methyl ether, dimethylformamide, ethanol, 2-propanol. Solution 2: dimethyl sulfoxide, ethyl acetate, ethylene glycol, methanol. Solution 3: acetonitrile, diglyme, dioxane, HMPA, pyridine. Solution 4: 1,2-dimethoxyethane, dimethylacetamide, ethyl methyl ketone, triethylamine. Solution 5: acetic acid, *tert*-butyl alcohol, diethyl ether, tetrahydrofuran. In  $\text{D}_2\text{O}$  and  $\text{CD}_3\text{OD}$  nitromethane was run separately, as the protons exchanged with deuterium in presence of triethylamine.

### Results

**Proton Spectra** (Table 1). A sample of 0.6 mL of the solvent, containing 1  $\mu\text{L}$  of  $\text{TMS}^1$ , was first run on its own. From this spectrum we determined the chemical shifts of the solvent residual peak<sup>2</sup> and the water peak. It should be noted that the latter is quite temperature-



**Figure 1.** Chemical shift of HDO as a function of temperature.

dependent (*vide infra*). Also, any potential hydrogen-bond acceptor will tend to shift the water signal downfield; this is particularly true for nonpolar solvents. In contrast, in *e.g.* DMSO the water is already strongly hydrogen-bonded to the solvent, and solutes have only a negligible effect on its chemical shift. This is also true for  $\text{D}_2\text{O}$ ; the chemical shift of the residual HDO is very temperature-dependent (*vide infra*) but, maybe counter-intuitively, remarkably solute (and pH) independent.

We then added 3  $\mu\text{L}$  of one of our stock solutions to the NMR tube. The chemical shifts were read and are presented in Table 1. Except where indicated, the coupling constants, and therefore the peak shapes, are essentially solvent-independent and are presented only once.

For  $\text{D}_2\text{O}$  as a solvent, the accepted reference peak ( $\delta = 0$ ) is the methyl signal of the sodium salt of 3-(trimethylsilyl)propanesulfonic acid; one crystal of this was added to each NMR tube. This material has several disadvantages, however: it is not volatile, so it cannot be readily eliminated if the sample has to be recovered. In addition, unless one purchases it in the relatively expensive deuterated form, it adds three more signals to the spectrum (methylenes 1, 2, and 3 appear at 2.91, 1.76, and 0.63 ppm, respectively). We suggest that the residual HDO peak be used as a secondary reference; we find that if the effects of temperature are taken into account (*vide infra*), this is very reproducible. For  $\text{D}_2\text{O}$ , we used a different set of stock solutions, since many of the less polar substrates are not significantly water-soluble (see Table 1). We also ran sodium acetate and sodium formate (chemical shifts: 1.90 and 8.44 ppm, respectively).

**Carbon Spectra** (Table 2). To each tube, 50  $\mu\text{L}$  of the stock solution and 3  $\mu\text{L}$  of  $\text{TMS}^1$  were added. The solvent chemical shifts<sup>3</sup> were obtained from the spectra containing the solutes, and the ranges of chemical shifts

(2) *I.e.*, the signal of the proton for the isotopomer with one less deuterium than the perdeuterated material, *e.g.*,  $\text{CHCl}_3$  in  $\text{CDCl}_3$  or  $\text{C}_6\text{D}_5\text{H}$  in  $\text{C}_6\text{D}_6$ . Except for  $\text{CHCl}_3$ , the splitting due to  $J_{\text{HD}}$  is typically observed (to a good approximation, it is 1/6.5 of the value of the corresponding  $J_{\text{HH}}$ ). For  $\text{CHD}_2$  groups (deuterated acetone, DMSO, acetonitrile), this signal is a 1:2:3:2:1 quintet with a splitting of *ca.* 2 Hz.

(3) In contrast to what was said in note 2, in the  $^{13}\text{C}$  spectra the solvent signal is due to the perdeuterated isotopomer, and the one-bond couplings to deuterium are always observable (*ca.* 20–30 Hz).

(1) For recommendations on the publication of NMR data, see: IUPAC Commission on Molecular Structure and Spectroscopy. *Pure Appl. Chem.* 1972, 29, 627; 1976, 45, 217.

Table 1. <sup>1</sup>H NMR Data

	proton	mult	CDCl <sub>3</sub>	(CD <sub>3</sub> ) <sub>2</sub> CO	(CD <sub>3</sub> ) <sub>2</sub> SO	C <sub>6</sub> D <sub>6</sub>	CD <sub>3</sub> CN	CD <sub>3</sub> OD	D <sub>2</sub> O
solvent residual peak			7.26	2.05	2.50	7.16	1.94	3.31	4.79
H <sub>2</sub> O		s	1.56	2.84 <sup>a</sup>	3.33 <sup>a</sup>	0.40	2.13	4.87	
acetic acid	CH <sub>3</sub>	s	2.10	1.96	1.91	1.55	1.96	1.99	2.08
acetone	CH <sub>3</sub>	s	2.17	2.09	2.09	1.55	2.08	2.15	2.22
acetonitrile	CH <sub>3</sub>	s	2.10	2.05	2.07	1.55	1.96	2.03	2.06
benzene	CH	s	7.36	7.36	7.37	7.15	7.37	7.33	
<i>tert</i> -butyl alcohol	CH <sub>3</sub>	s	1.28	1.18	1.11	1.05	1.16	1.40	1.24
	OH <sup>c</sup>	s			4.19	1.55	2.18		
<i>tert</i> -butyl methyl ether	CCH <sub>3</sub>	s	1.19	1.13	1.11	1.07	1.14	1.15	1.21
	OCH <sub>3</sub>	s	3.22	3.13	3.08	3.04	3.13	3.20	3.22
BHT <sup>b</sup>	ArH	s	6.98	6.96	6.87	7.05	6.97	6.92	
	OH <sup>c</sup>	s	5.01		6.65	4.79	5.20		
	ArCH <sub>3</sub>	s	2.27	2.22	2.18	2.24	2.22	2.21	
	ArC(CH <sub>3</sub> ) <sub>3</sub>	s	1.43	1.41	1.36	1.38	1.39	1.40	
chloroform	CH	s	7.26	8.02	8.32	6.15	7.58	7.90	
cyclohexane	CH <sub>2</sub>	s	1.43	1.43	1.40	1.40	1.44	1.45	
1,2-dichloroethane	CH <sub>2</sub>	s	3.73	3.87	3.90	2.90	3.81	3.78	
dichloromethane	CH <sub>2</sub>	s	5.30	5.63	5.76	4.27	5.44	5.49	
diethyl ether	CH <sub>3</sub>	t, 7	1.21	1.11	1.09	1.11	1.12	1.18	1.17
	CH <sub>2</sub>	q, 7	3.48	3.41	3.38	3.26	3.42	3.49	3.56
diglyme	CH <sub>2</sub>	m	3.65	3.56	3.51	3.46	3.53	3.61	3.67
	CH <sub>2</sub>	m	3.57	3.47	3.38	3.34	3.45	3.58	3.61
	OCH <sub>3</sub>	s	3.39	3.28	3.24	3.11	3.29	3.35	3.37
1,2-dimethoxyethane	CH <sub>3</sub>	s	3.40	3.28	3.24	3.12	3.28	3.35	3.37
	CH <sub>2</sub>	s	3.55	3.46	3.43	3.33	3.45	3.52	3.60
dimethylacetamide	CH <sub>3</sub> CO	s	2.09	1.97	1.96	1.60	1.97	2.07	2.08
	NCH <sub>3</sub>	s	3.02	3.00	2.94	2.57	2.96	3.31	3.06
	NCH <sub>3</sub>	s	2.94	2.83	2.78	2.05	2.83	2.92	2.90
dimethylformamide	CH	s	8.02	7.96	7.95	7.63	7.92	7.97	7.92
	CH <sub>3</sub>	s	2.96	2.94	2.89	2.36	2.89	2.99	3.01
	CH <sub>3</sub>	s	2.88	2.78	2.73	1.86	2.77	2.86	2.85
dimethyl sulfoxide	CH <sub>3</sub>	s	2.62	2.52	2.54	1.68	2.50	2.65	2.71
dioxane	CH <sub>2</sub>	s	3.71	3.59	3.57	3.35	3.60	3.66	3.75
ethanol	CH <sub>3</sub>	t, 7	1.25	1.12	1.06	0.96	1.12	1.19	1.17
	CH <sub>2</sub>	q, 7 <sup>d</sup>	3.72	3.57	3.44	3.34	3.54	3.60	3.65
	OH	s <sup>c,d</sup>	1.32	3.39	4.63		2.47		
ethyl acetate	CH <sub>3</sub> CO	s	2.05	1.97	1.99	1.65	1.97	2.01	2.07
	CH <sub>2</sub> CH <sub>3</sub>	q, 7	4.12	4.05	4.03	3.89	4.06	4.09	4.14
	CH <sub>2</sub> CH <sub>3</sub>	t, 7	1.26	1.20	1.17	0.92	1.20	1.24	1.24
ethyl methyl ketone	CH <sub>3</sub> CO	s	2.14	2.07	2.07	1.58	2.06	2.12	2.19
	CH <sub>2</sub> CH <sub>3</sub>	q, 7	2.46	2.45	2.43	1.81	2.43	2.50	3.18
	CH <sub>2</sub> CH <sub>3</sub>	t, 7	1.06	0.96	0.91	0.85	0.96	1.01	1.26
ethylene glycol	CH	s <sup>e</sup>	3.76	3.28	3.34	3.41	3.51	3.59	3.65
"grease" <sup>f</sup>	CH <sub>3</sub>	m	0.86	0.87		0.92	0.86	0.88	
	CH <sub>2</sub>	br s	1.26	1.29		1.36	1.27	1.29	
<i>n</i> -hexane	CH <sub>3</sub>	t	0.88	0.88	0.86	0.89	0.89	0.90	
	CH <sub>2</sub>	m	1.26	1.28	1.25	1.24	1.28	1.29	
HMPA <sup>g</sup>	CH <sub>3</sub>	d, 9.5	2.65	2.59	2.53	2.40	2.57	2.64	2.61
methanol	CH <sub>3</sub>	s <sup>h</sup>	3.49	3.31	3.16	3.07	3.28	3.34	3.34
	OH	s <sup>c,h</sup>	1.09	3.12	4.01		2.16		
nitromethane	CH <sub>3</sub>	s	4.33	4.43	4.42	2.94	4.31	4.34	4.40
<i>n</i> -pentane	CH <sub>3</sub>	t, 7	0.88	0.88	0.86	0.87	0.89	0.90	
	CH <sub>2</sub>	m	1.27	1.27	1.27	1.23	1.29	1.29	
2-propanol	CH <sub>3</sub>	d, 6	1.22	1.10	1.04	0.95	1.09	1.50	1.17
	CH	sep, 6	4.04	3.90	3.78	3.67	3.87	3.92	4.02
pyridine	CH(2)	m	8.62	8.58	8.58	8.53	8.57	8.53	8.52
	CH(3)	m	7.29	7.35	7.39	6.66	7.33	7.44	7.45
	CH(4)	m	7.68	7.76	7.79	6.98	7.73	7.85	7.87
silicone grease <sup>i</sup>	CH <sub>3</sub>	s	0.07	0.13		0.29	0.08	0.10	
tetrahydrofuran	CH <sub>2</sub>	m	1.85	1.79	1.76	1.40	1.80	1.87	1.88
	CH <sub>2</sub> O	m	3.76	3.63	3.60	3.57	3.64	3.71	3.74
toluene	CH <sub>3</sub>	s	2.36	2.32	2.30	2.11	2.33	2.32	
	CH( <i>o/p</i> )	m	7.17	7.1–7.2	7.18	7.02	7.1–7.3	7.16	
	CH( <i>m</i> )	m	7.25	7.1–7.2	7.25	7.13	7.1–7.3	7.16	
triethylamine	CH <sub>3</sub>	t, 7	1.03	0.96	0.93	0.96	0.96	1.05	0.99
	CH <sub>2</sub>	q, 7	2.53	2.45	2.43	2.40	2.45	2.58	2.57

<sup>a</sup> In these solvents the intermolecular rate of exchange is slow enough that a peak due to HDO is usually also observed; it appears at 2.81 and 3.30 ppm in acetone and DMSO, respectively. In the former solvent, it is often seen as a 1:1:1 triplet, with <sup>2</sup>J<sub>H,D</sub> = 1 Hz. <sup>b</sup> 2,6-Dimethyl-4-*tert*-butylphenol. <sup>c</sup> The signals from exchangeable protons were not always identified. <sup>d</sup> In some cases (see note *a*), the coupling interaction between the CH<sub>2</sub> and the OH protons may be observed (*J* = 5 Hz). <sup>e</sup> In CD<sub>3</sub>CN, the OH proton was seen as a multiplet at δ 2.69, and extra coupling was also apparent on the methylene peak. <sup>f</sup> Long-chain, linear aliphatic hydrocarbons. Their solubility in DMSO was too low to give visible peaks. <sup>g</sup> Hexamethylphosphoramide. <sup>h</sup> In some cases (see notes *a*, *d*), the coupling interaction between the CH<sub>3</sub> and the OH protons may be observed (*J* = 5.5 Hz). <sup>i</sup> Poly(dimethylsiloxane). Its solubility in DMSO was too low to give visible peaks.

show their degree of variability. Occasionally, in order to distinguish between peaks whose assignment was

ambiguous, a further 1–2 μL of a specific substrate were added and the spectra run again.

Table 2.  $^{13}\text{C}$  NMR Data<sup>a</sup>

		$\text{CDCl}_3$	$(\text{CD}_3)_2\text{CO}$	$(\text{CD}_3)_2\text{SO}$	$\text{C}_6\text{D}_6$	$\text{CD}_3\text{CN}$	$\text{CD}_3\text{OD}$	$\text{D}_2\text{O}$
solvent signals		$77.16 \pm 0.06$	$29.84 \pm 0.01$ $206.26 \pm 0.13$	$39.52 \pm 0.06$	$128.06 \pm 0.02$	$1.32 \pm 0.02$ $118.26 \pm 0.02$	$49.00 \pm 0.01$	
acetic acid	CO	175.99	172.31	171.93	175.82	173.21	175.11	177.21
	CH <sub>3</sub>	20.81	20.51	20.95	20.37	20.73	20.56	21.03
acetone	CO	207.07	205.87	206.31	204.43	207.43	209.67	215.94
	CH <sub>3</sub>	30.92	30.60	30.56	30.14	30.91	30.67	30.89
acetonitrile	CN	116.43	117.60	117.91	116.02	118.26	118.06	119.68
	CH <sub>3</sub>	1.89	1.12	1.03	0.20	1.79	0.85	1.47
benzene	CH	128.37	129.15	128.30	128.62	129.32	129.34	
<i>tert</i> -butyl alcohol	C	69.15	68.13	66.88	68.19	68.74	69.40	70.36
	CH <sub>3</sub>	31.25	30.72	30.38	30.47	30.68	30.91	30.29
<i>tert</i> -butyl methyl ether	OCH <sub>3</sub>	49.45	49.35	48.70	49.19	49.52	49.66	49.37
	C	72.87	72.81	72.04	72.40	73.17	74.32	75.62
	CCH <sub>3</sub>	26.99	27.24	26.79	27.09	27.28	27.22	26.60
BHT	C(1)	151.55	152.51	151.47	152.05	152.42	152.85	
	C(2)	135.87	138.19	139.12	136.08	138.13	139.09	
	CH(3)	125.55	129.05	127.97	128.52	129.61	129.49	
	C(4)	128.27	126.03	124.85	125.83	126.38	126.11	
	CH <sub>3</sub> Ar	21.20	21.31	20.97	21.40	21.23	21.38	
	CH <sub>3</sub> C	30.33	31.61	31.25	31.34	31.50	31.15	
	C	34.25	35.00	34.33	34.35	35.05	35.36	
chloroform	CH	77.36	79.19	79.16	77.79	79.17	79.44	
cyclohexane	CH <sub>2</sub>	26.94	27.51	26.33	27.23	27.63	27.96	
1,2-dichloroethane	CH <sub>2</sub>	43.50	45.25	45.02	43.59	45.54	45.11	
dichloromethane	CH <sub>2</sub>	53.52	54.95	54.84	53.46	55.32	54.78	
diethyl ether	CH <sub>3</sub>	15.20	15.78	15.12	15.46	15.63	15.46	14.77
	CH <sub>2</sub>	65.91	66.12	62.05	65.94	66.32	66.88	66.42
diglyme	CH <sub>3</sub>	59.01	58.77	57.98	58.66	58.90	59.06	58.67
	CH <sub>2</sub>	70.51	71.03	69.54	70.87	70.99	71.33	70.05
	CH <sub>2</sub>	71.90	72.63	71.25	72.35	72.63	72.92	71.63
1,2-dimethoxyethane	CH <sub>3</sub>	59.08	58.45	58.01	58.68	58.89	59.06	58.67
	CH <sub>2</sub>	71.84	72.47	71.07	72.21	72.47	72.72	71.49
dimethylacetamide	CH <sub>3</sub>	21.53	21.51	21.29	21.16	21.76	21.32	21.09
	CO	171.07	170.61	169.54	169.95	171.31	173.32	174.57
	NCH <sub>3</sub>	35.28	34.89	37.38	34.67	35.17	35.50	35.03
	NCH <sub>3</sub>	38.13	37.92	34.42	37.03	38.26	38.43	38.76
dimethylformamide	CH	162.62	162.79	162.29	162.13	163.31	164.73	165.53
	CH <sub>3</sub>	36.50	36.15	35.73	35.25	36.57	36.89	37.54
	CH <sub>3</sub>	31.45	31.03	30.73	30.72	31.32	31.61	32.03
dimethyl sulfoxide	CH <sub>3</sub>	40.76	41.23	40.45	40.03	41.31	40.45	39.39
dioxane	CH <sub>2</sub>	67.14	67.60	66.36	67.16	67.72	68.11	67.19
ethanol	CH <sub>3</sub>	18.41	18.89	18.51	18.72	18.80	18.40	17.47
	CH <sub>2</sub>	58.28	57.72	56.07	57.86	57.96	58.26	58.05
ethyl acetate	CH <sub>3</sub> CO	21.04	20.83	20.68	20.56	21.16	20.88	21.15
	CO	171.36	170.96	170.31	170.44	171.68	172.89	175.26
	CH <sub>2</sub>	60.49	60.56	59.74	60.21	60.98	61.50	62.32
	CH <sub>3</sub>	14.19	14.50	14.40	14.19	14.54	14.49	13.92
ethyl methyl ketone	CH <sub>3</sub> CO	29.49	29.30	29.26	28.56	29.60	29.39	29.49
	CO	209.56	208.30	208.72	206.55	209.88	212.16	218.43
	CH <sub>2</sub> CH <sub>3</sub>	36.89	36.75	35.83	36.36	37.09	37.34	37.27
	CH <sub>2</sub> CH <sub>3</sub>	7.86	8.03	7.61	7.91	8.14	8.09	7.87
ethylene glycol	CH <sub>2</sub>	63.79	64.26	62.76	64.34	64.22	64.30	63.17
"grease"	CH <sub>2</sub>	29.76	30.73	29.20	30.21	30.86	31.29	
<i>n</i> -hexane	CH <sub>3</sub>	14.14	14.34	13.88	14.32	14.43	14.45	
	CH <sub>2</sub> (2)	22.70	23.28	22.05	23.04	23.40	23.68	
	CH <sub>2</sub> (3)	31.64	32.30	30.95	31.96	32.36	32.73	
HMPA <sup>b</sup>	CH <sub>3</sub>	36.87	37.04	36.42	36.88	37.10	37.00	36.46
methanol	CH <sub>3</sub>	50.41	49.77	48.59	49.97	49.90	49.86	49.50 <sup>c</sup>
nitromethane	CH <sub>3</sub>	62.50	63.21	63.28	61.16	63.66	63.08	63.22
<i>n</i> -pentane	CH <sub>3</sub>	14.08	14.29	13.28	14.25	14.37	14.39	
	CH <sub>2</sub> (2)	22.38	22.98	21.70	22.72	23.08	23.38	
	CH <sub>2</sub> (3)	34.16	34.83	33.48	34.45	34.89	35.30	
2-propanol	CH <sub>3</sub>	25.14	25.67	25.43	25.18	25.55	25.27	24.38
	CH	64.50	63.85	64.92	64.23	64.30	64.71	64.88
pyridine	CH(2)	149.90	150.67	149.58	150.27	150.76	150.07	149.18
	CH(3)	123.75	124.57	123.84	123.58	127.76	125.53	125.12
	CH(4)	135.96	136.56	136.05	135.28	136.89	138.35	138.27
silicone grease	CH <sub>3</sub>	1.04	1.40		1.38		2.10	
tetrahydrofuran	CH <sub>2</sub>	25.62	26.15	25.14	25.72	26.27	26.48	25.67
	CH <sub>2</sub> O	67.97	68.07	67.03	67.80	68.33	68.83	68.68
toluene	CH <sub>3</sub>	21.46	21.46	20.99	21.10	21.50	21.50	
	C( <i>i</i> )	137.89	138.48	137.35	137.91	138.90	138.85	
	CH( <i>o</i> )	129.07	129.76	128.88	129.33	129.94	129.91	
	CH( <i>m</i> )	128.26	129.03	128.18	128.56	129.23	129.20	
	CH( <i>p</i> )	125.33	126.12	125.29	125.68	126.28	126.29	
triethylamine	CH <sub>3</sub>	11.61	12.49	11.74	12.35	12.38	11.09	9.07
	CH <sub>2</sub>	46.25	47.07	45.74	46.77	47.10	46.96	47.19

<sup>a</sup> See footnotes for Table 1. <sup>b</sup>  $^2J_{\text{PC}} = 3$  Hz. <sup>c</sup> Reference material; see text.

For D<sub>2</sub>O solutions there is no accepted reference for carbon chemical shifts. We suggest the addition of a drop of methanol, and the position of its signal to be defined as 49.50 ppm; on this basis, the entries in Table 2 were recorded. The chemical shifts thus obtained are, on the whole, very similar to those for the other solvents. Alternatively, we suggest the use of dioxane when the methanol peak is expected to fall in a crowded area of the spectrum. We also report the chemical shifts of sodium formate (171.67 ppm), sodium acetate (182.02 and 23.97 ppm), sodium carbonate (168.88 ppm), sodium bicarbonate (161.08 ppm), and sodium 3-(trimethylsilyl)propanesulfonate [54.90, 19.66, 15.56 (methylenes 1, 2, and 3, respectively), and -2.04 ppm (methyls)], in D<sub>2</sub>O.

**Temperature Dependence of HDO Chemical Shifts.** We recorded the <sup>1</sup>H spectrum of a sample of D<sub>2</sub>O, containing a crystal of sodium 3-(trimethylsilyl)propanesulfonate as reference, as a function of temperature. The

data are shown in Figure 1. The solid line connecting the experimental points corresponds to the equation

$$\delta = 5.060 - 0.0122T + (2.11 \times 10^{-5})T^2 \quad (1)$$

which reproduces the measured values to better than 1 ppb. For the 0 - 50°C range, the simpler

$$\delta = 5.051 - 0.0111T \quad (2)$$

gives values correct to 10 ppb. For both equations, *T* is the temperature in °C.

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# NMR Chemical Shifts of Trace Impurities: Common Laboratory Solvents, Organics, and Gases in Deuterated Solvents Relevant to the Organometallic Chemist

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Tables of <sup>1</sup>H and <sup>13</sup>C NMR chemical shifts have been compiled for common organic compounds often used as reagents or found as products or contaminants in deuterated organic solvents. Building upon the work of Gottlieb, Kotlyar, and Nudelman in the *Journal of Organic Chemistry*, signals for common impurities are now reported in additional NMR solvents (tetrahydrofuran-*d*<sub>8</sub>, toluene-*d*<sub>8</sub>, dichloromethane-*d*<sub>2</sub>, chlorobenzene-*d*<sub>5</sub>, and 2,2,2-trifluoroethanol-*d*<sub>3</sub>) which are frequently used in organometallic laboratories. Chemical shifts for other organics which are often used as reagents or internal standards or are found as products in organometallic chemistry are also reported for all the listed solvents.

Hanging above the desk of most every chemist whose work relies heavily on using NMR spectroscopy<sup>1</sup> is *NMR Chemical Shifts of Common Laboratory Solvents as Trace Impurities* by Gottlieb, Kotlyar, and Nudelman.<sup>2</sup> By compiling the chemical shifts of a large number of contaminants commonly encountered in synthetic chemistry, the publication has become an essential reference, allowing for easy identification of known impurities in a variety of deuterated organic solvents. However, despite the utility of Gottlieb et al.'s work,<sup>3</sup> the chemical shifts of impurities in a number of NMR solvents often used by organometallic chemists were not included. Tetrahydrofuran-*d*<sub>8</sub> (THF-*d*<sub>8</sub>), toluene-*d*<sub>8</sub>, dichloromethane-*d*<sub>2</sub> (CD<sub>2</sub>Cl<sub>2</sub>), chlorobenzene-*d*<sub>5</sub> (C<sub>6</sub>D<sub>5</sub>Cl), and 2,2,2-trifluoroethanol-*d*<sub>3</sub> (TFE-*d*<sub>3</sub>) are commonplace in laboratories practicing inorganic syntheses. Therefore, we have expanded the spectral data compilation with the inclusion of chemical shifts of common impurities recorded in the deuterated solvents heavily employed in our organometallic laboratories. The chemical shifts of various gases (hydrogen, methane, ethane, propane,

ethylene, propylene, and carbon dioxide) often encountered as reagents or products in organometallic reactions, along with organic compounds relevant to organometallic chemists (allyl acetate, benzaldehyde, carbon disulfide, carbon tetrachloride, 18-crown-6, cyclohexanone, diallyl carbonate, dimethyl carbonate, dimethyl malonate, furan, Apiezon H grease, hexamethylbenzene, hexamethyldisiloxane, imidazole, pyrrole, and pyrrolidine), have also been added to this expanded list.

## Experimental Section

All deuterated solvents were obtained commercially through Cambridge Isotope Laboratories, Inc. NMR spectra were recorded at 298 K using 300, 500, or 600 MHz spectrometers (<sup>13</sup>C{<sup>1</sup>H} NMR frequencies of 75.5, 126, or 151 MHz, respectively). Adopting the previously reported strategy,<sup>2</sup> standard solutions of mixtures of specific impurities were used to reduce the number of necessary individual NMR experiments. The combinations of organic compounds were chosen in a way in which intermolecular interactions and resonance convolution would be minimized. Unless otherwise stated, the standard solutions were prepared with qualitatively equal molar amounts of the following compounds: (solution 1) acetone, dimethylformamide, ethanol, toluene; (solution 2) benzene, dimethyl sulfide, ethyl acetate, methanol; (solution 3) acetic acid, chloroform, diethyl ether, 2-propanol, tetrahydrofuran; (solution 4) acetonitrile, dichloromethane, 1,4-dioxane, *n*-hexane, hexamethylphosphoramide (HMPA); (solution 5) 1,2-dichloroethane, *n*-pentane, pyridine, hexamethylbenzene; (solution 6) *tert*-butyl alcohol, 2,6-di-*tert*-butyl-4-methylphenol (BHT), cyclohexane,

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(1) For general information on <sup>1</sup>H and <sup>13</sup>C{<sup>1</sup>H} NMR spectroscopy, see: Balci, M. *Basic <sup>1</sup>H- and <sup>13</sup>C-NMR Spectroscopy*; Elsevier: Amsterdam, 2005.

(2) Gottlieb, H. E.; Kotlyar, V.; Nudelman, A. *J. Org. Chem.* **1997**, *62*, 7512.

(3) According to ACS Publications as of December 2009 (<http://pubs.acs.org/>), Gottlieb et al.'s publication<sup>2</sup> is the most downloaded *Journal of Organic Chemistry* article over the preceding 12 months.

Table 1. <sup>1</sup>H NMR Data<sup>a</sup>

	proton	mult	THF- <i>d</i> <sub>6</sub>	CD <sub>2</sub> Cl <sub>2</sub>	CDCl <sub>3</sub>	toluene- <i>d</i> <sub>8</sub>	C <sub>6</sub> D <sub>6</sub>	C <sub>6</sub> D <sub>5</sub> Cl	(CD <sub>3</sub> ) <sub>2</sub> CO	(CD <sub>3</sub> ) <sub>2</sub> SO	CD <sub>3</sub> CN	TFE- <i>d</i> <sub>3</sub>	CD <sub>3</sub> OD	D <sub>2</sub> O
solvent residual signals			1.72	5.32	7.26	2.08	7.16	6.96	2.05	2.50	1.94	5.02	3.31	4.79
			3.58			6.97		6.99				3.88		
						7.01		7.14						
						7.09								
water	OH	s	2.46	1.52	1.56	0.43	0.40	1.03	2.84 <sup>b</sup>	3.33 <sup>b</sup>	2.13	3.66	4.87	
acetic acid	CH <sub>3</sub>	s	1.89	2.06	2.10	1.57	1.52	1.76	1.96	1.91	1.96	2.06	1.99	2.08
acetone	CH <sub>3</sub>	s	2.05	2.12	2.17	1.57	1.55	1.77	2.09	2.09	2.08	2.19	2.15	2.22
acetonitrile	CH <sub>3</sub>	s	1.95	1.97	2.10	0.69	0.58	1.21	2.05	2.07	1.96	1.95	2.03	2.06
benzene	CH	s	7.31	7.35	7.36	7.12	7.15	7.20	7.36	7.37	7.37	7.36	7.33	7.33
<i>tert</i> -butyl alcohol	CH <sub>3</sub>	s	1.15	1.24	1.28	1.03	1.05	1.12	1.18	1.11	1.16	1.28	1.40	1.24
	OH	s <sup>c</sup>	3.16			0.58	0.63	1.30			4.19	2.18	2.20	
chloroform	CH	s	7.89	7.32	7.26	6.10	6.15	6.74	8.02	8.32	7.58	7.33	7.90	
18-crown-6	CH <sub>2</sub>	s	3.57	3.59	3.67	3.36	3.39	3.41	3.59	3.51	3.51	3.64	3.64	3.80
cyclohexane	CH <sub>2</sub>	s	1.44	1.44	1.43	1.40	1.40	1.37	1.43	1.40	1.44	1.47	1.45	
1,2-dichloroethane	CH <sub>2</sub>	s	3.77	3.76	3.73	2.91	2.90	3.26	3.87	3.90	3.81	3.71	3.78	
dichloromethane	CH <sub>2</sub>	s	5.51	5.33	5.30	4.32	4.27	4.77	5.63	5.76	5.44	5.24	5.49	
diethyl ether	CH <sub>3</sub>	t, 7	1.12	1.15	1.21	1.10	1.11	1.10	1.11	1.09	1.12	1.20	1.18	1.17
	CH <sub>2</sub>	q, 7	3.38	3.43	3.48	3.25	3.26	3.31	3.41	3.38	3.42	3.58	3.49	3.56
diglyme	CH <sub>2</sub>	m	3.43	3.57	3.65	3.43	3.46	3.49	3.56	3.51	3.53	3.67	3.61	3.67
	CH <sub>2</sub>	m	3.53	3.50	3.57	3.31	3.34	3.37	3.47	3.38	3.45	3.62	3.58	3.61
	OCH <sub>3</sub>	s	3.28	3.33	3.39	3.12	3.11	3.16	3.28	3.24	3.29	3.41	3.35	3.37
dimethylformamide	CH	s	7.91	7.96	8.02	7.57	7.63	7.73	7.96	7.95	7.92	7.86	7.97	7.92
	CH <sub>3</sub>	s	2.88	2.91	2.96	2.37	2.36	2.51	2.94	2.89	2.89	2.98	2.99	3.01
	CH <sub>3</sub>	s	2.76	2.82	2.88	1.96	1.86	2.30	2.78	2.73	2.77	2.88	2.86	2.85
1,4-dioxane	CH <sub>2</sub>	s	3.56	3.65	3.71	3.33	3.35	3.45	3.59	3.57	3.60	3.76	3.66	3.75
DME	CH <sub>3</sub>	s	3.28	3.34	3.40	3.12	3.12	3.17	3.28	3.24	3.28	3.40	3.35	3.37
	CH <sub>2</sub>	s	3.43	3.49	3.55	3.31	3.33	3.37	3.46	3.43	3.45	3.61	3.52	3.60
ethane	CH <sub>3</sub>	s	0.85	0.85	0.87	0.81	0.80	0.79	0.83	0.82	0.85	0.85	0.85	0.82
ethanol	CH <sub>3</sub>	t, 7	1.10	1.19	1.25	0.97	0.96	1.06	1.12	1.06	1.12	1.22	1.19	1.17
	CH <sub>2</sub>	q, 7 <sup>d</sup>	3.51	3.66	3.72	3.36	3.34	3.51	3.57	3.44	3.54	3.71	3.60	3.65
	OH	s <sup>c,d</sup>	3.30	1.33	1.32	0.83	0.50	1.39	3.39	4.63	2.47			
ethyl acetate	CH <sub>3</sub> CO	s	1.94	2.00	2.05	1.69	1.65	1.78	1.97	1.99	1.97	2.03	2.01	2.07
	CH <sub>2</sub> CH <sub>3</sub>	q, 7	4.04	4.08	4.12	3.87	3.89	3.96	4.05	4.03	4.06	4.14	4.09	4.14
	CH <sub>2</sub> CH <sub>3</sub>	t, 7	1.19	1.23	1.26	0.94	0.92	1.04	1.20	1.17	1.20	1.26	1.24	1.24
ethylene	CH <sub>2</sub>	s	5.36	5.40	5.40	5.25	5.25	5.29	5.38	5.41	5.41	5.40	5.39	5.44
ethylene glycol	CH <sub>2</sub>	s <sup>e</sup>	3.48	3.66	3.76	3.36	3.41	3.58	3.28	3.34	3.51	3.72	3.59	3.65
H grease <sup>f</sup>	CH <sub>3</sub>	m	0.85–0.91	0.84–0.90	0.84–0.87	0.89–0.96	0.90–0.98	0.86–0.92	0.90	0.82–0.88		0.88–0.94	0.86–0.93	
	CH <sub>2</sub>	br s	1.29	1.27	1.25	1.33	1.32	1.30	1.29	1.24		1.33	1.29	
hexamethylbenzene	CH <sub>3</sub>	s	2.18	2.20	2.24	2.10	2.13	2.10	2.17	2.14	2.19	2.24	2.19	
<i>n</i> -hexane	CH <sub>3</sub>	t, 7	0.89	0.89	0.88	0.88	0.89	0.85	0.88	0.86	0.89	0.91	0.90	
	CH <sub>2</sub>	m	1.29	1.27	1.26	1.22	1.24	1.19	1.28	1.25	1.28	1.31	1.29	
HMDSO	CH <sub>3</sub>	s	0.07	0.07	0.07	0.10	0.12	0.10	0.07	0.06	0.07	0.08	0.07	0.28
HMPA	CH <sub>3</sub>	d, 9.5	2.58	2.60	2.65	2.42	2.40	2.47	2.59	2.53	2.57	2.63	2.64	2.61
hydrogen	H <sub>2</sub>	s	4.55	4.59	4.62	4.50	4.47	4.49	4.54	4.61	4.57	4.53	4.56	4.56
imidazole	CH(2)	s	7.48	7.63	7.67	7.30	7.33	7.53	7.62	7.63	7.57	7.61	7.67	7.78
	CH(4,5)	s	6.94	7.07	7.10	6.86	6.90	7.01	7.04	7.01	7.01	7.03	7.05	7.14
methane	CH <sub>4</sub>	s	0.19	0.21	0.22	0.17	0.16	0.15	0.17	0.20	0.20	0.18	0.20	0.18
methanol	CH <sub>3</sub>	s <sup>g</sup>	3.27	3.42	3.49	3.03	3.07	3.25	3.31	3.16	3.28	3.44	3.34	3.34
	OH	s <sup>c,g</sup>	3.02	1.09	1.09			1.30	3.12	4.01	2.16			
nitromethane	CH <sub>3</sub>	s	4.31	4.31	4.33	3.01	2.94	3.59	4.43	4.42	4.31	4.28	4.34	4.40
<i>n</i> -pentane	CH <sub>3</sub>	t, 7	0.89	0.89	0.88	0.87	0.87	0.84	0.88	0.86	0.89	0.90	0.90	
	CH <sub>2</sub>	m	1.31	1.30	1.27	1.25	1.23	1.23	1.27	1.27	1.29	1.33	1.29	
propane	CH <sub>3</sub>	t, 7.3	0.90	0.90	0.90	0.89	0.86	0.84	0.88	0.87	0.90	0.90	0.91	0.88
	CH <sub>2</sub>	sept, 7.3	1.33	1.32	1.32	1.32	1.26	1.26	1.31	1.29	1.33	1.33	1.34	1.30
2-propanol	CH <sub>3</sub>	d, 6	1.08	1.17	1.22	0.95	0.95	1.04	1.10	1.04	1.09	1.20	1.50	1.17
	CH	sept, 6	3.82	3.97	4.04	3.65	3.67	3.82	3.90	3.78	3.87	4.05	3.92	4.02
propylene	CH <sub>3</sub>	dt, 6.4, 1.5	1.69	1.71	1.73	1.55	1.55	1.58	1.68	1.68	1.70	1.70	1.70	1.70
	CH <sub>2</sub> (1)	dm, 10	4.89	4.93	4.94	4.92	4.95	4.91	4.90	4.94	4.93	4.93	4.91	4.95
	CH <sub>2</sub> (2)	dm, 17	4.99	5.03	5.03	4.98	5.01	4.98	5.00	5.03	5.04	5.03	5.01	5.06
pyridine	CH	m	5.79	5.84	5.83	5.70	5.72	5.72	5.81	5.80	5.85	5.87	5.82	5.90
	CH(2,6)	m	8.54	8.59	8.62	8.47	8.53	8.51	8.58	8.58	8.57	8.45	8.53	8.52
	CH(3,5)	m	7.25	7.28	7.29	6.67	6.66	6.90	7.35	7.39	7.33	7.40	7.44	7.45
	CH(4)	m	7.65	7.68	7.68	6.99	6.98	7.25	7.76	7.79	7.73	7.82	7.85	7.87
pyrrole	NH	br t	9.96	8.69	8.40	7.71	7.80	8.61	10.02	10.75	9.27			
	CH(2,5)	m	6.66	6.79	6.83	6.43	6.48	6.62	6.77	6.73	6.75	6.84	6.72	6.93
	CH(3,4)	m	6.02	6.19	6.26	6.27	6.37	6.27	6.07	6.01	6.10	6.24	6.08	6.26
pyrrolidine <sup>h</sup>	CH <sub>2</sub> (2,5)	m	2.75	2.82	2.87	2.54	2.54	2.64		2.67	2.75	3.11	2.80	3.07
	CH <sub>2</sub> (3,4)	m	1.59	1.67	1.68	1.36	1.33	1.43	1.55	1.61	1.93	1.72	1.87	
silicone grease	CH <sub>3</sub>	s	0.11	0.09	0.07	0.26	0.29	0.14	0.13	–0.06	0.08	0.16	0.10	
tetrahydrofuran	CH <sub>2</sub> (2,5)	m	3.62	3.69	3.76	3.54	3.57	3.59	3.63	3.60	3.64	3.78	3.71	3.74
	CH <sub>2</sub> (3,4)	m	1.79	1.82	1.85	1.43	1.40	1.55	1.79	1.76	1.80	1.91	1.87	1.88
toluene	CH <sub>3</sub>	s	2.31	2.34	2.36	2.11	2.11	2.16	2.32	2.30	2.33	2.33	2.32	
	CH(2,4,6)	m	7.10	7.15	7.17	6.96–7.01	7.02	7.01–7.08	7.10–7.20	7.18	7.10–7.30	7.10–7.30	7.16	
	CH(3,5)	m	7.19	7.24	7.25	7.09	7.13	7.10–7.17	7.10–7.20	7.25	7.10–7.30	7.10–7.30	7.16	
triethylamine	CH <sub>3</sub>	t, 7	0.97	0.99	1.03	0.95	0.96	0.93	0.96	0.93	0.96	1.31	1.05	0.99
	CH <sub>2</sub>	q, 7	2.46	2.48	2.53	2.39	2.40	2.39	2.45	2.43	2.45	3.12	2.58	2.57

<sup>a</sup> Except for the compounds in solutions 8–10, as well as the gas samples, hexamethylbenzene, and the corrected values mentioned in the Supporting Information, all data for the solvents CDCl<sub>3</sub>, C<sub>6</sub>D<sub>6</sub>, (CD<sub>3</sub>)<sub>2</sub>CO, (CD<sub>3</sub>)<sub>2</sub>SO, CD<sub>3</sub>CN, CD<sub>3</sub>OD, and D<sub>2</sub>O were previously reported in ref 2. <sup>b</sup> A signal for HDO is also observed in (CD<sub>3</sub>)<sub>2</sub>SO (3.30 ppm) and (CD<sub>3</sub>)<sub>2</sub>CO (2.81 ppm), often seen as a 1:1:1 triplet (<sup>2</sup>J<sub>H,D</sub> = 1 Hz). <sup>c</sup> Not all OH signals were observable. <sup>d</sup> In some solvents, the coupling interaction between the CH<sub>2</sub> and the OH protons may be observed (*J* = 5 Hz). <sup>e</sup> In CD<sub>3</sub>CN, the OH proton was seen as a multiplet at 2.69 ppm, as well as extra coupling to the CH<sub>3</sub> resonance. <sup>f</sup> Apiezon brand H grease. <sup>g</sup> In some solvents, a coupling interaction between the CH<sub>3</sub> and the OH protons may be observed (*J* = 5.5 Hz). <sup>h</sup> Pyrrolidine was observed to react with (CD<sub>3</sub>)<sub>2</sub>CO.

Table 2.  $^{13}\text{C}\{^1\text{H}\}$  NMR Data<sup>a</sup>

	carbon	THF- <i>d</i> <sub>6</sub>	CD <sub>2</sub> Cl <sub>2</sub>	CDCl <sub>3</sub>	toluene- <i>d</i> <sub>8</sub>	C <sub>6</sub> D <sub>6</sub>	C <sub>6</sub> D <sub>5</sub> Cl	(CD <sub>3</sub> ) <sub>2</sub> CO	(CD <sub>3</sub> ) <sub>2</sub> SO	CD <sub>3</sub> CN	TFE- <i>d</i> <sub>3</sub>	CD <sub>3</sub> OD	D <sub>2</sub> O
solvent signals		67.21	53.84	77.16	137.48	128.06	134.19	29.84	39.52	1.32	61.50	49.00	
		25.31			128.87		129.26	206.26		118.26	126.28		
					127.96		128.25						
					125.13		125.96						
acetic acid	CO	171.69	175.85	175.99	175.30	175.82	175.67	172.31	171.93	173.21	177.96	175.11	177.21
	CH <sub>3</sub>	20.13	20.91	20.81	20.27	20.37	20.40	20.51	20.95	20.73	20.91	20.56	21.03
acetone	CO	204.19	206.78	207.07	204.00	204.43	204.83	205.87	206.31	207.43	32.35	209.67	215.94
	CH <sub>3</sub>	30.17	31.00	30.92	30.03	30.14	30.12	30.60	30.56	30.91	214.98	30.67	30.89
acetonitrile	CN	116.79	116.92	116.43	115.76	116.02	115.93	117.60	117.91	118.26	118.95	118.06	119.68
	CH <sub>3</sub>	0.45	2.03	1.89	0.03	0.20	0.63	1.12	1.03	1.79	1.00	0.85	1.47
benzene	CH	128.84	128.68	128.37	128.57	128.62	128.38	129.15	128.30	129.32	129.84	129.34	
<i>tert</i> -butyl alcohol	(CH <sub>3</sub> ) <sub>3</sub> C	67.50	69.11	69.15	68.12	68.19	68.19	68.13	66.88	68.74	72.35	69.40	70.36
	(CH <sub>3</sub> ) <sub>2</sub> C	30.57	31.46	31.25	30.49	30.47	31.13	30.72	30.38	30.68	31.07	30.91	30.29
carbon dioxide	CO <sub>2</sub>	125.69	125.26	124.99	124.86	124.76	126.08	125.81	124.21	125.89	126.92	126.31	
carbon disulfide	CS <sub>2</sub>	193.37	192.95	192.83	192.71	192.69	192.49	193.58	192.63	193.60	196.26	193.82	197.25
carbon tetrachloride	CCl <sub>4</sub>	96.89	96.52	96.34	96.57	96.44	96.38	96.65	95.44	96.68	97.74	97.21	96.73
chloroform	CH	79.24	77.99	77.36	77.89	77.79	77.67	79.19	79.16	79.17	78.83	79.44	
18-crown-6	CH <sub>2</sub>	71.34	70.47	70.55	70.86	70.59	70.55	71.25	69.85	71.22	70.80	71.47	70.14
cyclohexane	CH <sub>2</sub>	27.58	27.38	26.94	27.31	27.23	26.99	27.51	26.33	27.63	28.34	27.96	
1,2-dichloroethane	CH <sub>2</sub>	44.64	44.35	43.50	43.40	43.59	43.60	45.25	45.02	45.54	45.28	45.11	
dichloromethane	CH <sub>2</sub>	54.67	54.24	53.52	53.47	53.46	53.54	54.95	54.84	55.32	54.46	54.78	
diethyl ether	CH <sub>3</sub>	15.49	15.44	15.20	15.47	15.46	15.35	15.78	15.12	15.63	15.33	15.46	14.77
	CH <sub>2</sub>	66.14	66.11	65.91	65.94	65.94	65.79	66.12	62.05	66.32	67.55	66.88	66.42
diglyme	CH <sub>3</sub>	58.72	58.95	59.01	58.62	58.66	58.42	58.77	59.98	58.90	59.40	59.06	58.67
	CH <sub>2</sub>	71.17	70.70	70.51	70.92	70.87	70.56	71.03	69.54	70.99	73.05	71.33	70.05
dimethylformamide	CH <sub>2</sub>	72.72	72.25	71.90	72.39	72.35	72.07	72.63	71.25	72.63	71.33	72.92	71.63
	CH	161.96	162.57	162.62	161.93	162.13	162.01	162.79	162.29	163.31	166.01	164.73	165.53
	CH <sub>3</sub>	35.65	36.56	36.50	35.22	35.25	35.45	36.15	35.73	36.57	37.76	36.89	37.54
	CH <sub>3</sub>	30.70	31.39	31.45	30.64	30.72	30.71	31.03	30.73	31.32	30.96	31.61	32.03
1,4-dioxane	CH <sub>2</sub>	67.65	67.47	67.14	67.17	67.16	66.95	67.60	66.36	67.72	68.52	68.11	67.19
DME	CH <sub>3</sub>	58.72	59.02	59.08	58.63	58.68	58.31	58.45	58.03	58.89	59.52	59.06	58.67
	CH <sub>2</sub>	72.58	72.24	71.84	72.25	72.21	71.81	72.47	71.17	72.47	72.87	72.72	71.49
ethane	CH <sub>3</sub>	6.79	6.91	6.89	6.94	6.96	6.91	6.88	6.61	6.99	7.01	6.98	
ethanol	CH <sub>3</sub>	18.90	18.69	18.41	18.78	18.72	18.55	18.89	18.51	18.80	18.11	18.40	17.47
	CH <sub>2</sub>	57.60	58.57	58.28	57.81	57.86	57.63	57.72	56.07	57.96	59.68	58.26	58.05
ethyl acetate	CH <sub>3</sub> CO	20.45	21.15	21.04	20.46	20.56	20.50	20.83	20.68	21.16	21.18	20.88	21.15
	CO	170.32	171.24	171.36	170.02	170.44	170.20	170.96	170.31	171.68	175.55	172.89	175.26
	CH <sub>2</sub>	60.30	60.63	60.49	60.08	60.21	60.06	60.56	59.74	60.98	62.70	61.50	62.32
ethylene glycol	CH <sub>2</sub>	123.09	123.20	123.13	122.92	122.96	122.95	123.47	123.52	123.69	124.08	123.46	
	CH <sub>2</sub>	64.35	64.08	63.79	64.29	64.34	64.03	64.26	62.76	64.22	64.87	64.30	63.17
H grease <sup>b</sup>	CH <sub>2</sub>	30.45	30.14	29.71	30.31	30.22	30.11						
hexamethylbenzene	C	131.88	132.09	132.21	131.72	131.79	131.54	132.22	131.10	132.61	134.04	132.53	
	CH <sub>3</sub>	16.71	16.93	16.98	16.84	16.95	16.68	16.86	16.60	16.94	17.04	16.90	
<i>n</i> -hexane	CH <sub>3</sub>	14.22	14.28	14.14	14.34	14.32	14.18	14.34	13.88	14.43	14.63	14.45	
	CH <sub>2</sub> (2,5)	23.33	23.07	22.70	23.12	23.04	22.86	23.28	22.05	23.40	24.06	23.68	
	CH <sub>2</sub> (3,4)	32.34	32.01	31.64	32.06	31.96	31.77	32.30	30.95	32.36	33.17	32.73	
HMDSO	CH <sub>3</sub>	1.83	1.96	1.97	1.99	2.05	1.92	2.01	1.96	2.07	2.09	1.99	2.31
HMPA <sup>c</sup>	CH <sub>3</sub>	36.89	36.99	36.87	36.80	36.88	36.64	37.04	36.42	37.10	37.21	37.00	36.46
imidazole	CH(2)	135.72	135.76	135.38	135.57	135.76	135.50	135.89	135.15	136.33	136.58	136.31	136.65
	CH(4,5)	122.20	122.16	122.00	122.13	122.16	121.96	122.31	121.55	122.78	122.93	122.60	122.43
methane	CH <sub>4</sub>	-4.90	-4.33	-4.63	-4.34	-4.29	-4.33	-5.33	-4.01	-4.61	-5.88	-4.90	
methanol	CH <sub>3</sub>	49.64	50.45	50.41	49.90	49.97	49.66	49.77	48.59	49.90	50.67	49.86	49.50 <sup>d</sup>
nitromethane	CH <sub>3</sub>	62.49	63.03	62.50	61.14	61.16	61.68	63.21	63.28	63.66	63.17	63.08	63.22
<i>n</i> -pentane	CH <sub>3</sub>	14.18	14.24	14.08	14.27	14.25	14.10	14.29	13.28	14.37	14.54	14.39	
	CH <sub>2</sub> (2,4)	23.00	22.77	22.38	22.79	22.72	22.54	22.98	21.70	23.08	23.75	23.38	
	CH <sub>2</sub> (3)	34.87	34.57	34.16	34.54	34.45	34.26	34.83	33.48	34.89	35.76	35.30	
propane	CH <sub>3</sub>	16.60	16.63	16.63	16.65	16.66	16.56	16.68	16.34	16.73	16.93	16.80	
	CH <sub>2</sub>	16.82	16.63	16.37	16.63	16.60	16.48	16.78	15.67	16.91	17.46	17.19	
2-propanol	CH <sub>3</sub>	25.70	25.43	25.14	25.24	25.18	25.14	25.67	25.43	25.55	25.21	25.27	24.38
	CH	66.14	64.67	64.50	64.12	64.23	64.18	63.85	64.92	64.30	66.69	64.71	64.88
propylene	CH <sub>3</sub>	19.27	19.47	19.50	19.32	19.38	19.32	19.42	19.20	19.48	19.63	19.50	
	CH <sub>2</sub>	115.74	115.70	115.74	115.89	115.92	115.86	116.03	116.07	116.12	116.38	116.04	
	CH	134.02	134.21	133.91	133.61	133.69	133.57	134.34	133.55	134.78	136.00	134.61	
pyridine	CH(2,6)	150.57	150.27	149.90	150.25	150.27	149.93	150.67	149.58	150.76	149.76	150.07	149.18
	CH(3,5)	124.08	124.06	123.75	123.46	123.58	123.49	124.57	123.84	127.76	126.27	125.53	125.12
	CH(4)	135.99	136.16	135.96	135.17	135.28	135.32	136.56	136.05	136.89	139.62	138.35	138.27
pyrrole	CH(2,5)	118.03	117.93	117.77	117.61	117.78	117.65	117.98	117.32	118.47	119.61	118.28	119.06
	CH(3,4)	107.74	108.02	107.98	108.15	108.21	108.03	108.04	107.07	108.31	108.85	108.11	107.83
pyrrolidine <sup>e</sup>	CH <sub>2</sub> (2,5)	45.82	47.02	46.93	47.12	46.86	46.75		46.51	47.57	47.43	47.23	46.83
	CH <sub>2</sub> (3,4)	26.17	25.83	25.56	25.75	25.65	25.59		25.26	26.34	25.73	26.29	25.86
silicone grease	CH <sub>3</sub>	1.20	1.22	1.19	1.37	1.38	1.09	1.40			2.87	2.10	
	CH <sub>2</sub> (2,5)	68.03	68.16	67.97	67.75	67.80	67.64	68.07	67.03	68.33	69.53	68.83	68.68
tetrahydrofuran	CH <sub>2</sub> (3,4)	26.19	25.98	25.62	25.79	25.72	25.68	26.15	25.14	26.27	26.69	26.48	25.67
	CH <sub>3</sub>	21.29	21.53	21.46	21.37	21.10	21.23	21.46	20.99	21.50	21.62	21.50	
toluene	C(1)	138.24	138.36	137.89	137.84	137.91	137.65	138.48	137.35	138.90	139.92	138.85	
	CH(2,6)	129.47	129.35	129.07	129.33	129.33	129.12	129.76	128.88	129.94	130.58	129.91	
	CH(3,5)	128.71	128.54	128.26	128.51	128.56	128.31	129.03	128.18	129.23	129.79		



1,2-dimethoxyethane (DME), nitromethane, poly(dimethylsiloxane) (silicone grease), triethylamine; (solution 7) diglyme, dimethylacetamide, ethylene glycol, ethyl methyl ketone; (solution 8) allyl acetate, 2,6-di-*tert*-butyl-4-methoxyphenol (BHA), long-chain, linear aliphatic hydrocarbons from pump oil;<sup>4</sup> (solution 9) benzaldehyde, carbon disulfide, carbon tetrachloride, cyclohexanone, dimethyl malonate, furan, Apiezon H grease (H grease); (solution 10) 18-crown-6, diallyl carbonate, dimethyl carbonate, hexamethyldisiloxane (HMDSO), imidazole, pyrrole, pyrrolidine.<sup>5</sup> In the case of TFE-*d*<sub>3</sub>, nitromethane was omitted from solution 6 and run separately, since the protons of nitromethane exchange with deuterium from TFE-*d*<sub>3</sub> in the presence of triethylamine. In the case of (CD<sub>3</sub>)<sub>2</sub>CO, pyrrolidine was omitted from solution 10, since the two compounds were observed to react with each other. The gases used in this study included hydrogen, methane, ethane, propane, ethylene, propylene, and carbon dioxide.

Before examining the various standard contaminant solutions by <sup>1</sup>H NMR spectroscopy, solvent residual signals<sup>6</sup> and chemical shifts for H<sub>2</sub>O<sup>7</sup> for each NMR solvent were referenced against tetramethylsilane (TMS, δ 0 ppm) and reported. Before collecting <sup>13</sup>C{<sup>1</sup>H} NMR spectral data, solvent signals<sup>6</sup> were recorded with reference to the signal of a TMS internal standard. For D<sub>2</sub>O, <sup>1</sup>H NMR spectra were referenced to the methyl signal (δ 0 ppm) of sodium 3-(trimethylsilyl)propane-sulfonate,<sup>8,9</sup> and <sup>13</sup>C{<sup>1</sup>H} NMR spectra were referenced to the signal for the methyl group of methanol (one drop, added as an internal standard), which was set to 49.50 ppm.<sup>2</sup>

In a typical experiment for collecting <sup>1</sup>H NMR spectral data, a 3 μL sample of a standard contaminant solution was added to an NMR tube containing approximately 0.4 mL of a deuterated solvent. For <sup>13</sup>C{<sup>1</sup>H} NMR spectral data collection, an approximately 50 μL sample of the standard contaminant solution was added. When there was any uncertainty in the assignment of a resonance, the solution was spiked with an additional 1–2 μL of the impurity in question to accurately identify its chemical shift. In cases where the chemical shifts of resonances were highly dependent on the concentration of the impurities present, ambiguous resonances were instead resolved via gradient-

(4) VWR brand vacuum pump oil #19.

(5) The components of solution 10 were stable together in dilute solution but unstable when neat mixtures were prepared. In general, it was observed that the nitrogen-containing compounds and possibly 18-crown-6 catalyzed the hydrolysis of the carbonates, reacted directly with them, or both. Therefore, for the purpose of storage, the solution was partitioned into two subsolutions: (solution 10A) 18-crown-6, imidazole, pyrrole, pyrrolidine; (solution 10B) diallyl carbonate, dimethyl carbonate, hexamethyldisiloxane. These subsolutions were stable for long periods as neat mixtures and were combined to form solution 10 by adding equal portions to an NMR tube containing the desired deuterated solvent.

(6) For <sup>1</sup>H NMR spectra, the solvent residual signals arise from the proton of isotopomers containing one less deuterium atom than the perdeuterated solvent: e.g., CDHCl<sub>2</sub> in CD<sub>2</sub>Cl<sub>2</sub>. For <sup>13</sup>C NMR spectra, the solvent signals arise from the <sup>13</sup>C atoms at natural abundance in the perdeuterated solvent.

(7) The chemical shift for H<sub>2</sub>O can vary depending on the temperature, [H<sub>2</sub>O], and the solutes present: e.g., a downfield shift may be observed in the presence of any hydrogen bond acceptors. For more information see page 75 of ref 1.

(8) Harris, R. K.; Becker, E. D.; Cabral de Menezes, S. M.; Granger, P.; Hoffman, R. E.; Zilm, K. W. *Pure Appl. Chem.* **2008**, *80*, 59.

(9) For information on the temperature dependence of HDO chemical shifts in D<sub>2</sub>O, see ref 2.

selected heteronuclear single-quantum coherence (gs-HSQC) and gradient-selected heteronuclear multiple-quantum coherence (gs-HMQC) NMR spectroscopies. For the experiments involving gases, a J. Young NMR tube containing approximately 0.4 mL of NMR solvent was first degassed with three freeze–pump–thaw cycles. Using a vacuum line equipped with a gas manifold, 1 atm of the desired gas was added to the tube. Each gas was run separately, degassing between each gas sample.

## Results and Discussion

Chemical shifts for each of the impurities are reported in the tables: <sup>1</sup>H and <sup>13</sup>C{<sup>1</sup>H} NMR spectral data of all substrates are presented in Tables 1 and 2, respectively. Notably, physically larger tables, containing all the data from Tables 1 and 2 as well as the chemical shifts of additional organic compounds, are provided in the Supporting Information. Unless noted otherwise, coupling constants (reported in Hz) and resonance multiplicities (abbreviated as follows: s = singlet, d = doublet, t = triplet, q = quartet, p = pentet, sept = septet, m = multiplet, br = broad) were observed to be solvent-independent.

It was noted that the amount of gas dissolved in solution gave <sup>1</sup>H NMR signal integrations that were qualitatively comparable to those for the solutions made with the 3 μL additions of the liquid or solid contaminants. However, typically in order to observe signals for the gas samples by <sup>13</sup>C{<sup>1</sup>H} NMR spectroscopy, additional time for data collection was required. The solubility of each gas in D<sub>2</sub>O was extremely limited, making <sup>13</sup>C detection impractical. Of all the gases, methane required the most number of transients in order to obtain an observable signal by <sup>13</sup>C{<sup>1</sup>H} NMR spectroscopy. In most cases, the <sup>13</sup>C chemical shift of methane was acquired through the use of gs-HMQC NMR spectroscopy to provide enhanced sensitivity. In order to reflect what would be observed in typical NMR-scale experiments, <sup>13</sup>C detection was not pursued with isotopically enriched gases. A number of misreported values were discovered in the years since the original publication<sup>10</sup> and in the preparation of this paper. These are detailed in the Supporting Information, and the values are now correctly listed in Tables 1 and 2.

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**Supporting Information Available:** Large-format tables of the all the NMR data. This material is available free of charge via the Internet at <http://pubs.acs.org>.

(10) The misreported value for acetonitrile in C<sub>6</sub>D<sub>6</sub> from the original paper<sup>2</sup> was also pointed out by Dr. Jongwook Choi, to whom we are grateful.