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 ¹H); 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 ¹H and ¹³C 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 ¹H and ¹³C, respectively). Unless otherwise indicated, all were run at room temperature (24 ± 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 D₂O 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 D_2O . 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, tertbutyl alcohol, diethyl ether, tetrahydrofuran. In D_2O and CD₃OD 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 μ L of TMS,¹ was first run on its own. From this spectrum we determined the chemical shifts of the solvent residual peak² and the water peak. It should be noted that the latter is quite temperature-

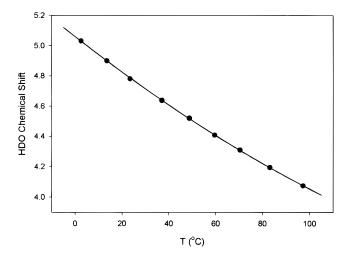


Figure 1. Chemical shift of *H*DO as a function of temperature.

dependent (*vide infra*). Also, any potential hydrogenbond 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 D₂O; the chemical shift of the residual HDO is very temperature-dependent (*vide infra*) but, maybe counterintuitively, remarkably solute (and pH) independent.

We then added 3 μ 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 D_2O as a solvent, the accepted reference peak (δ = 0) is the methyl signal of the sodium salt of 3-(trimethvlsilyl)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 D_2O , we used a different set of stock solutions, since many of the less polar substrates are not significantly watersoluble (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 μ L of the stock solution and 3 μ L of TMS¹ were added. The solvent chemical shifts³ were obtained from the spectra containing the solutes, and the ranges of chemical shifts

⁽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.

⁽²⁾ *Le.*, the signal of the proton for the isotopomer with one less deuterium than the perdeuterated material, *e.g.*, *CHC*l₃ in CDCl₃ or C_6D_5H in C_6D_6 . Except for CHCl₃, the splitting due to J_{HD} is typically observed (to a good approximation, it is 1/6.5 of the value of the corresponding J_{HH}). For CHD₂ 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 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).

Table 1. ¹H NMR Data

			Table 1.	¹ H NMR Da	ata				
	proton	mult	$CDCl_3$	(CD ₃) ₂ CO	$(CD_3)_2SO$	C_6D_6	CD ₃ CN	CD ₃ OD	D ₂ O
solvent residual peak			7.26	2.05	2.50	7.16	1.94	3.31	4.79
H ₂ O		S	1.56	2.84^{a}	3.33 ^a	0.40	2.13	4.87	
acetic acid	CH_3	S	2.10	1.96	1.91	1.55	1.96	1.99	2.08
acetone	CH_3	S	2.17	2.09	2.09	1.55	2.08	2.15	2.22
acetonitrile	CH_3	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 ₃	S	1.28	1.18	1.11	1.05	1.16	1.40	1.24
	OH ^c	S			4.19	1.55	2.18		1.04
<i>tert</i> -butyl methyl ether	CCH ₃	S	1.19	1.13	1.11	1.07	1.14	1.15	1.21
DUT	OCH ₃	S	3.22	3.13	3.08	3.04	3.13	3.20	3.22
BHT ^b	ArH OH ^c	S	6.98 5.01	6.96	6.87	7.05 4.79	6.97 5.20	6.92	
	ArCH ₃	S	5.01 2.27	2.22	6.65 2.18	4.79 2.24	5.20 2.22	2.21	
	ArCH ₃ ArC(CH ₃) ₃	S S	1.43	1.41	1.36	1.38	1.39	1.40	
chloroform	CH	s s	7.26	8.02	8.32	6.15	7.58	7.90	
cyclohexane	CH_2	S	1.43	1.43	1.40	1.40	1.44	1.45	
1,2-dichloroethane	CH ₂	s	3.73	3.87	3.90	2.90	3.81	3.78	
dichloromethane	CH_2	s	5.30	5.63	5.76	4.27	5.44	5.49	
diethyl ether	CH_2 CH_3	t, 7	1.21	1.11	1.09	1.11	1.12	1.18	1.17
diedily'i ether	CH_2	q, 7	3.48	3.41	3.38	3.26	3.42	3.49	3.56
diglyme	CH ₂	m	3.65	3.56	3.51	3.46	3.53	3.61	3.67
85	CH_2	m	3.57	3.47	3.38	3.34	3.45	3.58	3.61
	OCH_3	s	3.39	3.28	3.24	3.11	3.29	3.35	3.37
1,2-dimethoxyethane	CH ₃	s	3.40	3.28	3.24	3.12	3.28	3.35	3.37
Ũ	CH_2	s	3.55	3.46	3.43	3.33	3.45	3.52	3.60
dimethylacetamide	CH ₃ CO	S	2.09	1.97	1.96	1.60	1.97	2.07	2.08
	NCH ₃	s	3.02	3.00	2.94	2.57	2.96	3.31	3.06
	NCH_3	S	2.94	2.83	2.78	2.05	2.83	2.92	2.90
dimethylformamide	СН	S	8.02	7.96	7.95	7.63	7.92	7.97	7.92
	CH_3	S	2.96	2.94	2.89	2.36	2.89	2.99	3.01
	CH_3	S	2.88	2.78	2.73	1.86	2.77	2.86	2.85
dimethyl sulfoxide	CH ₃	S	2.62	2.52	2.54	1.68	2.50	2.65	2.71
dioxane	CH_2	s	3.71	3.59	3.57	3.35	3.60	3.66	3.75
ethanol	CH_3	t, 7	1.25	1.12	1.06	0.96	1.12	1.19	1.17
	CH ₂	q , 7 ^d	3.72	3.57	3.44	3.34	3.54	3.60	3.65
	OH	$\mathbf{s}^{c,d}$	1.32	3.39	4.63	1.05	2.47	0.01	0.07
ethyl acetate	CH ₃ CO	s	2.05 4.12	1.97 4.05	1.99	1.65 3.89	1.97	2.01 4.09	2.07 4.14
	CH_2CH_3	q, 7 t, 7	4.12	4.05	4.03 1.17	3.89 0.92	4.06 1.20	4.09	4.14
ethyl methyl ketone	CH ₂ C <i>H</i> ₃ CH ₃ CO		2.14	2.07	2.07	1.58	2.06	2.12	2.19
ethyl methyl ketone	CH_3CO CH_2CH_3	s q, 7	2.14	2.45	2.43	1.38	2.00	2.12	3.18
	CH_2CH_3 CH_2CH_3	ų, 7 t, 7	1.06	0.96	0.91	0.85	0.96	1.01	1.26
ethylene glycol	CH CH	s ^e	3.76	3.28	3.34	3.41	3.51	3.59	3.65
"grease" ^f	CH_3	m	0.86	0.87	0.01	0.92	0.86	0.88	0.00
Broube	CH ₂	br s	1.26	1.29		1.36	1.27	1.29	
<i>n</i> -hexane	CH ₃	t	0.88	0.88	0.86	0.89	0.89	0.90	
	CH_2	m	1.26	1.28	1.25	1.24	1.28	1.29	
HMPA ^g	$\tilde{CH_{3}}$	d, 9.5	2.65	2.59	2.53	2.40	2.57	2.64	2.61
methanol	CH ₃	s ^h	3.49	3.31	3.16	3.07	3.28	3.34	3.34
	OH	$\mathbf{s}^{c,h}$	1.09	3.12	4.01		2.16		
nitromethane	CH_3	s	4.33	4.43	4.42	2.94	4.31	4.34	4.40
<i>n</i> -pentane	CH_3	t, 7	0.88	0.88	0.86	0.87	0.89	0.90	
	CH_2	m	1.27	1.27	1.27	1.23	1.29	1.29	
2-propanol	CH_3	d, 6	1.22	1.10	1.04	0.95	1.09	1.50	1.17
	СН	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 ⁱ	CH ₃	S	0.07	0.13		0.29	0.08	0.10	
tetrahydrofuran	CH_2	m	1.85	1.79	1.76	1.40	1.80	1.87	1.88
	CH ₂ O	m	3.76	3.63	3.60	3.57	3.64	3.71	3.74
toluene	CH ₃	S	2.36	2.32	2.30	2.11	2.33	2.32	
	CH(o/p)	m	7.17	7.1-7.2	7.18	7.02	7.1-7.3	7.16	
4	CH(m)	m	7.25	7.1-7.2	7.25	7.13	7.1-7.3	7.16	0.00
triethylamine	CH ₃	t,7	1.03	0.96	0.93	0.96	0.96	1.05	0.99
	CH_2	q, 7	2.53	2.45	2.43	2.40	2.45	2.58	2.57

^{*a*} 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 ${}^{2}J_{H,D} = 1$ Hz. ^{*b*} 2,6-Dimethyl-4-*tert*-butylphenol. ^{*c*} The signals from exchangeable protons were not always identified. ^{*d*} In some cases (see note *a*), the coupling interaction between the CH₂ and the OH protons may be observed (J = 5 Hz). ^{*e*} In CD₃CN, the OH proton was seen as a multiplet at δ 2.69, and extra coupling was also apparent on the methylene peak. ^{*i*} Long-chain, linear aliphatic hydrocarbons. Their solubility in DMSO was too low to give visible peaks. ^{*g*} Hexamethylphosphoramide. ^{*h*} In some cases (see notes *a*, *d*), the coupling interaction between the CH₃ and the OH protons may be observed (J = 5.5 Hz). ^{*i*} 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 $1-2 \mu L$ of a specific substrate were added and the spectra run again.

			Table 2. ¹	³ C NMR Data ⁴	2			
		CDCl ₃	(CD ₃) ₂ CO	(CD ₃) ₂ SO	C ₆ D ₆	CD ₃ CN	CD ₃ OD	D_2O
solvent signals		$\textbf{77.16} \pm \textbf{0.06}$	$\begin{array}{c} 29.84 \pm 0.01 \\ 206.26 \pm 0.13 \end{array}$	39.52 ± 0.06	128.06 ± 0.02	$\begin{array}{c} 1.32 \pm 0.02 \\ 118.26 \pm 0.02 \end{array}$	49.00±0.01	
acetic acid	CO	175.99	172.31	171.93	175.82	173.21	175.11	177.21
acetone	CH_3 CO	20.81 207.07	20.51 205.87	20.95 206.31	20.37 204.43	20.73 207.43	20.56 209.67	21.03 215.94
acetone	CU CH ₃	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 ₃	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	70.90
<i>tert</i> -butyl alcohol	C CH3	69.15 31.25	68.13 30.72	66.88 30.38	68.19 30.47	68.74 30.68	69.40 30.91	70.36 30.29
<i>tert</i> -butyl methyl ether	OCH ₃	49.45	49.35	48.70	49.19	49.52	49.66	49.37
jj	C	72.87	72.81	72.04	72.40	73.17	74.32	75.62
	С <i>С</i> Н ₃	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) CH(3)	135.87 125.55	138.19 129.05	139.12 127.97	136.08 128.52	138.13 129.61	139.09 129.49	
	C(4)	128.27	126.03	124.85	125.83	126.38	126.11	
	CH ₃ Ar	21.20	21.31	20.97	21.40	21.23	21.38	
	CH ₃ C	30.33	31.61	31.25	31.34	31.50	31.15	
.1.1	C	34.25	35.00	34.33	34.35	35.05	35.36	
chloroform cyclohexane	CH CH_2	77.36 26.94	79.19 27.51	79.16 26.33	77.79 27.23	79.17 27.63	79.44 27.96	
1,2-dichloroethane	CH_2 CH_2	43.50	45.25	20.33 45.02	43.59	45.54	45.11	
dichloromethane	CH_2	53.52	54.95	54.84	53.46	55.32	54.78	
diethyl ether	CH ₃	15.20	15.78	15.12	15.46	15.63	15.46	14.77
	CH_2	65.91	66.12	62.05	65.94	66.32	66.88	66.42
diglyme	$CH_3 CH_2$	59.01 70.51	58.77 71.03	57.98 69.54	58.66 70.87	58.90 70.99	59.06 71.33	58.67 70.05
	CH_2 CH ₂	70.31	72.63	71.25	72.35	72.63	72.92	70.03
1,2-dimethoxyethane	CH ₃	59.08	58.45	58.01	58.68	58.89	59.06	58.67
.	CH_2	71.84	72.47	17.07	72.21	72.47	72.72	71.49
dimethylacetamide	CH ₃	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 ₃ NCH ₃	35.28 38.13	34.89 37.92	37.38 34.42	34.67 37.03	35.17 38.26	35.50 38.43	35.03 38.76
dimethylformamide	CH	162.62	162.79	162.29	162.13	163.31	164.73	165.53
J	CH_3	36.50	36.15	35.73	35.25	36.57	36.89	37.54
	CH_3	31.45	31.03	30.73	30.72	31.32	31.61	32.03
dimethyl sulfoxide	CH_3	40.76	41.23	40.45	40.03	41.31	40.45	39.39
dioxane ethanol	CH_2 CH_3	67.14 18.41	67.60 18.89	66.36 18.51	67.16 18.72	67.72 18.80	68.11 18.40	67.19 17.47
ethalioi	CH ₂	58.28	57.72	56.07	57.86	57.96	58.26	58.05
ethyl acetate	CH ₃ 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_2	60.49	60.56	59.74	60.21	60.98	61.50	62.32
ethyl methyl ketone	CH ₃ CH ₃ CO	14.19 29.49	14.50 29.30	14.40 29.26	14.19 28.56	14.54 29.60	14.49 29.39	13.92 29.49
etilyi metilyi ketone	CO	209.56	208.30	208.72	206.55	209.88	212.16	218.43
	CH_2CH_3	36.89	36.75	35.83	36.36	37.09	37.34	37.27
	CH_2CH_3	7.86	8.03	7.61	7.91	8.14	8.09	7.87
ethylene glycol	CH_2	63.79	64.26	62.76	64.34	64.22	64.30	63.17
"grease"	CH_2	29.76	30.73	29.20	30.21	30.86	31.29	
<i>n</i> -hexane	CH_3 $CH_2(2)$	14.14 22.70	14.34 23.28	13.88 22.05	14.32 23.04	14.43 23.40	14.45 23.68	
	$CH_2(2)$ $CH_2(3)$	31.64	32.30	30.95	31.96	32.36	32.73	
$HMPA^{b}$	CH ₃	36.87	37.04	36.42	36.88	37.10	37.00	36.46
methanol	CH_3	50.41	49.77	48.59	49.97	49.90	49.86	49.50 ^a
nitromethane	CH_3	62.50	63.21	63.28	61.16	63.66	63.08	63.22
<i>n</i> -pentane	CH ₃ CH ₂ (2)	14.08 22.38	14.29 22.98	13.28 21.70	14.25 22.72	14.37 23.08	14.39 23.38	
	$CH_2(2)$ $CH_2(3)$	34.16	34.83	33.48	34.45	23.08 34.89	35.30	
2-propanol	CH_3	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
silicone grease	CH(4) CH ₃	135.96 1.04	136.56 1.40	136.05	135.28 1.38	136.89	138.35 2.10	138.27
tetrahydrofuran	CH ₂	25.62	26.15	25.14	25.72	26.27	26.48	25.67
U U	CH_2O	67.97	68.07	67.03	67.80	68.33	68.83	68.68
toluene	CH ₃	21.46	21.46	20.99	21.10	21.50	21.50	
	C(i)	137.89	138.48	137.35	137.91	138.90	138.85	
	CH(o)	129.07	129.76	128.88	129.33	129.94	129.91	
	CH(<i>m</i>) CH(<i>p</i>)	128.26 125.33	129.03 126.12	128.18 125.29	128.56 125.68	129.23 126.28	129.20 126.29	
triethylamine	CH(p) CH_3	11.61	12.49	11.74	12.35	12.38	11.09	9.07
· · · · · · · · · · · · · · · · · · ·	CH ₂	46.25	47.07	45.74	46.77	47.10	46.96	47.19

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

Notes

For D_2O 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_2O .

Temperature Dependence of HDO Chemical Shifts. We recorded the ¹H spectrum of a sample of D_2O , 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

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

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

$$\delta = 5.051 - 0.0111T \tag{2}$$

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 ¹H and ¹³C 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_8 , toluene- d_8 , dichloromethane- d_2 , chlorobenzene- d_5 , and 2,2,2-trifluoroethanol- d_3) 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 spectroscopy¹ is NMR Chemical Shifts of Common Laboratory Solvents as Trace Impurities by Gottlieb, Kotlyar, and Nudelman.² 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,³ the chemical shifts of impurities in a number of NMR solvents often used by organometallic chemists were not included. Tetrahydrofuran- d_8 (THF- d_8), toluene- d_8 , dichloromethane- d_2 (CD₂Cl₂), chlorobenzene- d_5 (C_6D_5Cl) , and 2,2,2-trifluoroethanol- d_3 (TFE- d_3) 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,

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

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 $(^{13}C{^{1}H}$ NMR frequencies of 75.5, 126, or 151 MHz, respectively). Adopting the previously reported strategy,² 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 sulfoxide, 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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For general information on ¹H and ¹³C{¹H} NMR spectroscopy, see: Balcí, M. Basic ¹H- and ¹³C-NMR Spectroscopy; Elsevier: Amsterdam, 2005.

⁽³⁾ According to ACS Publications as of December 2009 (http://pubs. acs.org/), Gottlieb et al.'s publication² is the most downloaded *Journal* of Organic Chemistry article over the preceding 12 months.

Table 1. ¹H NMR Data^a

	proton	mult	THF-d ₈	CD ₂ Cl ₂	CDCl ₃	toluene-d ₈	C ₆ D ₆		(CD ₃) ₂ CO	(CD ₃) ₂ SO	CD ₃ CN	TFE-d ₃	CD ₃ OD	D ₂ O
solvent residual	proton	man	1.72	5.32	7.26	2.08	7.16	6.96	2.05	2.50	1.94	5.02	3.31	4.79
signals			3.58	5.52	1.20	6.97 7.01 7.09	7.10	6.99 7.14	2.00	2.50	1.91	3.88	5.51	1.75
water	OH	s	2.46	1.52	1.56	0.43	0.40	1.03	2.84^{b}	3.33 ^b	2.13	3.66	4.87	• • • •
acetic acid	CH ₃	s	1.89 2.05	2.06 2.12	2.10 2.17	1.57 1.57	1.52 1.55	1.76 1.77	1.96	1.91 2.09	1.96 2.08	2.06 2.19	1.99 2.15	2.08 2.22
acetone acetonitrile	CH_3 CH_3	s s	1.95	1.97	2.17	0.69	0.58	1.77	2.09 2.05	2.09	2.08	1.95	2.13	2.22
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	
tert -butyl alcohol	CH ₃	S of	1.15	1.24	1.28	1.03	1.05	1.12	1.18	1.11	1.16	1.28	1.40	1.24
chloroform	OH CH	s ^c s	3.16 7.89	7.32	7.26	0.58 6.10	0.63 6.15	1.30 6.74	8.02	4.19 8.32	2.18 7.58	2.20 7.33	7.90	
18-crown-6	CH ₂	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_2	8	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 dichloromethane	$CH_2 \\ CH_2$	s s	3.77 5.51	3.76 5.33	3.73 5.30	2.91 4.32	2.90 4.27	3.26 4.77	3.87 5.63	3.90 5.76	3.81 5.44	3.71 5.24	3.78 5.49	
diethyl ether	CH ₂ CH ₃	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_2	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_2	m	3.43 3.53	3.57	3.65 3.57	3.43 3.31	3.46 3.34	3.49 3.37	3.56	3.51 3.38	3.53 3.45	3.67 3.62	3.61 3.58	3.67 3.61
	CH ₂ OCH ₃	m s	3.28	3.50 3.33	3.37	3.12	3.11	3.16	3.47 3.28	3.38	3.43	3.62	3.38	3.37
dimethylformamide		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 ₃	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
1,4-dioxane	CH_3 CH_2	s s	2.76 3.56	2.82 3.65	2.88 3.71	1.96 3.33	1.86 3.35	2.30 3.45	2.78 3.59	2.73 3.57	2.77 3.60	2.88 3.76	2.86 3.66	2.85 3.75
DME	CH ₂	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_2	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 ethanol	CH ₃ CH ₃	s t, 7	0.85 1.10	0.85 1.19	0.87 1.25	0.81 0.97	$0.80 \\ 0.96$	0.79 1.06	0.83 1.12	0.82 1.06	0.85 1.12	0.85 1.22	0.85 1.19	0.82 1.17
ctilalioi	CH ₂	$a 7^d$	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 ^{c,d}	3.30	1.33	1.32	0.83	0.50	1.39	3.39	4.63	2.47			
ethyl acetate	CH ₃ CO	s 7	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_2CH_3 CH_2CH_3	q, 7 t, 7	4.04 1.19	4.08 1.23	4.12 1.26	3.87 0.94	3.89 0.92	3.96 1.04	4.05 1.20	4.03 1.17	4.06 1.20	4.14 1.26	4.09 1.24	4.14 1.24
ethylene	CH ₂	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 ₂	s ^e	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	CH_3 CH_2	m br s	0.85-0.91	0.84-0.90	0.84-0.8 1.25	7 0.89-0.96 (1.33	0.90-0.93 1.32	8 0.86-0.92 1.30	0.90	0.82-0.88		0.88-0.94 1.33	0.86-0.9.	3
hexamethylbenzene	CH ₂	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 ₃	t, 7	0.89	0.89	0.88	0.88	0.89	0.85	0.88	0.86	0.89	0.91	0.90	
HMDSO	CH ₂ CH ₃	m s	1.29 0.07	1.27 0.07	1.26 0.07	1.22 0.10	1.24 0.12	1.19 0.10	1.28 0.07	1.25 0.06	1.28 0.07	1.31 0.08	1.29 0.07	0.28
HMPA	CH ₃	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 ₂	s	4.55	4.59	4.62	4.50	4.47	4.49	4.54	4.61	4.57	4.53	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
methane	CH(4,5) CH ₄	s s	6.94 0.19	7.07 0.21	7.10 0.22	6.86 0.17	6.90 0.16	7.01 0.15	7.04 0.17	7.01 0.20	7.01 0.20	7.03 0.18	7.05 0.20	7.14 0.18
methanol	CH ₃	s ^g	3.27	3.42	3.49	3.03	3.07	3.25	3.31	3.16	3.28	3.44	3.34	3.34
· 1	OH	s ^{c,g}	3.02	1.09	1.09	2.01	2.04	1.30	3.12	4.01	2.16	4.00	4.24	4 40
nitromethane <i>n</i> -pentane	CH ₃ CH ₃	s t, 7	4.31 0.89	4.31 0.89	4.33 0.88	3.01 0.87	2.94 0.87	3.59 0.84	4.43 0.88	4.42 0.86	4.31 0.89	4.28 0.90	4.34 0.90	4.40
n pontano	CH ₂	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 ₃	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
2-propanol	CH ₂ CH ₃	sept, 7.3 d, 6	1.33 1.08	1.32 1.17	1.32 1.22	1.32 0.95	1.26 0.95	1.26 1.04	1.31 1.10	1.29 1.04	1.33 1.09	1.33 1.20	1.34 1.50	1.30 1.17
2-propanoi	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_3	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
	$CH_2(1)$ $CH_2(2)$	dm, 10 dm, 17	4.89 4.99	4.93 5.03	4.94 5.03	4.92 4.98	4.95 5.01	4.91 4.98	4.90 5.00	4.94 5.03	4.93 5.04	4.93 5.03	4.91 5.01	4.95 5.06
	CH ₂₍₂₎ CH	m 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
pyridine	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
pyrrole	CH(4) NH	m br t	7.65 9.96	7.68 8.69	7.68 8.40	6.99 7.71	6.98 7.80	7.25 8.61	7.76 10.02	7.79 10.75	7.73 9.27	7.82	7.85	7.87
pyrrote	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
1 h	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 ^h	$CH_2(2,5)$ $CH_2(3,4)$	m	2.75 1.59	2.82 1.67	2.87 1.68	2.54 1.36	2.54 1.33	2.64 1.43		2.67 1.55	2.75 1.61	3.11 1.93	2.80	3.07 1.87
silicone grease	$CH_{2}(3,4)$ CH_{3}	m s	0.11	0.09	0.07	0.26	0.29	0.14	0.13	-0.06	0.08	0.16	1.72 0.10	1.0/
tetrahydrofuran	$CH_2(2,5)$	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
4 - 1	$CH_2(3,4)$	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 ₃ CH(2,4,6)	s m	2.31 7.10	2.34 7.15	2.36 7.17	2.11 6.96-7.01	2.11 7.02	2.16 7.01-7.08	2.32 7.10-7.20	2.30 7.18	2.33 7 10-7 30	2.33 7.10-7.30	2.32 7.16	
	CH(2,4,0) CH(3,5)	m	7.10	7.24	7.25	7.09	7.13		7.10-7.20	7.18) 7.10-7.30	7.16	
triethylamine	CH ₃	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_2	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

^{*a*} 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 CDCl₃, C₆D₆, (CD₃)₂CO, (CD₃)₂SO, CD₃CN, CD₃OD, and D₂O were previously reported in ref 2. ^{*b*} A signal for HDO is also observed in (CD₃)₂SO (3.30 ppm) and (CD₃)₂CO (2.81 ppm), often seen as a 1:1:1 triplet (²J_{H,D} = 1 Hz). ^{*c*} Not all OH signals were observable. ^{*d*} In some solvents, the coupling interaction between the CH₂ and the OH protons may be observed (J = 5 Hz). ^{*e*} In CD₃CN, the OH proton was seen as a multiplet at 2.69 ppm, as well as extra coupling to the CH₂ resonance. ^{*f*} Apiezon brand H grease. ^{*g*} In some solvents, a coupling interaction between the CH₃ and the OH protons may be observed to react with (CD₃)₂CO.

	Table 2. ¹³ C{ ¹ H} NMR Data ^a												
	carbon	$\mathrm{THF}\text{-}d_8$	CD_2Cl_2	$CDCl_3$	toluene- d_8	C_6D_6	C ₆ D ₅ Cl	(CD ₃) ₂ CO	(CD ₃) ₂ SO	CD ₃ CN	TFE- d_3	CD ₃ OD	D_2O
solvent signals		67.21 25.31	53.84	77.16	137.48 128.87 127.96 125.13 20.43	128.06	134.19 129.26 128.25 125.96	29.84 206.26	39.52	1.32 118.26	61.50 126.28	49.00	
acetic acid	CO CH ₃	171.69 20.13	175.85 20.91	175.99 20.81	175.30 20.27	175.82 20.37	175.67 20.40	172.31 20.51	171.93 20.95	173.21 20.73	177.96 20.91	175.11 20.56	177.21 21.03
acetone	CO CH ₃	204.19 30.17	206.78 31.00	207.07 30.92	204.00 30.03	204.43 30.14	204.83 30.12	205.87 30.60	206.31 30.56	207.43 30.91	32.35 214.98	209.67 30.67	215.94 30.89
acetonitrile	CN CH ₃	116.79 0.45	116.92 2.03	116.43 1.89	115.76 0.03	116.02 0.20	115.93 0.63	117.60 1.12	117.91 1.03	118.26 1.79	118.95 1.00	118.06 0.85	119.68 1.47
benzene <i>tert</i> -butyl alcohol	CH (CH ₃) ₃ C	128.84 67.50	128.68 69.11	128.37 69.15	128.57 68.12	128.62 68.19	128.38 68.19	129.15 68.13	128.30 66.88	129.32 68.74	129.84 72.35	129.34 69.40	70.36
	(CH ₃) ₃ C (CH ₃) ₃ C CO ₂	30.57 125.69	31.46 125.26	31.25 124.99	30.49 124.86	30.47 124.76	31.13	30.72 125.81	30.38 124.21	30.68 125.89	31.07 126.92	30.91 126.31	30.29
carbon dioxide carbon disulfide	CS_2	193.37	192.95	192.83	192.71	192.69	126.08 192.49	193.58	192.63	193.60	196.26	193.82	197.25
carbon tetrachloride chloroform	CCl ₄ CH	96.89 79.24	96.52 77.99	96.34 77.36	96.57 77.89	96.44 77.79	96.38 77.67	96.65 79.19	95.44 79.16	96.68 79.17	97.74 78.83	97.21 79.44	96.73
18-crown-6 cyclohexane	$CH_2 \\ CH_2$	71.34 27.58	70.47 27.38	70.55 26.94	70.86 27.31	70.59 27.23	70.55 26.99	71.25 27.51	69.85 26.33	71.22 27.63	70.80 28.34	71.47 27.96	70.14
1,2-dichloroethane dichloromethane	$CH_2 \\ CH_2$	44.64 54.67	44.35 54.24	43.50 53.52	43.40 53.47	43.59 53.46	43.60 53.54	45.25 54.95	45.02 54.84	45.54 55.32	45.28 54.46	45.11 54.78	
diethyl ether	CH_3 CH_2	15.49 66.14	15.44 66.11	15.20 65.91	15.47 65.94	15.46 65.94	15.35 65.79	15.78 66.12	15.12 62.05	15.63 66.32	15.33 67.55	15.46 66.88	14.77 66.42
diglyme	CH ₃ CH ₂	58.72 71.17	58.95 70.70	59.01 70.51	58.62 70.92	58.66 70.87	58.42 70.56	58.77 71.03	57.98 69.54	58.90 70.99	59.40 73.05	59.06 71.33	58.67 70.05
dimethylformamide	CH ₂ CH	72.72 161.96	72.25 162.57	71.90 162.62	72.39 161.93	72.35 162.13	72.07 162.01	72.63 162.79	71.25 162.29	72.63 163.31	71.33 166.01	72.92 164.73	71.63
dimethynormanide	CH ₃ CH ₃	35.65	36.56 31.39	36.50 31.45	35.22 30.64	35.25 30.72	35.45 30.71	36.15 31.03	35.73 30.73	36.57 31.32	37.76 30.96	36.89	37.54 32.03
1,4-dioxane	CH_2	30.70 67.65	67.47	67.14	67.17	67.16	66.95	67.60	66.36	67.72	68.52	31.61 68.11	67.19
DME	CH_3 CH_2	58.72 72.58	59.02 72.24	59.08 71.84	58.63 72.25	58.68 72.21	58.31 71.81	58.45 72.47	58.03 71.17	58.89 72.47	59.52 72.87	59.06 72.72	58.67 71.49
ethane ethanol	CH_3 CH_3	6.79 18.90	6.91 18.69	6.89 18.41	6.94 18.78	6.96 18.72	6.91 18.55	6.88 18.89	6.61 18.51	6.99 18.80	7.01 18.11	6.98 18.40	17.47
ethyl acetate	CH ₂ CH ₃ CO	57.60 20.45	58.57 21.15	58.28 21.04	57.81 20.46	57.86 20.56	57.63 20.50	57.72 20.83	56.07 20.68	57.96 21.16	59.68 21.18	58.26 20.88	58.05 21.15
-	CO CH ₂	170.32 60.30	171.24 60.63	171.36 60.49	170.02 60.08	170.44 60.21	170.20 60.06	170.96 60.56	170.31 59.74	171.68 60.98	175.55 62.70	172.89 61.50	175.26 62.32
ethylene	CH_3 CH_2	14.37 123.09	14.37 123.20	14.19 123.13	14.23 122.92	14.19 122.96	14.07 122.95	14.50 123.47	14.40 123.52	14.54 123.69	14.36 124.08	14.49 123.46	13.92
ethylene glycol H grease ⁶	CH ₂ CH ₂	64.35 30.45	64.08 30.14	63.79 29.71	64.29 30.31	64.34 30.22	64.03 30.11	64.26	62.76	64.22	64.87	64.30	63.17
hexamethylbenzene	C C CH ₃	131.88 16.71	132.09 16.93	132.21 16.98	131.72 16.84	131.79 16.95	131.54 16.68	132.22 16.86	131.10 16.60	132.61 16.94	134.04 17.04	132.53 16.90	
<i>n</i> -hexane	CH ₃	14.22 23.33	14.28 23.07	14.14 22.70	14.34 23.12	14.32 23.04	14.18 22.86	14.34	13.88 22.05	14.43	14.63	14.45	
	$CH_2(2,5)$ $CH_2(3,4)$	32.34	32.01	31.64	32.06	31.96	31.77	23.28 32.30	30.95	23.40 32.36	24.06 33.17	23.68 32.73	
HMDSO HMPA ^c	CH ₃ CH ₃	1.83 36.89	1.96 36.99	1.97 36.87	1.99 36.80	2.05 36.88	1.92 36.64	2.01 37.04	1.96 36.42	2.07 37.10	2.09 37.21	1.99 37.00	2.31 36.46
imidazole	CH(2) CH(4,5)	135.72 122.20	135.76 122.16	135.38 122.00	135.57 122.13	135.76 122.16	135.50 121.96	135.89 122.31	135.15 121.55	136.33 122.78	136.58 122.93	136.31 122.60	136.65 122.43
methane methanol	CH_4 CH_3	$-4.90 \\ 49.64$	-4.33 50.45	-4.63 50.41	-4.34 49.90	-4.29 49.97	-4.33 49.66	-5.33 49.77	-4.01 48.59	-4.61 49.90	-5.88 50.67	-4.90 49.86	49.50 ^d
nitromethane <i>n</i> -pentane	CH ₃ CH ₃	62.49 14.18	63.03 14.24	62.50 14.08	61.14 14.27	61.16 14.25	61.68 14.10	63.21 14.29	63.28 13.28	63.66 14.37	63.17 14.54	63.08 14.39	63.22
	CH ₂ (2,4) CH ₂ (3)	23.00 34.87	22.77 34.57	22.38 34.16	22.79 34.54	22.72 34.45	22.54 34.26	22.98 34.83	21.70 33.48	23.08 34.89	23.75 35.76	23.38 35.30	
propane	CH ₃ CH ₂	16.60 16.82	16.63 16.63	16.63 16.37	16.65 16.63	16.66 16.60	16.56 16.48	16.68 16.78	16.34 15.67	16.73 16.91	16.93 17.46	16.80 17.19	
2-propanol	CH ₃ CH	25.70 66.14	25.43 64.67	25.14 64.50	25.24 64.12	25.18 64.23	25.14 64.18	25.67 63.85	25.43 64.92	25.55 64.30	25.21 66.69	25.27 64.71	24.38 64.88
propylene	$CH_3 \\ CH_2$	19.27 115.74	19.47 115.70	19.50 115.74	19.32 115.89	19.38 115.92	19.32 115.86	19.42 116.03	19.20 116.07	19.48 116.12	19.63 116.38	19.50 116.04	04.00
pyridine	CH CH(2,6) CH(3,5)	134.02 150.57 124.08	134.21 150.27 124.06	133.91 149.90 123.75	133.61 150.25 123.46	133.69 150.27 123.58	133.57 149.93 123.49	134.34 150.67 124.57	133.55 149.58 123.84	134.78 150.76 127.76	136.00 149.76 126.27	134.61 150.07 125.53	149.18 125.12
pyrrole	CH(4) CH(2,5)	135.99 118.03	136.16 117.93	135.96 117.77	135.17 117.61	135.28 117.78	135.32 117.65	136.56 117.98	136.05 117.32	136.89 118.47	139.62 119.61	138.35 118.28	138.27 119.06
pyrrolidine ^e	CH(3,4) $CH_2(2,5)$	107.74 45.82	108.02 47.02	107.98 46.93	108.15 47.12	108.21 46.86	108.03 46.75	108.04	107.07 46.51 25.26	108.31 47.57 26.24	108.85 47.43	108.11 47.23	107.83 46.83
silicone grease tetrahydrofuran	$CH_{2}(3,4)$ CH_{3} $CH_{2}(2,5)$ $CH_{2}(2,4)$	26.17 1.20 68.03	25.83 1.22 68.16	25.56 1.19 67.97	25.75 1.37 67.75	25.65 1.38 67.80	25.59 1.09 67.64	1.40 68.07	25.26 67.03	26.34 68.33	25.73 2.87 69.53	26.29 2.10 68.83	25.86 68.68
toluene	CH ₂ (3,4) CH ₃ C(1) CH(2,6) CH(3,5)	26.19 21.29 138.24 129.47 128.71	25.98 21.53 138.36 129.35 128.54	25.62 21.46 137.89 129.07 128.26	25.79 21.37 137.84 129.33 128.51	25.72 21.10 137.91 129.33 128.56	25.68 21.23 137.65 129.12 128.31	26.15 21.46 138.48 129.76 129.03	25.14 20.99 137.35 128.88 128.18	26.27 21.50 138.90 129.94 129.23	26.69 21.62 139.92 130.58 129.79	26.48 21.50 138.85 129.91 129.20	25.67
triethylamine	CH(4) CH ₃ CH ₂	125.84 12.51 47.18	125.62 12.12 46.75	125.33 11.61 46.25	125.66 12.39 46.82	125.68 12.35 46.77	125.43 11.87 46.36	126.12 12.49 47.07	125.29 11.74 45.74	126.28 12.38 47.10	126.82 9.51 48.45	126.29 11.09 46.96	9.07 47.19

^{*a*} 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 CDCl₃, C₆D₆, (CD₃)₂CO, (CD₃)₂SO, CD₃CN, CD₃OD, and D₂O were previously reported in ref 2. ^{*b*} Apiezon brand H grease. ^{*c*} Phosphorus coupling was observed (²J_{PC} = 3 Hz). ^{*d*} Internal reference; see text. ^{*e*} Pyrrolidine was observed to react with (CD₃)₂CO.

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), longchain, linear aliphatic hydrocarbons from pump oil;⁴ (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.⁵ In the case of TFE- d_3 , nitromethane was omitted from solution 6 and run separately, since the protons of nitromethane exchange with deuterium from TFE- d_3 in the presence of triethylamine. In the case of (CD₃)₂CO, 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 ¹H NMR spectroscopy, solvent residual signals⁶ and chemical shifts for H_2O^7 for each NMR solvent were referenced against tetramethylsilane (TMS, δ 0 ppm) and reported. Before collecting ¹³C{¹H} NMR spectral data, solvent signals⁶ were recorded with reference to the signal of a TMS internal standard. For D₂O, ¹H NMR spectra were referenced to the methyl signal (δ 0 ppm) of sodium 3-(trimethylsilyl)propane-sulfonate, ^{8,9} and ¹³C{¹H} 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.²

In a typical experiment for collecting ¹H NMR spectral data, a 3 μ L sample of a standard contaminant solution was added to an NMR tube containing approximately 0.4 mL of a deuterated solvent. For ¹³C{¹H} NMR spectral data collection, an approximately 50 μ L 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 μ L 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-

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: ¹H and ¹³C{¹H} 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 ¹H NMR signal integrations that were qualitatively comparable to those for the solutions made with the 3 μ L additions of the liquid or solid contaminants. However, typically in order to observe signals for the gas samples by ${}^{13}C{}^{1}H{}$ NMR spectroscopy, additional time for data collection was required. The solubility of each gas in D₂O was extremely limited, making ¹³C detection impractical. Of all the gases, methane required the most number of transients in order to obtain an observable signal by ${}^{13}C{}^{1}H$ NMR spectroscopy. In most cases, the ¹³C 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, ¹³C detection was not pursued with isotopically enriched gases. A number of misreported values were discovered in the years since the original publication¹⁰ 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.

⁽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 ¹H NMR spectra, the solvent residual signals arise from the proton of isotopomers containing one less deuterium atom than the perdeuterated solvent: e.g., CDHCl₂ in CD₂Cl₂. For ¹³C NMR spectra, the solvent signals arise from the ¹³C atoms at natural abundance in the perdeuterated solvent.

⁽⁷⁾ The chemical shift for H_2O can vary depending on the temperature, $[H_2O]$, 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_2O , see ref 2.

⁽¹⁰⁾ The misreported value for acetonitrile in C_6D_6 from the original paper² was also pointed out by Dr. Jongwook Choi, to whom we are grateful.