Supporting Information for

Understanding paramagnetic relaxation phenomena in water-soluble gadofullerenes

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Appendix. Equations used in the analysis of NMRD data.

Table S1. Proton relaxivities as a function of phosphate concentration measured on $\text{Gd@C}_{60}(\text{OH})_x$.

Table S2. Variable temperature proton relaxivities measured on disaggregated $\text{Gd@C}_{60}(\text{OH})_x$ (in presence of phosphate).

Table S3. Variable temperature proton relaxivities measured on aggregated $\text{Gd@C}_{60}(\text{OH})_x$ (in absence of phosphate).

Table S4. Proton relaxivities as a function of phosphate concentration measured on $\text{Gd@C}_{60}[\text{C}(\text{COOH})_2]_{10}$.

Table S5. Variable temperature proton relaxivities measured on disaggregated $\text{Gd@C}_{60}[\text{C}(\text{COOH})_2]_{10}$ (in presence of phosphate).

Table S6. Variable temperature proton relaxivities measured on aggregated $\text{Gd@C}_{60}[\text{C}(\text{COOH})_2]_{10}$ (in absence of phosphate).

Table S7. Variable temperature reduced transverse and longitudinal ^{17}O relaxation rates measured on disaggregated $\text{Gd@C}_{60}(\text{OH})_x$ at 9.4 T.

Table S8. Variable temperature reduced transverse and longitudinal ^{17}O relaxation rates measured on disaggregated $\text{Gd@C}_{60}(\text{OH})_x$ at 4.7 T.

Table S9. Variable temperature reduced transverse and longitudinal ^{17}O relaxation rates measured on aggregated $\text{Gd@C}_{60}(\text{OH})_x$ at 9.4 T.

Table S10. Variable temperature reduced transverse and longitudinal ^{17}O relaxation rates measured on aggregated $\text{Gd@C}_{60}(\text{OH})_x$ at 4.7 T.

Table S11. Variable temperature reduced transverse and longitudinal ^{17}O relaxation rates measured on disaggregated $\text{Gd@C}_{60}[\text{C}(\text{COOH})_2]_{10}$ at 9.4 T.

Table S12. Variable temperature reduced transverse and longitudinal ^{17}O relaxation rates measured on disaggregated $\text{Gd@C}_{60}[\text{C}(\text{COOH})_2]_{10}$ at 4.7 T.

Table S13. Variable temperature reduced transverse and longitudinal ^{17}O relaxation rates measured on aggregated $\text{Gd@C}_{60}[\text{C}(\text{COOH})_2]_{10}$ at 9.4 T.

Table S14. Variable temperature reduced transverse and longitudinal ^{17}O relaxation rates measured on aggregated $\text{Gd@C}_{60}[\text{C}(\text{COOH})_2]_{10}$ at 4.7 T.

Appendix: NMRD

The measured proton relaxivities (normalized to 1 mM Gd(III) concentration) contain both inner sphere and outer sphere contributions :

$$r_1 = r_{\text{lis}} + r_{\text{los}} \quad (1)$$

The inner sphere term is given by eq. 2, where q is the number of inner sphere protons.

$$r_{\text{lis}} = \frac{1}{1000} \times \frac{q}{55.55} \times \frac{1}{T_{1m}^H + \tau_m} \quad (2)$$

The longitudinal relaxation rate of inner sphere protons, $1/T_{1m}^H$ is given by eq. 3:^{1,2}

$$\frac{1}{T_{1m}^H} = \frac{2}{15} \left(\frac{\mu_o}{4\pi} \right)^2 \frac{\hbar^2 \gamma_S^2 \gamma_I^2}{r_{\text{GdH}}^6} S(S+1) \left[\frac{3\tau_{d1}}{1 + \omega_I^2 \tau_{d1}^2} + \frac{7\tau_{d2}}{1 + \omega_S^2 \tau_{d2}^2} \right] \quad (3)$$

In eq. 3 r_{GdH} is the effective distance between the Gd(III) electron spin and the protons, ω_I is the proton resonance frequency, and τ_{di} is given by eq. 4 :

$$\frac{1}{\tau_{di}} = \frac{1}{\tau_m} + \frac{1}{\tau_R} + \frac{1}{T_{ie}} \quad i = 1, 2 \quad (4)$$

The outer-sphere contribution can be described by eq. 5,^{3,4} where N_A is the Avogadro constant, and J_{OS} is a spectral density function.

$$r_{\text{los}} = \frac{32N_A \pi}{405} \left(\frac{\mu_o}{4\pi} \right)^2 \frac{\hbar^2 \gamma_S^2 \gamma_I^2}{a_{\text{GdH}} D_{\text{GdH}}} S(S+1) [3J_{\text{os}}(\omega_I, T_{1e}) + 7J_{\text{os}}(\omega_S, T_{2e})] \quad (5)$$

$$J_{\text{os}}(\omega, T_{je}) = \text{Re} \left[\frac{1 + \frac{1}{4} \left(i\omega\tau_{\text{GdH}} + \frac{\tau_{\text{GdH}}}{T_{je}} \right)^{1/2}}{\left[1 + \left(i\omega\tau_{\text{GdH}} + \frac{\tau_{\text{GdH}}}{T_{je}} \right)^{1/2} \right]^2 + \frac{4}{9} \left(i\omega\tau_{\text{GdH}} + \frac{\tau_{\text{GdH}}}{T_{je}} \right) + \frac{1}{9} \left(i\omega\tau_{\text{GdH}} + \frac{\tau_{\text{GdH}}}{T_{je}} \right)^{3/2}} \right] \quad (6)$$

j = 1, 2

[1] N. J. Bloembergen *Chem. Phys.* **27**, 572 (1957)

[2] I. Solomon *Phys. Rev.* **99**, 559 (1955)

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For the temperature dependence of the diffusion coefficient for the diffusion of a water proton away from a Gd(III) complex, D_{GdH} , we assume an exponential temperature dependence, with an activation energy E_{DGdH} :

$$D_{\text{GdH}} = D_{\text{GdH}}^{298} \exp\left\{\frac{E_{\text{DGdH}}}{R}\left(\frac{1}{T} - \frac{1}{298.15}\right)\right\} \quad (7)$$

All solutions for this part were prepared from the second batch of gadofullerenes ($\text{Gd}@C_{60}(\text{OH})_x$: 2.68% (m_{Gd}/m) and $\text{Gd}@C_{60}[\text{C}(\text{COOH})_2]_{10}$: 1.64% (m_{Gd}/m)). The solutions were kept at 37°C for one month before recording the NMR data to ensure that the equilibrium state has been reached.

Table 1. Proton relaxivities (r_1 ; $\text{mM}^{-1} \text{s}^{-1}$) of $\text{Gd}@C_{60}(\text{OH})_x$ as a function of phosphate concentration ($c_{\text{Gd(III)}} = 0.499 \text{ mM}$, pH 7.4, 25°C; 60 MHz, measured 5 days after the preparation of the sample).

$C_{\text{phosphate}} / \text{mM}$	$r_1 / \text{mM}^{-1} \text{s}^{-1}$
0	97.65
10	27.89
50	13.73
100	13.05

Table 2. Variable temperature proton relaxivities (r_1 ; $\text{mM}^{-1} \text{s}^{-1}$) of $\text{Gd}@C_{60}(\text{OH})_x$ in presence of phosphate ($c_{\text{Gd(III)}} = 0.519 \text{ mM}$, $c_{\text{phosphate}} = 100 \text{ mM}$, pH 7.4).

$\nu (^1\text{H})$ / MHz/	5.0°C	25.0°C	37.0°C	50.0°C
0.010	4.769	4.501	4.090	3.915
0.014	4.749	4.500	4.089	3.887
0.021	4.764	4.504	4.086	3.898
0.030	4.759	4.493	4.084	3.914
0.043	4.708	4.471	4.051	3.856
0.062	4.669	4.466	4.017	3.868
0.089	4.693	4.429	3.990	3.852
0.127	4.615	4.392	3.973	3.818
0.183	4.556	4.331	3.908	3.801
0.264	4.490	4.262	3.815	3.754
0.379	4.424	4.238	3.766	3.705
0.546	4.338	4.120	3.684	3.629
0.784	4.167	4.039	3.605	3.612
1.13	4.076	3.962	3.508	3.525
1.62	3.959	3.862	3.354	3.427
2.34	3.843	3.727	3.234	3.324
3.36	3.670	3.547	3.039	3.193
4.83	3.482	3.397	2.863	3.000
6.95	3.231	3.087	2.815	2.827
10	3.163	3.025	2.847	2.752
12	3.341	3.312	3.340	2.822
14	3.762	3.617	3.684	3.304
16	4.095	4.276	4.136	3.643
18	4.439	4.863	5.164	3.908
20	4.746	6.337	7.214	
30	8.601	9.940	9.553	9.366
40	8.80	10.69	10.30	10.26
60	8.81	10.95	10.84	10.83
200	5.097	5.354	5.916	5.739
400	3.129	3.740	3.914	3.788

Table 3. Variable temperature proton relaxivities (r_1 ; $\text{mM}^{-1} \text{s}^{-1}$) of $\text{Gd}@\text{C}_{60}(\text{OH})_x$ in absence of phosphate ($c_{\text{Gd(III)}} = 0.499 \text{ mM}$, pH 7.4).

$\nu (^1\text{H})$ / MHz/	5.0°C	25.0°C	37.0°C	50.0°C
0.010	66.22	61.35	57.36	57.73
0.014	66.13	61.42	57.26	57.48
0.021	65.85	61.27	57.21	57.49
0.030	66.06	61.50	57.09	57.44
0.043	65.79	61.50	57.18	57.63
0.062	65.46	61.35	57.24	57.52
0.089	65.78	61.43	56.96	57.19
0.127	65.17	60.99	57.03	57.26
0.183	64.75	60.85	56.75	56.87
0.264	64.79	60.42	56.12	56.31
0.379	64.04	59.72	55.47	55.95
0.546	63.03	58.72	54.56	54.66
0.784	60.99	57.41	53.30	53.50
1.13	59.09	55.83	51.74	51.61
1.62	57.24	53.29	49.52	49.54
2.34	54.65	50.58	47.29	47.02
3.36	51.62	48.62	45.05	44.78
4.83	51.72	48.05	44.05	43.05
6.95	52.66	49.45	44.97	43.20
10	62.38	55.61	49.84	48.15
12	68.42	55.92	55.74	51.68
14	75.32	61.79	59.46	55.21
16	82.54	66.56	63.99	58.61
18	87.51	71.65	66.84	62.05
20	94.48	76.13	70.61	65.55
30	111.88	94.02	84.58	78.97
40	116.52	99.72	89.41	83.42
50	114.21	100.35	90.29	84.02
60	101.62	93.44	85.87	79.90
100	66.20	66.45	65.29	60.80
200	31.00	33.46	33.57	33.64
400	15.03	16.31	16.69	17.35

Table 4. Proton relaxivities (r_1 ; $\text{mM}^{-1} \text{s}^{-1}$) of $\text{Gd@C}_{60}[\text{C}(\text{COOH})_2]_{10}$ as a function of phosphate concentration ($c_{\text{Gd(III)}} = 0.665 \text{ mM}$, $\text{pH } 7.4$, 25°C ; 60 MHz , measured 5 days after the preparation of the sample).

$C_{\text{phosphate}} / \text{mM}$	$r_1 / \text{mM}^{-1} \text{s}^{-1}$
0	14.83
10	6.709
50	4.690
100	4.585

Table 5. Variable temperature proton relaxivities (r_1 ; $\text{mM}^{-1} \text{s}^{-1}$) of $\text{Gd@C}_{60}[\text{C}(\text{COOH})_2]_{10}$ in presence of phosphate ($c_{\text{Gd(III)}} = 0.701 \text{ mM}$, $c_{\text{phosphate}} = 100 \text{ mM}$, $\text{pH } 7.4$).

$\nu (^1\text{H})$ / MHz /	5.0°C	25.0°C	37.0°C	50.0°C
0.010	6.53	4.22	3.52	3.06
0.014	6.57	4.24	3.49	3.05
0.021	6.70	4.22	3.47	3.04
0.030	6.69	4.21	3.49	3.06
0.043	6.60	4.21	3.47	3.03
0.062	6.52	4.18	3.46	3.04
0.089	6.54	4.17	3.47	3.03
0.127	6.47	4.12	3.47	3.00
0.183	6.41	4.12	3.40	2.99
0.264	6.36	4.06	3.37	2.95
0.379	6.23	4.03	3.30	2.92
0.546	6.11	3.93	3.23	2.85
0.784	6.02	3.84	3.19	2.80
1.13	5.78	3.70	3.11	2.74
1.62	5.62	3.58	2.96	2.64
2.34	5.49	3.40	2.82	2.52
3.36	5.25	3.22	2.66	2.40
4.83	4.96	2.97	2.48	2.25
6.95	4.69	2.72	2.22	2.06
10	3.93	2.28	1.77	1.64
12	3.78	2.16	1.89	1.67
14	4.03	2.42	2.08	1.82
16	4.72	2.75	2.19	1.90
18	5.04	2.91	2.31	1.99
30	5.55	4.61	4.07	3.75
40	5.31	4.70	4.18	3.92
60	5.06	4.60	4.24	3.97
200		2.99	2.66	3.06
400	2.22	2.06	1.72	1.64

Table 6. Variable temperature proton relaxivities (r_1 ; $\text{mM}^{-1} \text{s}^{-1}$) of $\text{Gd@C}_{60}[\text{C}(\text{COOH})_2]_{10}$ in absence of phosphate ($C_{\text{Gd(III)}} = 0.665 \text{ mM}$, pH 7.4).

$\nu (^1\text{H})$ / MHz/	5.0°C	25.0°C	37.0°C	50.0°C
0.010	18.17	11.86	10.77	11.77
0.014	18.29	11.85	10.76	11.63
0.021	18.17	11.79	10.73	11.85
0.030	18.23	11.80	10.73	11.75
0.043	18.20	11.80	10.68	11.70
0.062	18.12	11.80	10.69	11.70
0.089	18.20	11.74	10.67	11.67
0.127	18.21	11.79	10.63	11.56
0.183	18.08	11.69	10.60	11.56
0.264	17.91	11.60	10.50	11.48
0.379	17.64	11.50	10.42	11.37
0.546	17.47	11.34	10.23	11.16
0.784	17.02	11.07	10.03	10.95
1.13	16.39	10.76	9.773	10.62
1.62	15.91	10.42	9.447	10.12
2.34	15.23	10.07	9.057	9.620
3.36	14.44	9.62	8.633	9.105
4.83	13.91	9.28	8.296	8.581
6.95	13.18	9.24	8.236	7.917
10	14.45	9.85	8.561	8.251
12	14.86	10.25	8.817	8.497
14	15.69	10.83	9.121	
16	17.14	11.34	9.514	
18		11.73	9.808	
30	19.88	15.03	12.55	10.74
40	20.96	15.61	12.88	11.17
50	20.69	15.75	12.90	11.42
60	19.62	15.29	12.68	10.98
100	15.15	12.45	10.84	9.57
200	9.159	8.152	7.162	6.539
400	5.979	5.484	4.730	4.721

Table 7. Variable temperature reduced transverse and longitudinal ^{17}O relaxation rates of disaggregated $\text{Gd@C}_{60}(\text{OH})_x$ at 9.4 T ($c_{\text{Gd(III)}} = 0.01026 \text{ mol kg}^{-1}$, $c_{\text{phosphate}} = 1 \text{ M}$, pH 7.4; 1 M phosphate reference, pH 7.4).

T / K	$1/T_{1A}$ /s $^{-1}$	$1/T_1$ /s $^{-1}$	$1/T_{2A}$ /s $^{-1}$	$1/T_2$ /s $^{-1}$
296.3	232.67	283.21	232.13	377.02
311.5	154.18	187.83	155.09	266.67
345.1	76.96	95.57	76.95	164.80
325.2	112.33	139.12	113.02	212.40
364.8	57.28	70.05	56.81	127.10
290.6	278.01	335.91	277.55	432.53
275.4	484.50	572.41	478.70	695.89
284.0	347.46	413.91	346.38	524.38
279.2	416.84	490.92	412.88	602.77
304.6	183.02	223.16	183.55	303.58

Table 8. Variable temperature reduced transverse and longitudinal ^{17}O relaxation rates of disaggregated $\text{Gd@C}_{60}(\text{OH})_x$ at 4.7 T ($c_{\text{Gd(III)}} = 0.01026 \text{ mol kg}^{-1}$, $c_{\text{phosphate}} = 1 \text{ M}$, pH 7.4; 1 M phosphate reference, pH 7.4).

T / K	$1/T_{1A}$ /s $^{-1}$	$1/T_1$ /s $^{-1}$	$1/T_{2A}$ /s $^{-1}$	$1/T_2$ /s $^{-1}$
322.5	119.90	148.43	119.16	196.23
305.9	176.68	217.58	176.49	268.53
366.0	55.65	68.78	56.09	102.33
341.7	81.37	102.10	82.24	139.98
287.6	301.20	380.37	306.18	447.43
312.7	149.32	185.67	151.06	238.15
277.9	426.80	536.19	434.22	625.00
298.3	217.30	272.48	220.70	332.89
283.2	353.11	439.37	353.48	514.14
331.7	97.77	121.37	98.06	162.07

Table 9. Variable temperature reduced transverse and longitudinal ^{17}O relaxation rates of $\text{Gd}@\text{C}_{60}(\text{OH})_x$ at 9.4 T ($c_{\text{Gd(III)}} = 0.01046 \text{ mol kg}^{-1}$, pH 7.4; water reference, pH 3.7).

T / K	$1/T_{1A}$ /s $^{-1}$	$1/T_1$ /s $^{-1}$	$1/T_{2A}$ /s $^{-1}$	$1/T_2$ /s $^{-1}$
296.3	146.26	218.63	143.76	836.83
311.5	100.87	165.89	100.16	761.67
345.1	53.84	108.83	53.95	546.75
325.2	75.84	136.39	74.81	672.04
364.8	41.09	89.20	40.87	409.50
290.6	171.09	246.67	170.18	896.06
275.4	282.09	375.09	280.66	989.12
284.0	209.91	289.35	207.13	933.71
279.2	246.67	331.02	242.72	1000.00
304.6	116.73	186.05	115.90	793.02

Table 10. Variable temperature reduced transverse and longitudinal ^{17}O relaxation rates of $\text{Gd}@\text{C}_{60}(\text{OH})_x$ at 4.7 T ($c_{\text{Gd(III)}} = 0.01046 \text{ mol kg}^{-1}$, pH 7.4; water reference, pH 3.7).

T / K	$1/T_{1A}$ /s $^{-1}$	$1/T_1$ /s $^{-1}$	$1/T_{2A}$ /s $^{-1}$	$1/T_2$ /s $^{-1}$
322.5	78.36	196.12	80.83	631.71
305.9	111.09	241.60	110.30	714.29
366.0	39.06	119.86	39.72	356.89
341.7	56.35	155.98	55.44	476.64
287.6	186.29	327.01	186.71	841.75
312.7	99.00	218.96	100.77	666.22
277.9	256.15	414.77	256.28	975.61
298.3	137.08	268.89	136.09	781.25
283.2	215.80	360.62	208.77	894.45
331.7	65.25	172.74	66.47	551.27

Table 11. Variable temperature reduced transverse and longitudinal ^{17}O relaxation rates of disaggregated $\text{Gd@C}_{60}[\text{C}(\text{COOH})_2]_{10}$ at 9.4 T ($c_{\text{Gd(III)}} = 0.00996 \text{ mol kg}^{-1}$, $c_{\text{phosphate}} = 1 \text{ M}$, pH 7.4; 1 M phosphate reference, pH 7.4).

T / K	$1/T_{1A}$ /s $^{-1}$	$1/T_1$ /s $^{-1}$	$1/T_{2A}$ /s $^{-1}$	$1/T_2$ /s $^{-1}$
296.3	232.67	311.53	232.13	339.90
311.5	154.18	198.97	155.09	217.77
345.1	76.96	93.63	76.95	101.75
325.2	112.33	141.60	113.02	155.38
364.8	57.28	67.80	56.81	74.72
290.6	278.01	377.93	277.55	405.52
275.4	484.50	685.40	478.70	745.16
284.0	347.46	476.42	346.38	514.67
279.2	416.84	582.07	412.88	627.75
304.6	183.02	239.46	183.55	259.07

Table 12. Variable temperature reduced transverse and longitudinal ^{17}O relaxation rates of disaggregated $\text{Gd@C}_{60}[\text{C}(\text{COOH})_2]_{10}$ at 4.7 T ($c_{\text{Gd(III)}} = 0.00996 \text{ mol kg}^{-1}$, $c_{\text{phosphate}} = 1 \text{ M}$, pH 7.4; 1 M phosphate reference, pH 7.4).

T / K	$1/T_{1A}$ /s $^{-1}$	$1/T_1$ /s $^{-1}$	$1/T_{2A}$ /s $^{-1}$	$1/T_2$ /s $^{-1}$
322.5	119.90	152.74	119.16	166.78
305.9	176.68	230.89	176.49	252.84
366.0	55.65	65.99	56.09	71.40
341.7	81.37	101.03	82.24	109.57
287.6	301.20	427.53	306.18	456.62
312.7	149.32	194.29	151.06	211.69
277.9	426.80	619.96	434.22	676.59
298.3	217.30	290.87	220.70	314.56
283.2	353.11	499.75	353.48	540.83
331.7	97.77	121.80	98.06	131.93

Table 13. Variable temperature reduced transverse and longitudinal ^{17}O relaxation rates of $\text{Gd@C}_{60}[\text{C}(\text{COOH})_2]_{10}$ at 9.4 T ($c_{\text{Gd(III)}} = 0.00831 \text{ mol kg}^{-1}$, pH 7.4; water reference, pH 3.7).

T / K	$1/T_{1A}$ /s $^{-1}$	$1/T_1$ /s $^{-1}$	$1/T_{2A}$ /s $^{-1}$	$1/T_2$ /s $^{-1}$
296.3	146.26	185.32	143.76	283.05
311.5	100.87	125.87	100.16	202.43
345.1	53.84	65.69	53.95	103.35
325.2	75.84	95.53	74.81	152.53
364.8	41.09	49.41	40.87	73.77
290.6	171.09	213.13	170.18	321.54
275.4	282.09	354.86	280.66	485.20
284.0	209.91	259.74	207.13	381.68
279.2	246.67	308.55	242.72	438.02
304.6	116.73	145.56	115.90	228.52

Table 14. Variable temperature reduced transverse and longitudinal ^{17}O relaxation rates of $\text{Gd@C}_{60}[\text{C}(\text{COOH})_2]_{10}$ at 4.7 T ($c_{\text{Gd(III)}} = 0.00831 \text{ mol kg}^{-1}$, pH 7.4; water reference, pH 3.7).

T / K	$1/T_{1A}$ /s $^{-1}$	$1/T_1$ /s $^{-1}$	$1/T_{2A}$ /s $^{-1}$	$1/T_2$ /s $^{-1}$
322.5	78.36	102.23	80.83	154.32
305.9	111.09	143.20	110.30	217.58
366.0	39.06	49.02	39.72	66.93
341.7	56.35	70.44	55.44	100.68
287.6	186.29	240.21	186.71	333.22
312.7	99.00	124.30	100.77	183.55
277.9	256.15	329.16	256.28	442.09
298.3	137.08	176.34	136.09	259.61
283.2	215.80	275.18	208.77	381.10
331.7	65.25	84.40	66.47	131.93