## **Electronic Supplementary Information**

# Solvent-Dependent Structural Dynamics of Azido-Platinum Complex Revealed by Linear and Nonlinear Infrared Spectroscopies

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## S1. Calculated IR spectrum at the level of DFT using the B3LYP functional and potential energy surface scan



**Fig. S1** Line-broadened IR spectrum (black solid line) of *trans, trans, trans*- $[Pt(N_3)_2(OH)_2(py)_2]$  in the N<sub>3</sub> absorption region with the distribution of the transition intensities (red sticks) at computed harmonic normal-mode vibration frequency positions. The high-frequency component arises from the ss mode of the two N<sub>3</sub> groups, and the low-frequency component arises from the as mode of the two N<sub>3</sub> groups. The computational method has been given in Section 2.3, and the freely optimized dihedral angle is 104° (see Table S1).

The potential energy surface of *trans, trans, trans*-[Pt(N<sub>3</sub>)<sub>2</sub>(OH)<sub>2</sub>(py)<sub>2</sub>] in gas phase was scanned by changing the dihedral angle  $\theta$  between the two N<sub>3</sub> groups ( $\theta = \angle N7N6N9N10$ , defined in Fig. S2) with a step of  $\Delta \theta = 30^{\circ}$  (with a step of  $\Delta \theta = 10^{\circ}$  for those whose dihedral angles close to the freely optimized dihedral angle, *i.e.*, 104°). The B3LYP functional was used with the 6-31+G\*\* basis set for C, H, O, N atoms and the LanL2DZ basis set and effective core potential for the Pt atom. At each dihedral angle, structural optimization and vibrational frequency calculation were carried out.

The calculated results were listed in Table S1. Based on the computed transition intensities of the ss and as modes, it is found that only the structures with  $\theta = 90 - 110^{\circ}$  are in agreement with the FTIR observation (Table 1). Freely optimized structure has the dihedral angle  $\theta = 104^{\circ}$  that was initially set to 119° according to the crystallographic structure of this prodrug.<sup>1</sup> The computed transition intensities of the ss and as modes of this optimized structure also agrees with FTIR observation shown in Table 1. Therefore, it is likely that in solution, the dihedral angle  $\theta$  is approximately in the range of 90 - 110°. The calculated diagonal anharmonicities of the as and ss modes at different dihedral angles are on the same order of 14 - 15 cm<sup>-1</sup> for these probable structures, which are found to be *ca*. within  $\pm 5$  cm<sup>-1</sup> of the experimentally determined values (Fig. S5 and Table S3). Both the computed and experimentally determined anharmonicities are smaller than that of free N<sub>3</sub><sup>-</sup>,<sup>2</sup> which is also listed in Table S1.

The PBE1PBE method,<sup>3, 4</sup> a generalized-gradient-approximation exchange correlation functional proposed by Perdew, Burke, and Ernzerhof, which has been used previously in calculating vibrational spectra of antitumor drugs,<sup>5</sup> was used in this work as a comparison. The basis set used for C, H, O, N atoms was the same as above, while the SDD and the LanL2DZ basis set was used for the Pt atom, respectively. The computational results at this level, which are also listed in Table S1, basically agree with those using the B3LYP functional.



Fig. S2 Structures of the Pt-complex with different dihedral angles ( $\theta = \angle N7N6N9N10$ , as labeled in the middle structure) between the two N<sub>3</sub> groups. The direction of the transition dipole moment of the as mode is given in each molecular structure as red arrow. The freely optimized molecular structure ( $\theta = 104^\circ$ ) at the level of B3LYP is given in the middle with atoms labeled.

**Table S1** Calculated harmonic vibrational frequency ( $\omega_{harm.}$ , in cm<sup>-1</sup>), anharmonic vibrational frequency ( $\omega_{anharm.}$ , in cm<sup>-1</sup>), transition intensity (I, in km·mol<sup>-1</sup>), transition dipole (Dipole, in Debye), diagonal anharmonicity ( $\Delta_{diag.}$ , in cm<sup>-1</sup>) and the IR intensity ratio ( $I_{ss}/I_{as}$ ) of the N<sub>3</sub> as and ss modes in *trans, trans, trans-*[Pt(N<sub>3</sub>)<sub>2</sub>(OH)<sub>2</sub>(py)<sub>2</sub>] at different dihedral angles ( $\theta$ , in °) between the two N<sub>3</sub> groups as defined in Fig. S2.

θ	Mode	$\omega_{harm.}$	Ι	Dipole	$I_{ss}/I_{as}$	ω <sub>anharm.</sub>	$\Delta_{\text{diag.}}$
0 a	SS	2157.2	527.9	0.31		2034.5	21.9
	as	2132.6	1087.6	0.45	0.49	2028.9	21.7
30 a	SS	2160.7	588.9	0.33		1965.9	15.5
	as	2141.4	1180.9	0.47	0.50	1926.9	14.5
60 a	SS	2160.0	503.2	0.30		2053.6	15.4
	as	2142.7	1251.0	0.48	0.40	2036.9	15.1
90 a	SS	2159.3	358.0	0.26		2059.8	15.5
	as	2144.7	1356.5	0.50	0.26	2045.9	15.0
100 <sup>a</sup>	SS	2158.9	302.1	0.24		2059.4	15.4
	as	2145.3	1398.9	0.51	0.22	2046.3	14.9
110 <sup>a</sup>	SS	2158.7	245.3	0.21		2059.4	15.5
	as	2145.9	1442.6	0.52	0.17	2046.3	15.1
120 a	SS	2158.4	189.5	0.19		2047.8	15.5
	as	2146.3	1486.2	0.53	0.13	2036.1	14.9
150 a	SS	2157.7	50.4	0.10		2037.8	15.5
	as	2147.3	1613.8	0.55	0.03	2027.8	15.0
180 a	SS	2157.3	0.0	0			
	as	2146.9	1691.7	0.56	0.0		
104 <sup>b</sup>	SS	2158.6	276.9	0.22		2058.5	15.3
	as	2145.6	1418.2	0.51	0.2	2045.7	14.9
106 <sup>b,c</sup>	SS	2235.4	296.1	0.23		2140.0	14.5
	as	2221.0	1455.9	0.51	0.20	2126.2	14.3
104 <sup>b,d</sup>	SS	2233.5	304.7	0.23		2136.8	14.6
	as	2218.6	1445.7	0.51	0.21	2122.4	14.1
	N <sub>3</sub> - as <sup>e</sup>	2096.0					26.0

<sup>a</sup> Fixed dihedral angle (defined in Fig. S2).

<sup>b</sup> Optimized dihedral angle, whose IR spectral signature is given in Fig. S1.

<sup>c</sup> Results obtained using the PBE1PBE functional with the SDD basis set for Pt atom.

<sup>d</sup> Results obtained using the PBE1PBE functional with the Lanl2dz basis set for Pt atom.

<sup>e</sup> Experimentally determined values from a previous work.<sup>2</sup>

### S2. Potential energy distributions analysis at the level of DFT using the B3LYP functional

$\omega$ / cm <sup>-1</sup>	I / km·mol <sup>-1</sup>	PED <sup>a</sup> / %			
2158.6	276.9	N <sub>7</sub> N <sub>8</sub> s (23), N <sub>11</sub> N <sub>10</sub> s (23), N <sub>7</sub> N <sub>6</sub> s (18), N <sub>10</sub> N <sub>9</sub> s (18)			
2145.6	1418.2	N <sub>7</sub> N <sub>8</sub> s (24), N <sub>11</sub> N <sub>10</sub> s (24), N <sub>7</sub> N <sub>6</sub> s (18), N <sub>10</sub> N <sub>9</sub> s (18)			
1332.7	17.7	N <sub>7</sub> N <sub>8</sub> s (6), N <sub>11</sub> N <sub>10</sub> s (6), N <sub>7</sub> N <sub>6</sub> s (15),			
		N <sub>10</sub> N <sub>9</sub> s (15), Pt <sub>1</sub> N <sub>9</sub> s (6), Pt <sub>1</sub> N <sub>6</sub> s (6),			
1325.1	205.4	N <sub>7</sub> N <sub>6</sub> s (11), N <sub>10</sub> N <sub>9</sub> s (11)			
1029.7	16.8	$H_{14}C_{13}C_{15}H_{16} t (8), H_{20}C_{19}C_{21}H_{22} t (8),$			
		$H_{16}C_{15}C_{17}H_{18} t (9), H_{18}C_{17}C_{19}H_{20} t (9)$			
1025.3	99.1	$H_{3}O_{2}Pt_{1} b (12), H_{5}O_{4}Pt_{1} b (12), H_{18}C_{17}C_{19}C_{21} t (8)$			
		H <sub>14</sub> C <sub>13</sub> C <sub>15</sub> H <sub>16</sub> t (6), H <sub>16</sub> C <sub>15</sub> C <sub>17</sub> H <sub>18</sub> t (9),			
		$H_{18}C_{17}C_{19}H_{20} t (9), H_{20}C_{19}C_{21}H_{22} t (6)$			
687.6	3.7	Pt <sub>1</sub> N <sub>9</sub> s (8), Pt <sub>1</sub> N <sub>6</sub> s (8), Pt <sub>1</sub> N <sub>9</sub> s (6), Pt <sub>1</sub> N <sub>6</sub> N <sub>7</sub> b (9),			
		Pt <sub>1</sub> N <sub>9</sub> N <sub>10</sub> b (9), Pt <sub>1</sub> N <sub>8</sub> N <sub>7</sub> N <sub>6</sub> lb (13), Pt <sub>1</sub> N <sub>11</sub> N <sub>10</sub> N <sub>9</sub> lb (13),			
679.1	1.3	Pt <sub>1</sub> N <sub>9</sub> s (6), Pt <sub>1</sub> N <sub>6</sub> s (6), Pt <sub>1</sub> N <sub>9</sub> s (6), Pt <sub>1</sub> N <sub>6</sub> N <sub>7</sub> b (8),			
		Pt <sub>1</sub> N <sub>9</sub> N <sub>10</sub> b (8), Pt <sub>1</sub> N <sub>8</sub> N <sub>7</sub> N <sub>6</sub> lb (12), Pt <sub>1</sub> N <sub>11</sub> N <sub>10</sub> N <sub>9</sub> lb (12),			
588.0	6.7	$Pt_1N_8N_7N_6$ lb (16), $Pt_1N_{11}N_{10}N_9$ lb (16), $N_{12}Pt_1N_6N_7$ t (6),			
		$O_2Pt_1N_9N_{10} t (6), O_4Pt_1N_9N_{10} t (6), N_{12}Pt_1N_9N_{10} t (6),$			
		$N_{23}Pt_1N_9N_{10} t (6), O_2Pt_1N_6N_7 t (6), O_4Pt_1N_6N_7 t (6),$			
		$N_{23}Pt_1N_6N_7 t$ (6), $N_{10}N_9N_6N_7 t$ (11)			
585.6	1.2	$Pt_1N_8N_7N_6$ lb (18), $Pt_1N_{11}N_{10}N_9$ lb (18), $N_{12}Pt_1N_6N_7$ t (6),			
		$O_2Pt_1N_9N_{10} t (6), O_4Pt_1N_9N_{10} t (6), N_{12}Pt_1N_9N_{10} t (6),$			
		$N_{23}Pt_1N_9N_{10} t (6), O_2Pt_1N_6N_7 t (6), O_4Pt_1N_6N_7 t (6),$			
		$N_{23}Pt_1N_6N_7 t$ (6)			
374.8	61.5	$Pt_1N_9 s (13), Pt_1N_6 s (13), Pt_1N_8N_7N_6 lb (5), Pt_1N_{11}N_{10}N_9 lb (5)$			
24.8	1.4	$O_2Pt_1N_9N_{10} t (6), O_4Pt_1N_9N_{10} t (6), N_{12}Pt_1N_9N_{10} t (6),$			
		$N_{23}Pt_1N_9N_{10} t$ (6), $O_2Pt_1N_6N_7 t$ (6), $O_4Pt_1N_6N_7 t$ (6),			
		$N_{12}Pt_1N_6N_7 t$ (6), $N_{23}Pt_1N_6N_7 t$ (6), $N_{10}N_9N_6N_7 t$ (11)			
23.2	1.1	$O_2Pt_1N_9N_{10} t (11), O_4Pt_1N_9N_{10} t (11), N_{12}Pt_1N_9N_{10} t (11),$			
		$N_{23}Pt_1N_9N_{10} t (11), O_2Pt_1N_6N_7 t (11), O_4Pt_1N_6N_7 t (11),$			
		$N_{12}Pt_1N_6N_7t(11), N_{23}Pt_1N_6N_7t(11)$			

**Table S2** Harmonic vibrational transition frequency ( $\omega$ ), transition intensity (I), and potential energy distributions (PEDs) of certain normal modes of *trans, trans, trans*-[Pt(N<sub>3</sub>)<sub>2</sub>(OH)<sub>2</sub>(py)<sub>2</sub>].

<sup>a</sup> PED analysis is computed on the basis of local modes whose contributions are listed in parentheses, with only  $\geq$  5 % considered. 's' is short for stretching, 'b' is for bending, 'lb' is for linear bending, 'o' for out-of-plane, and 't' for twisting. The atomic labelings are shown in the middle of Fig. S2.

#### S3. Additional kinetic fittings to the IR pump-probe signal



**Fig. S3** Kinetic traces and their corresponding fittings of the N<sub>3</sub> stretching mode in *trans, trans, trans*, *trans*-[Pt(N<sub>3</sub>)<sub>2</sub>(OH)<sub>2</sub>(py)<sub>2</sub>] at  $\omega_{probe} = 2010 \text{ cm}^{-1}$ , 2019 cm<sup>-1</sup> and 2044 cm<sup>-1</sup> in H<sub>2</sub>O (upper panel) and  $\omega_{probe} = 2001 \text{ cm}^{-1}$ , 2009 cm<sup>-1</sup>, 2028 cm<sup>-1</sup> and 2044 cm<sup>-1</sup> in DMSO (lower panel). The  $\omega_{probe}$  frequency positions for the absorption in both solvents were given in Fig. 2A and 2B as red dashed lines, the  $\omega_{probe}$  frequency positions for the bleach of the as mode in H<sub>2</sub>O and DMSO were given in Fig. 2A and 2B as blue dashed lines, and the  $\omega_{probe}$  frequency position for the bleach of the ss mode in DMSO was given in Fig. 2B as gray dashed line.

#### **S4.** Solute-solvent interaction



**Fig. S4** A: FTIR spectra of pure  $H_2O$  (purple curve) and  $D_2O$  (yellow curve), and *trans, trans, trans*-[Pt(N<sub>3</sub>)<sub>2</sub>(OH)<sub>2</sub>(py)<sub>2</sub>] solvated in  $H_2O$  (red curve) and  $D_2O$  (green curve) without solvent background subtracted; B: intensity normalized FTIR spectra of the [Pt(N<sub>3</sub>)<sub>2</sub>(OH)<sub>2</sub>(py)<sub>2</sub>] complex in  $H_2O$  (red curve) and  $D_2O$  (green curve), both with solvent background subtracted.

The FTIR spectra of the {Pt(N<sub>3</sub>)<sub>2</sub>} complex in H<sub>2</sub>O and D<sub>2</sub>O with solvent background subtracted are given in Fig. S4. It is clear that the difference between the absorption band in D<sub>2</sub>O and H<sub>2</sub>O is very small with the latter shifted *ca*. 1.4 cm<sup>-1</sup> to the blue side. This may be because the solute-solvent intermolecular hydrogen bond is stronger in H<sub>2</sub>O than that in D<sub>2</sub>O. It is also observed that the linewidth of the N<sub>3</sub> stretching mode in somewhat narrower in D<sub>2</sub>O (FWHM = 12.9 cm<sup>-1</sup>) than that in H<sub>2</sub>O (FWHM = 14.3 cm<sup>-1</sup>). Further study is needed to understand these spectral differences.



**Fig. S5** Illustrations of solvent-solute interaction of *trans, trans, trans*- $[Pt(N_3)_2(OH)_2(py)_2]$  in DMSO (left) and in water (right). For simplification, only one solvent molecule is shown in each case.

S5. Anharmonicity determination from 2D IR spectral slices and transient IR pump-probe spectrum at 15-ps delay time



**Fig. S6** Slices of 2D IR spectra at  $\omega_{\tau} = 2048 \text{ cm}^{-1}$  of *trans, trans, trans*-[Pt(N<sub>3</sub>)<sub>2</sub>(OH)<sub>2</sub>(py)<sub>2</sub>] in DMSO and their fittings along the  $\omega_t$  axis at dynamical times of T = 0.5 ps (A), 3.0 ps (B), 6.0 ps (C) and 15.0 ps (D) respectively, and the transient pump-probe signal and its fitting at delay time of 15 ps (E) in the range of 1980 - 2060 cm<sup>-1</sup>. The obtained diagonal anharmonicities of the N<sub>3</sub> ss mode in this Pt-N<sub>3</sub> complex are marked in red and the apparent off-diagonal-anharmonicities are marked in blue. As can be seen, the apparent off-diagonal-anharmonicity decreases as dynamical time increases.

Solvent	$T/\mathrm{ps}$	$\omega_{ex}$ / cm <sup>-1</sup>	$\omega$ / cm <sup>-1</sup>	$\Delta_{diag.}$ / cm <sup>-1</sup>	$\Delta'_{\rm off\text{-}diag.}$ / cm <sup>-1</sup>
	0.2	2044.0	2044.5		
			2022.8	21.7	
ЧО	0.7	2044.0	2044.7		
1120			2022.4	22.3	
	2.0	2044.0	2044.9		
			2023.8	21.1	
	0.5	2028.0	2027.2		
			2007.2	20.0	
	0.5		2045.3		
		2048.0	2035.3	10.0	
			2025.2		
			2003.3		21.9
			2045.0		
		2048.0	2035.3	9.7	
	3.0		2026.6		
			2007.6		19.0
DMCO			2045.5		
DMSO	6.0	2048.0	2035.5	10.0	
			2027.2		
			2012.0		15.2
			2046.2		
	15.0	2048.0	2035.7	10.5	
			2028.4		
			2018.5		9.9

**Table S3** A summary of diagonal anharmonicity ( $\Delta_{\text{diag.}}$ ) and apparent off-diagonal anharmonicity ( $\Delta'_{\text{off-diag.}}$ ), peak position ( $\omega$ ) and excitation frequency ( $\omega_{\text{ex}}$ ) by fitting 2D IR slices at different dynamical times (*T*) in H<sub>2</sub>O and DMSO respectively.

#### **S6. References**

1. N. J. Farrer, J. A. Woods, L. Salassa, Y. Zhao, K. S. Robinson, G. Clarkson, F. S. Mackay and P. J. Sadler, *Angew. Chem. Int. Edit.*, 2010, **49**, 8905-8908.

2. E. C. Fulmer, F. Ding and M. T. Zanni, J. Chem. Phys., 2005, 122, 034302.

3. J. P. Perdew, K. Burke and M. Ernzerhof, Phys. Rev. Lett., 1996, 77, 3865-3868.

4. J. P. Perdew, S. Kurth, A. Zupan and P. Blaha, *Phys. Rev. Lett.*, 1999, **82**, 2544-2547.

5. H. Gao, X. Wei, X. Liu and C. Huang, *Spectrochim. Acta, Part A*, 2010, **77**, 461-465.