

Geometry-wave potential quantified and unified properties in general chemistry

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In the thermodynamics- and quantum mechanics (QM)-pillared general chemistry, many size-dependent properties of particles (i.e. atoms, ions, molecules, and nanoparticles or NPs) haven't been quantitatively described, predicted, and unified to date. This work has introduced a geometry-wave potential to geometrically describe, quantitatively predict, and consistently unify these properties to complement the thermodynamics and QM. These properties include the inter-NP bonding strength, the NPs self-assembly spontaneity, and the reactivity of particles of all charges and geometries, macromolecules of fold and unfold, and defects of all sizes at all sites.

For example, if predicting a spontaneous self-assembly from 64 of 2-nm Au-NPs to an 8-nm NP, either directly (*Route-A*) or stepwise (*Routes B + C*) (**Fig. 1a**), each route's Gibbs free energy change¹ $\Delta G < 0$, presumably per the ΔG 's definition. However, the thermodynamics has never quantitatively defined NPs' formation enthalpy (ΔH_f), entropy (ΔS_f), and ΔG_f ($\approx \Delta H_f - T\Delta S_f$), leaving the NPs self-assemblies²⁻⁷ never quantified and/or predicted. To solve this longstanding problem and complement the thermodynamics, let's quantize the zero-dimensional (0D), 1D-, 2D-, and 3D-particles' Surface Area-to-Volume (SA/V) ratio {in the unit of (length⁻¹) } (see the **Extended Data Table S1**) into a geometry-wave (GW)-based wavenumber ($\tilde{\nu}_{GW}$) of the same unit. Thus, at $T = 298.15$ (°K) and 1 (atm), the $\tilde{\nu}_{GW}$ -based GW-potential $\mu_f^o_{GW} = hc \cdot \tilde{\nu}_{GW}$, where the c = speed of light, h = Planck constant, and $hc \approx 1.24$ (keV·nm). Accordingly,

- $\Delta\mu_f^o_{GW(\text{Route-A})} = \mu_f^o_{GW(8\text{nm-NP})} - 64\mu_f^o_{GW(2\text{nm-NPs})} = \{6/8 - 64(6/2)\}hc = -237.2$ (keV),

- $\Delta\mu_{f\text{GW}}^0(\text{Route-B}) = 8\mu_{f\text{GW}}^0(4\text{nm-NPs}) - 64\mu_{f\text{GW}}^0(2\text{nm-NPs}) = \{8(6/4) - 64(6/2)\}\hbar c = -223.2 \text{ (keV)},$
- $\Delta\mu_{f\text{GW}}^0(\text{Route-C}) = \mu_{f\text{GW}}^0(8\text{nm-NP}) - 8\mu_{f\text{GW}}^0(4\text{nm-NPs}) = \{6/8 - 8(6/4)\}\hbar c = -14.0 \text{ (keV)},$
- $\Delta\mu_{f\text{GW}}^0(\text{Route-A}) = \Delta\mu_{f\text{GW}}^0(\text{Route-B}) + \Delta\mu_{f\text{GW}}^0(\text{Route-C}),$ proving that the $\Delta\mu_{f\text{GW}}^0$ is a state function.

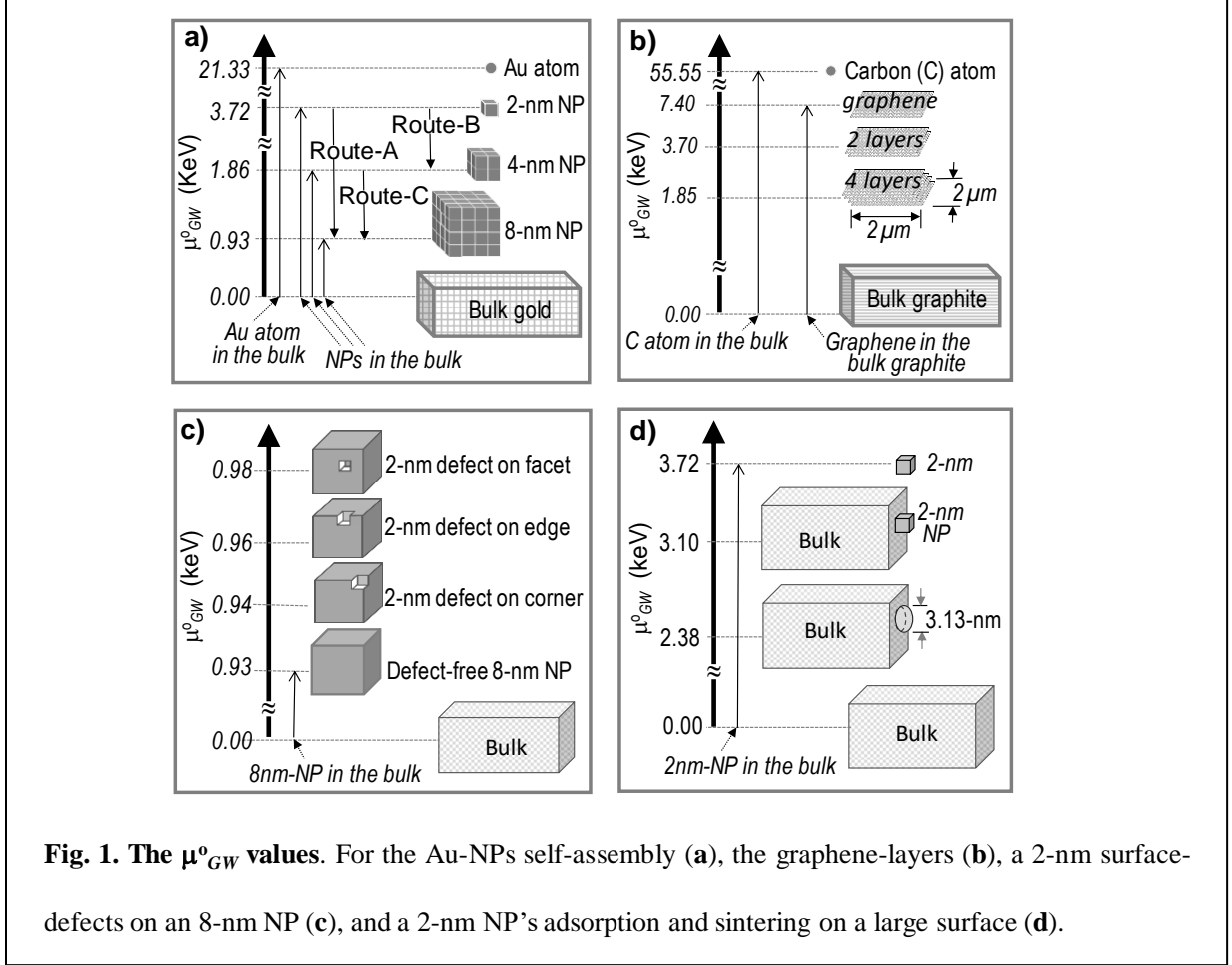


Fig. 1. The $\mu_{f\text{GW}}^0$ values. For the Au-NPs self-assembly (a), the graphene-layers (b), a 2-nm surface-defects on an 8-nm NP (c), and a 2-nm NP's adsorption and sintering on a large surface (d).

Therefore, the reduction of every NP's $\mu_{f\text{GW}}^0$ in the hierarchical self-assembly bonding (see the **Extended Data Table S2a**) is quantifiable:

- $\Delta\mu_{f\text{GW}}^0(2\text{nm-NP in } 8\text{nm-NP}) = \Delta\mu_{f\text{GW}}^0(\text{Route-A})/64 = -3.71 \text{ (keV)} = -(99.73\% \cdot \mu_{f\text{GW}}^0(2\text{nm-NP})),$
- $\Delta\mu_{f\text{GW}}^0(2\text{nm-NP in } 4\text{nm-NP}) = \Delta\mu_{f\text{GW}}^0(\text{Route-B})/64 = -3.49 \text{ (keV)} = -(96.16\% \cdot \mu_{f\text{GW}}^0(2\text{nm-NP})),$
- $\Delta\Delta\mu_{f\text{GW}}^0(4\text{nm-NP in } 8\text{nm-NP}) = \Delta\mu_{f\text{GW}}^0(\text{Route-C})/8 = -1.75 \text{ (keV)} = -(94.09\% \cdot \mu_{f\text{GW}}^0(4\text{nm-NP})).$

These have concluded the larger NPs' inter-bonding weaker than smaller NPs' depending only on NPs' geometry and regardless NPs' chemical composition, and every NP's $\mu_{f\text{GW}}^0$ -decrease near

100% in the bulk since $\tilde{v}_{GW(bulk)}^o = 0$ i.e. $\mu_{f_{GW(bulk)}}^o = 0$. This hierarchical bonding, driven by minimizations of smaller particles higher $\mu_{f_{GW}}^o$ which is generalizable to all-scales' self-assemblies²⁻⁷, can help expand the classic Chemical Bonding Theory⁸.

Assuming the $\Delta H_{f_{GW}}^o \ll \Delta \mu_{f_{GW}}^o$, then the $\Delta S_{f_{GW(environment)}}^o = -\Delta H_{f_{GW}}^o/T \approx 0$, and $\Delta S_{f_{GW}}^o \approx -\Delta \mu_{f_{GW}}^o/T > 0$. This can help quantitatively predict the $S_{f_{GW}}^o$ and $\mu_{f_{GW}}^o$ (see the **Extended Data Table S1**) and complement the Boltzmann entropy-based thermodynamics. For one mole of the 8-nm NPs at $T = 298$ (°K), for example, their $\mu_{mf_{GW(8nm-AuNP)}}^o = 0.93$ (keV/NP) $\times (6.023 \times 10^{23})$ (NP/mole) $\times (1.60 \times 10^{-19})$ (kJ/keV) $\approx 8.96 \times 10^4$ (kJ/mole), and the $S_{mf_{GW(8nm-AuNP)}}^o = -\mu_{mf_{GW(8nm-AuNP)}}^o/298 \approx -3.01 \times 10^5$ (J/K·mole).

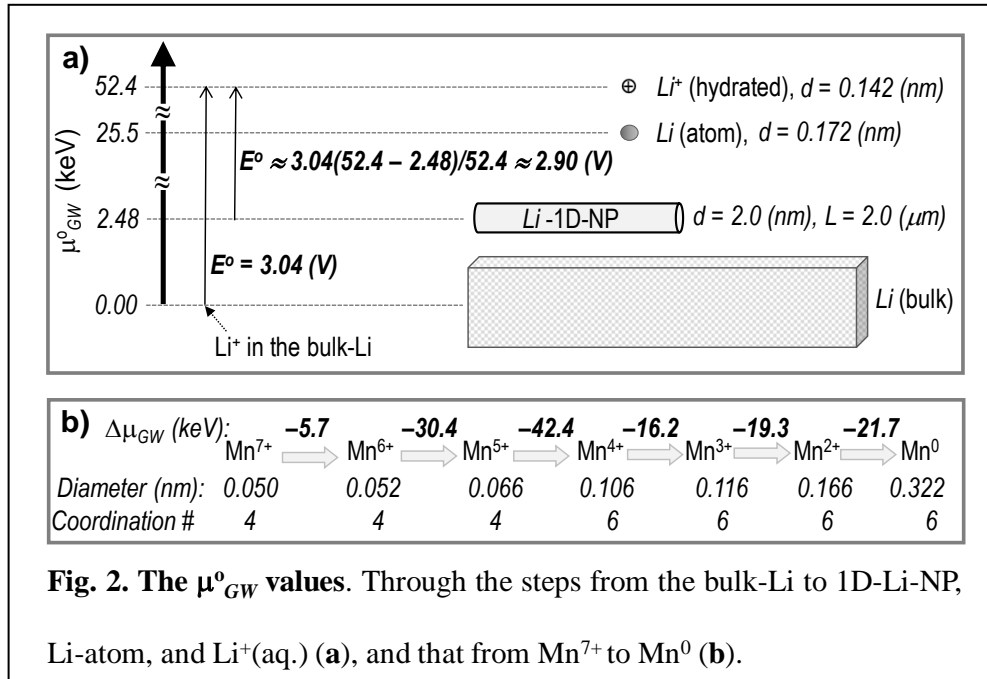
If folding a 150-nm long 1D-polyethylene (PE) to an 8-nm NP (or backward unfolding), given the $d_{(ethylene)} \approx 0.390$ (nm)⁹, the $\Delta \mu_{f_{GW(Folding)}}^o = \mu_{f_{GW(0D-PE-NP)}}^o - \mu_{f_{GW(1D-PE-oligomer)}}^o \approx (6/8)hc - (4/0.390)hc = -11.78$ (keV) $= -\Delta \mu_{f_{GW(Unfolding)}}^o$. This helps generalize all thinner 1D-NP's greater $\mu_{f_{GW}}^o$ (see the **Extended Data Table S1**) in quantifying macromolecules' chemical bonding, like that in the **Extended Data Table S2a**.

Given the $\Delta \mu_{f_{GW(bulk\ graphite)}}^o = 0$ and $d_{(C-atom)} \approx 0.134$ (nm)¹⁰, the $\mu_{f_{GW}}^o$ (see the **Extended Data Table S2b**) can help characterize large graphenes of different layers (~ 0.335 nm/layer) (**Fig. 1b**). The **Fig. 1b** can help quantify all thinner 2D-materials' higher $\mu_{f_{GW}}^o$ generally.

On an 8nm-NP, the $\mu_{f_{GW}}^o$ values of 2.0 nm-sized surface defects (see the **Extended Data Table S2c**) are facet-defect's > edge-defect's > corner-defect's (**Fig. 1c**). This in turn indicates that smaller defects' higher reactivity follows the order of facet's > edge's > corner's. On a bulk flat surface, the 2.0 nm-sized NP's spontaneous adsorption and then "sintering" (see the **Extended**

Data Table S2d) to a hemisphere are characterizable (**Fig. 1d**). This can help quantitatively predict the $\mu_{f\text{GW}}^{\circ}$ in both Surface Chemistry and Catalytic Chemistry.

In Li-ion batteries, the electrochemically hard-to-measuring¹¹ reduction potential between a $\text{Li}^+(\text{aq.})$ ¹² and a 2- μm -long, 2-nm-thick Li-1D-NP electrode (**Fig. 2a**) is estimable, e.g. $E^{\circ}_{(\text{cation-to-NP})} = E^{\circ}_{(\text{cation-to-bulk})} \cdot (\mu_{f\text{GW}}^{\circ}(\text{cation}) - \mu_{f\text{GW}}^{\circ}(\text{NP})) / \mu_{f\text{GW}}^{\circ}(\text{cation}) \approx -2.90$ (V) (see the **Extended Data Table S2e**). This helps quantify the $\Delta\mu_{f\text{GW}}^{\circ}$ -based changes (**Fig. 2b**) between NPs, atoms, and ions (see the **Extended Data Tables S2f&S3**) generally for expanding the Electrochemistry, Redox Chemistry, and Lewis Acid-Base Chemistry.



The **Extended Data Table S1** further supports a $\mu_{f\text{GW}}^{\circ}$ -based generalizable nomenclature, “ $\tilde{\nu}_{\text{GW}}$ -(point-group)-composition”, for distinguishing NPs-involved compounds geometrically. For example, an 1.5-nm PbS-0D-NP can be thus-labeled as (6/1.5)-(R₃)-PbS, a 10-nm 0D-ZnSe-NP as (6/10)-(R₃)-ZnSe, their one-on-one compound as (6/1.5)-(R₃)-PbS•(6/10)-(R₃)-ZnSe, and the 1.5-nm PbS-0D-NPs’ linear 100mer as 1D-{(6/1.5)-(D_{∞d})-PbS}₁₀₀, specifically.

In conclusion, the thermodynamics- and QM-complemented $\mu_{f,GW}^{\circ}$ enables us to geometrically characterize, quantitatively predict, and consistently unify the particles' geometry-quantized properties including the hierarchical self-assembly bonding, folding–unfolding, redox activity, and surface defects reactivity. All atoms' EN-complementary periodicity (**Extended Data Table S4**), generally expandable to ions and NPs (**Extended Data Tables S1&S3**), have supported further developments of new theories in basic chemistry¹⁴, which should be discussed separately.

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EXTENDED DATA.




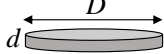
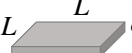



I. Extended Data Tables S1–S3.

The geometry-wave potential quantified and unified properties in general chemistry

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I. Extended Data Tables.

1). Extended Data Table S1.

Table S1. Simple-Shape Particles' \tilde{v}_{GW} and Point Group (Symmetry)					
	Shape	Surface-Area (SA)	Volume (V)	$\tilde{v}_{GW}(= SA/V)$	Point Group
0D	 d	πd^2	$\pi d^3/6$	$(6/d)^*$	R_3
1D	 L d	$4dL + 2d^2$	d^2L	$(4/d + 2/L)^{**}$ or $(4/d)^{**}$ if $d \ll L$	D_{2d}
	 L d	$\pi d^2/2 + \pi dL$	$\pi d^2L/4$	$(4/d + 2/L)^{**}$ or $(4/d)^{**}$ if $d \ll L$	$D_{\infty d}$
2D	 D d	$\pi D^2/2 + d\pi D$	$d\pi D^2/4$	$2/d + 4/D;$ or $2/d$ if $d \ll D$	$D_{\infty d}$
	 L L d	$2(aL + aL + L^2)$	aL^2	$2/d + 2/L + 2/L;$ or $2/d$ if $d \ll L$	D_{4d}
3D	 d	$6d^2$	d^3	$(6/d)^*$	O_h
	 d	$2 \times 3^{1/2}d^2$	$2^{1/2}d^3/3$	$3 \times 6^{1/2}/d$	O_h
	 d	$1.732d^2$	$0.118d^3$	$14.678/d$	T_d

*The spherical and cubic particles share the same \tilde{v}_{GW} formula;
 **The two 1D-particles share the same \tilde{v}_{GW} formula.

2). Extended Data Table S2.

Table S2. Calculations of the μ_{GW}^0

a) $\mu_{GW(\text{Au-atom})}^0 = (17.2)hc = 21.33 \text{ (keV)}$,
 $\mu_{GW(2\text{nm-AuNP})}^0 = (6/2)hc = 3.72 \text{ (keV)}$,
 $\mu_{GW(4\text{nm-AuNP})}^0 = (6/4)hc = 1.86 \text{ (keV)}$,
 $\mu_{GW(8\text{nm-AuNP})}^0 = (6/8)hc = 0.93 \text{ (keV)}$.

b) $\mu_{GW(\text{C-atom})}^0 = (44.8)hc = 55.55 \text{ (keV)}$,
 $\mu_{GW(1\text{-layer graphene})}^0 = hc\{2/(1 \times 0.335)\} = 7.40$,
 $\mu_{GW(2\text{-layer graphene})}^0 = hc\{2/(2 \times 0.335)\} = 3.70 \text{ (keV)}$,
 $\mu_{GW(4\text{-layer graphene})}^0 = hc\{2/(4 \times 0.335)\} = 1.85 \text{ (keV)}$.

c) $\mu_{GW(\text{facet-defect})}^0 = hc\{(SA/V)_{(2\text{-nm defect on 8-nm NP})}\} = hc\{(4 \times 2^2 + 6 \times 8^2)/(8^3 - 2^3)\} = hc\{(4 \times 2^2 + 384)/504\} = 0.98 \text{ (keV)}$,
 $\mu_{GW(\text{edge-defect})}^0 = hc\{(2 \times 2^2 + 384)/504\} = 0.96 \text{ (keV)}$,
 $\mu_{GW(\text{corner-defect})}^0 = hc\{384/504 - 17.2\} = 0.94 \text{ (keV)}$.

d) $\mu_{GW(2\text{nm-NP-on-large flat surface})}^0 = hc\{(5 \times 2^2)/8\} = 3.10 \text{ (keV)}$,
 $\mu_{GW(\text{hemisphere-on-large flat surface})}^0 = hc\{(\pi d^2)/(\pi d^3/6)\} \approx hc(6/d) = hc(6/3.13) = 2.38 \text{ (keV)}$.

e) $\mu_{GW(\text{Li (I) hydrated cation})}^0 = hc(SA/V)_{\text{hydrated-Li-(I)-cation}} = hc(6/0.142) = 52.4 \text{ (keV)}$,
 $\mu_{GW(\text{Li atom})}^0 = hc(SA/V)_{\text{Li-atom}} = hc(20.6) = 25.5 \text{ (keV)}$,
 $\mu_{GW(\text{Li-1D-NP})}^0 \approx hc(4/d) = hc(4/2) = 2.48 \text{ (keV)}$.

f) $\mu_{GW(\text{Mn(VII)})}^0 = hc(6/0.050) = 148.8 \text{ (keV)}$,
 $\mu_{GW(\text{Mn(VI)})}^0 = hc(6/0.052) = 143.1 \text{ (keV)}$,
 $\mu_{GW(\text{Mn(V)})}^0 = hc(6/0.066) = 112.7 \text{ (keV)}$,
 $\mu_{GW(\text{Mn(IV)})}^0 = hc(6/0.106) = 70.3 \text{ (keV)}$,
 $\mu_{GW(\text{Mn(III)})}^0 = hc(6/0.116) = 64.1 \text{ (keV)}$,
 $\mu_{GW(\text{Mn(II)})}^0 = hc(6/0.166) = 44.8 \text{ (keV)}$,
 $\mu_{GW(\text{Mn(0)})}^0 = hc(6/0.322) = 23.1 \text{ (keV)}$

3). Extended Data Table S3.

Table S3. Hydrated monoatomic ions' $\tilde{\nu}_{GW}$ values

ions	C.N.*	d/2 (nm)	6/d (nm ⁻¹)	ions	C.N.	d/2 (nm)	6/d (nm ⁻¹)	ions	C.N.	d/2 (nm)	6/d (nm ⁻¹)
F ⁻	6	0.133	22.6	Br ⁺⁷	4	0.025	120	Fe ⁺²	4	0.063	47.6
Cl ⁻	6	0.181	16.6		6	0.039	76.9		6	0.061	49.2
Br ⁻	6	0.196	15.3	C ⁺⁴	4	0.015	200		8	0.092	32.6
I ⁻	6	0.22	13.6		6	0.016	187.5	Fe ⁺³	4	0.049	61.2
OH ⁻	4	0.135	22.2	Ca ⁺²	6	0.1	30.0		6	0.055	54.5
	6	0.137	21.9		8	0.112	26.8		8	0.078	38.5
O ⁻²	2	0.12	25.0		10	0.123	24.4	Ga ⁺³	4	0.047	63.8
	6	0.14	21.4		12	0.134	22.4		6	0.062	48.4
	8	0.142	21.1	Cd ⁺²	4	0.078	38.5	Ge ⁺²	6	0.073	41.1
S ⁻²	6	0.184	16.3		6	0.095	31.6	Ge ⁺⁴	4	0.039	76.9
Se ⁻²	6	0.198	15.2		8	0.11	27.3		6	0.053	56.6
Te ⁻²	6	0.221	13.6		12	0.131	22.9	Hf ⁺⁴	4	0.058	51.7
				Ce ⁺³	6	0.101	29.7		6	0.071	42.3
Ac ⁺³	6	0.112	26.8		8	0.114	26.3		8	0.083	36.1
Ag ⁺¹	4	0.1	30.0		10	0.125	24.0	Hg ⁺¹	6	0.119	25.2
	6	0.115	26.8		12	0.134	22.4	Hg ⁺²	2	0.069	43.5
	8	0.128	23.4	Ce ⁺⁴	6	0.087	34.5		4	0.096	31.3
Ag ⁺²	4	0.079	38.0		8	0.097	30.9		6	0.102	29.4
	6	0.094	31.9		10	0.107	28.0		8	0.114	26.3
Al ⁺³	4	0.039	76.9		12	0.114	26.3	I ⁺⁵	3	0.044	68.2
	5	0.048	62.5	Cl ⁺⁵	3	0.095	31.6		6	0.095	31.6
	6	0.054	55.6	Cl ⁺⁷	4	0.082	36.6	I ⁺⁷	4	0.042	71.4
Am ⁺³	6	0.098	30.6	Co ⁺²	4	0.056	53.6		6	0.053	56.6
	8	0.109	27.5		6	0.065	46.2	In ⁺³	4	0.062	48.4
Am ⁺⁴	6	0.085	35.3		8	0.09	33.3		6	0.080	37.5
	8	0.095	31.6	Co ⁺³	6	0.055	54.5	Ir ⁺³	6	0.068	44.1
As ⁺³	6	0.058	51.7	Cr ⁺²	6	0.073	41.1	Ir ⁺⁴	6	0.063	47.6
As ⁺⁵	4	0.034	88.2	Cr ⁺³	6	0.062	48.4	Ir ⁺⁵	6	0.057	52.6
	6	0.046	65.2	Cr ⁺⁴	4	0.041	73.2	K ⁺¹	4	0.137	21.9
Au ⁺¹	6	0.137	21.9		6	0.055	54.5		6	0.138	21.7
Au ⁺³	4	0.064	46.9	Cr ⁺⁶	4	0.026	115.4		8	0.151	19.9
	6	0.085	35.3		6	0.044	68.2		12	0.164	18.3
Ba ⁺²	6	0.135	22.2	Cs ⁺¹	6	0.167	18.0	La ⁺³	6	0.103	29.1
	8	0.142	21.1		8	0.174	17.2		8	0.116	25.9
	12	0.161	18.6		10	0.181	16.6		10	0.127	23.6
Be ⁺²	4	0.027	111.1		12	0.188	16.0		12	0.136	22.1
	6	0.045	66.7	Cu ⁺¹	2	0.046	65.2	Li ⁺¹	4	0.059	50.8
Bi ⁺³	5	0.096	1.25		4	0.06	50.0		6	0.076	39.5
	6	0.103	29.1		6	0.077	39.0		8	0.092	32.6
	8	0.117	25.6	Cu ⁺²	4	0.057	52.6	Mg ⁺²	4	0.057	52.6
Bi ⁺⁵	6	0.076	39.5		6	0.073	41.1		6	0.072	41.7
Br ⁺⁵	3	0.031	96.8	F ⁺⁷	6	0.008	375.0		8	0.089	33.7

*C.N.: Coordination Number

3). Extended Data Table S3 (continued).

Table S3. Hydrated monoatomic ions' $\tilde{\nu}_{GW}$ values (continued)											
ions	C.N.	d/2 (nm)	6/d (nm ⁻¹)	ions	C.N.	d/2 (nm)	6/d (nm ⁻¹)	ions	C.N.	d/2 (nm)	6/d (nm ⁻¹)
Mn ⁺²	4	0.066	45.5	Pb ⁺⁴	4	0.065	46.2	Sr ⁺²	6	0.118	255.4
	6	0.083	36.1		6	0.078	38.5		8	0.126	23.8
	8	0.096	31.3		8	0.094	31.9		10	0.136	22.1
Mn ⁺³	6	0.058	51.7	Pd ⁺²	4	0.064	46.9		12	0.144	20.8
Mn ⁺⁴	4	0.039	76.9		6	0.086	34.9	Ta ⁺³	6	0.072	41.7
	6	0.053	56.6	Pd ⁺³	6	0.076	39.5	Ta ⁺⁴	6	0.068	44.1
Mn ⁺⁵	4	0.033	90.9	Pd ⁺⁴	6	0.062	48.4	Ta ⁺⁵	6	0.064	46.9
Mn ⁺⁶	4	0.026	115.4	Pt ⁺²	4	0.06	50.0	Tc ⁺⁴	6	0.065	46.2
Mn ⁺⁷	4	0.025	120.0		6	0.08	37.5	Ti ⁺²	6	0.086	34.9
Mo ⁺³	6	0.069	43.5	Pt ⁺⁴	6	0.063	47.6	Ti ⁺³	6	0.067	44.8
Mo ⁺⁴	6	0.065	46.2	Rb ⁺¹	6	0.152	19.7	Ti ⁺⁴	4	0.042	71.4
Mo ⁺⁵	4	0.046	65.2		8	0.161	18.6		6	0.061	49.2
	6	0.061	49.2		10	0.166	18.1		8	0.074	40.5
Mo ⁺⁶	4	0.041	73.2		12	0.172	17.4	Tl ⁺¹	6	0.15	20.0
	6	0.059	50.8	Re ⁺⁴	6	0.063	47.6		8	0.159	18.9
	7	0.073	41.1	Re ⁺⁵	6	0.058	51.7		12	0.17	17.6
N ⁺³	6	0.016	187.5	Re ⁺⁶	6	0.055	54.5	Tl ⁺³	4	0.075	40.0
N ⁺⁵	6	0.013	230.8	Re ⁺⁷	4	0.038	78.9		6	0.089	33.7
Na ⁺¹	4	0.099	30.3		6	0.053	56.6		8	0.098	30.6
	6	0.102	29.4	Rh ⁺³	6	0.067	44.8	V ⁺²	6	0.079	38.0
	8	0.118	25.4	Rh ⁺⁴	6	0.06	50.0	V ⁺³	6	0.064	46.9
	9	0.124	24.2	Rh ⁺⁵	6	0.055	54.5	V ⁺⁴	5	0.053	56.6
	12	0.13	23.1	Ru ⁺³	6	0.068	44.1		6	0.058	51.7
Nb ⁺³	6	0.072	41.7	Ru ⁺⁴	6	0.062	48.4		8	0.072	41.7
	8	0.079	38.0	Ru ⁺⁵	6	0.057	52.6	V ⁺⁵	4	0.042	71.4
Nb ⁺⁴	6	0.068	44.1	Ru ⁺⁷	4	0.038	78.9		5	0.051	58.8
Nb ⁺⁵	4	0.048	62.5	Ru ⁺⁸	4	0.036	83.3		6	0.06	50.0
	6	0.064	46.9	S ⁺⁴	6	0.037	81.1	W ⁺⁴	6	0.066	45.5
	8	0.074	40.5	S ⁺⁶	4	0.012	250.0	W ⁺⁵	6	0.062	48.4
Ni ⁺²	4	0.049	61.2		6	0.029	103.4	W ⁺⁶	4	0.042	71.4
	6	0.069	43.5	Sb ⁺³	4	0.076	39.5		5	0.051	58.8
Ni ⁺⁶	6	0.056	53.6		6	0.076	39.5		6	0.06	50.0
Os ⁺⁴	6	0.063	47.6	Sb ⁺⁵	6	0.06	50.0	Y ⁺³	6	0.09	33.3
Os ⁺⁵	6	0.058	51.7	Sc ⁺³	6	0.075	40.0		8	0.102	29.4
Os ⁺⁶	6	0.055	54.5		8	0.087	34.5		9	0.108	27.8
Os ⁺⁸	6	0.039	76.9	Se ⁺⁴	6	0.05	60.0	Zn ⁺²	4	0.06	50.0
P ⁺⁵	4	0.017	176.5	Se ⁺⁶	4	0.028	107.1		6	0.074	40.5
	6	0.038	78.9		6	0.042	71.4		8	0.09	33.3
Pb ⁺²	6	0.119	25.2	Si ⁺⁴	4	0.026	115.4	Zr ⁺⁴	4	0.059	50.8
	8	0.129	23.3		6	0.04	75.0		6	0.072	41.7
	10	0.14	21.4	Sn ⁺⁴	4	0.055	54.5		8	0.084	35.7
	12	0.149	20.1		6	0.069	43.5		9	0.089	33.7
					8	0.081	37.0				

4). Extended Data Table S4.

Table S4. Periodicities of Atoms and Monoatomic Ions $\tilde{\nu}_{GW}$ Values																																															
H 0.106 56.6 2.20																	He 0.062 96.8																														
Li 0.234 20.6 0.98	Be 0.224 26.8 1.57	<table border="1"> <tr> <td>La 0.308 19.5 1.10</td> <td colspan="10"> Atomic Symbol Atomic diameter* {unit: (nm)} $\tilde{\nu}_{GW}$ {unit: (nm⁻¹)} Pauling's EN** </td> </tr> </table>										La 0.308 19.5 1.10	Atomic Symbol Atomic diameter* {unit: (nm)} $\tilde{\nu}_{GW}$ {unit: (nm ⁻¹)} Pauling's EN**										B 0.174 34.5 2.04	C 0.134 44.8 2.55	N 0.112 53.6 3.04	O 0.096 62.5 3.44	F 0.084 71.4 3.98	Ne 0.076 78.9																			
La 0.308 19.5 1.10	Atomic Symbol Atomic diameter* {unit: (nm)} $\tilde{\nu}_{GW}$ {unit: (nm ⁻¹)} Pauling's EN**																																														
*Atomic diameters data source: https://en.wikipedia.org/wiki/Atomic_radii_of_the_elements_(data_page) , (Jan-8-2019).																																															
Na 0.380 15.8 0.93	Mg 0.290 20.7 1.31	**Pauling's EN data source: Lide, D. R. <i>CRC Handbook of Chem. and Phys.</i> (CRC Press, Boca Raton, FL, 2000).																																													
K 0.486 12.3 0.82	Ca 0.388 15.5 1.00	Sc 0.368 16.3 1.36	Ti 0.352 17.0 1.54	V 0.342 17.5 1.63	Cr 0.332 18.1 1.66	Mn 0.322 18.6 1.55	Fe 0.312 19.2 1.83	Co 0.304 19.7 1.88	Ni 0.298 20.1 1.91	Cu 0.290 20.7 1.90	Zn 0.282 21.3 1.65	Ga 0.272 22.1 1.81	Ge 0.250 24.0 2.01	As 0.228 26.3 2.18	Se 0.206 29.1 2.55	Br 0.188 31.9 2.96	Kr 0.176 34.1																														
Rb 0.530 11.3 0.82	Sr 0.438 13.7 0.95	Y 0.424 14.2 1.22	Zr 0.412 14.7 1.33	Nb 0.396 15.2 1.6	Mo 0.380 15.8 2.16	Tc 0.366 16.4 2.10	Ru 0.356 16.9 2.2	Rh 0.346 17.3 2.28	Pd 0.338 17.8 2.20	Ag 0.330 18.2 1.93	Cd 0.322 18.6 1.69	In 0.312 19.2 1.78	Sn 0.290 20.7 1.96	Sb 0.266 22.6 2.05	Te 0.246 24.4 2.1	I 0.230 26.1 2.66	Xe 0.216 27.8 2.60																														
Cs 0.596 10.1 0.79	Ba 0.506 11.9 0.89	La 0.390 15.4 1.10	Hf 0.416 14.4 1.3	Ta 0.400 15.0 1.5	W 0.386 15.5 1.7	Re 0.376 16.0 1.9	Os 0.370 16.2 2.2	Ir 0.360 16.7 2.2	Pt 0.354 16.9 2.2	Au 0.348 17.2 2.4	Hg 0.342 17.5 1.9	Tl 0.312 15.8 1.8	Pb 0.308 19.5 1.8	Bi 0.286 21.0 1.9	Po 0.270 22.2 2.0	At 0.300 20.0 2.2	Rn 0.240 25.0																														
<table border="1"> <tr> <td>La 0.390 15.4 1.10</td> <td>Ce 0.370 16.2 1.12</td> <td>Pr 0.370 16.2 1.13</td> <td>Nd 0.370 16.2 1.1</td> <td>Pm 0.370 16.2</td> <td>Sm 0.370 16.2 1.17</td> <td>Eu 0.370 16.2 1.20</td> <td>Gd 0.360 16.7 1.20</td> <td>Tb 0.350 17.1 1.22</td> <td>Dy 0.350 17.1 1.22</td> <td>Ho 0.350 17.1 1.23</td> <td>Er 0.350 17.1 1.24</td> <td>Tm 0.350 17.1 1.25</td> <td>Yb 0.350 17.1 1.25</td> <td>Lu 0.350 17.1 1.0</td> </tr> <tr> <td>Ac 0.390 15.4 1.1</td> <td>Th 0.360 16.7 1.3</td> <td>Pa 0.360 16.7 1.5</td> <td>U 0.350 17.1 1.7</td> <td>Np 0.350 17.1 1.3</td> <td>Pu 0.350 17.1 1.3</td> <td>Am 0.350 17.1</td> <td>Cm 0.238 25.2</td> <td>Bk 0.34 17.6</td> <td>Cf 0.372 16.1</td> <td>Es 0.372 16.1</td> <td>Fm 0.334 18.0</td> <td>Md 0.346 17.3</td> <td>No 0.332 18.1</td> <td>Lr 0.322 18.1</td> </tr> </table>																		La 0.390 15.4 1.10	Ce 0.370 16.2 1.12	Pr 0.370 16.2 1.13	Nd 0.370 16.2 1.1	Pm 0.370 16.2	Sm 0.370 16.2 1.17	Eu 0.370 16.2 1.20	Gd 0.360 16.7 1.20	Tb 0.350 17.1 1.22	Dy 0.350 17.1 1.22	Ho 0.350 17.1 1.23	Er 0.350 17.1 1.24	Tm 0.350 17.1 1.25	Yb 0.350 17.1 1.25	Lu 0.350 17.1 1.0	Ac 0.390 15.4 1.1	Th 0.360 16.7 1.3	Pa 0.360 16.7 1.5	U 0.350 17.1 1.7	Np 0.350 17.1 1.3	Pu 0.350 17.1 1.3	Am 0.350 17.1	Cm 0.238 25.2	Bk 0.34 17.6	Cf 0.372 16.1	Es 0.372 16.1	Fm 0.334 18.0	Md 0.346 17.3	No 0.332 18.1	Lr 0.322 18.1
La 0.390 15.4 1.10	Ce 0.370 16.2 1.12	Pr 0.370 16.2 1.13	Nd 0.370 16.2 1.1	Pm 0.370 16.2	Sm 0.370 16.2 1.17	Eu 0.370 16.2 1.20	Gd 0.360 16.7 1.20	Tb 0.350 17.1 1.22	Dy 0.350 17.1 1.22	Ho 0.350 17.1 1.23	Er 0.350 17.1 1.24	Tm 0.350 17.1 1.25	Yb 0.350 17.1 1.25	Lu 0.350 17.1 1.0																																	
Ac 0.390 15.4 1.1	Th 0.360 16.7 1.3	Pa 0.360 16.7 1.5	U 0.350 17.1 1.7	Np 0.350 17.1 1.3	Pu 0.350 17.1 1.3	Am 0.350 17.1	Cm 0.238 25.2	Bk 0.34 17.6	Cf 0.372 16.1	Es 0.372 16.1	Fm 0.334 18.0	Md 0.346 17.3	No 0.332 18.1	Lr 0.322 18.1																																	