

Electronic Supplementary Information

Theoretical Insight into the Binding Affinity Enhancement of Serine
with the Uranyl Ion through Phosphorylation

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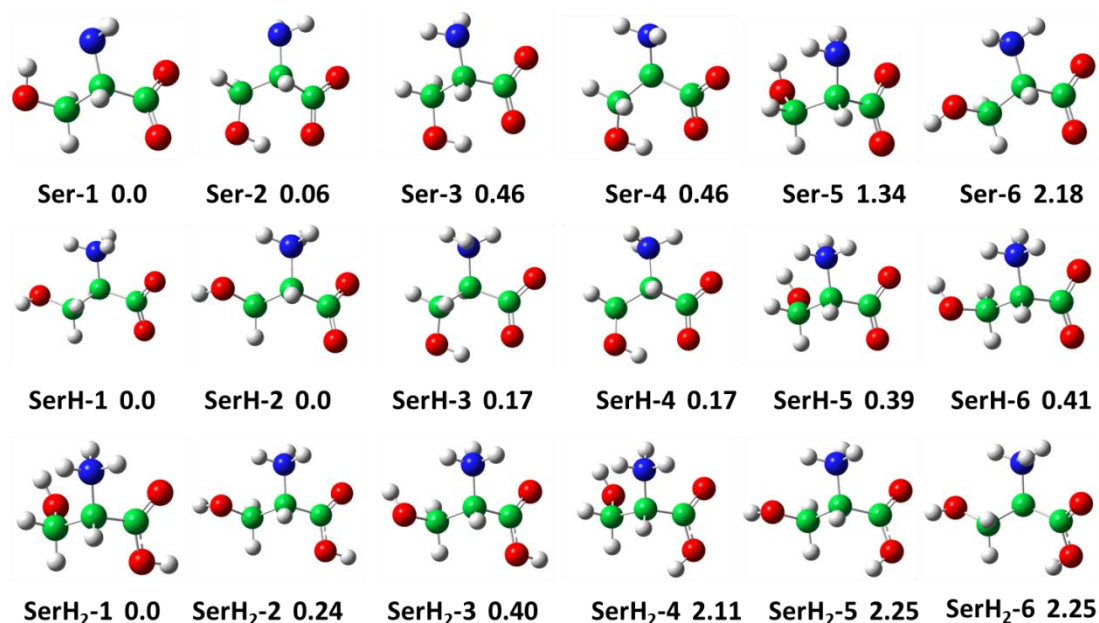


Fig. S1. Structures of the most stable protonated (cation, SerH₂), zwitterionic (neutral, SerH) and deprotonated (anion, Ser) serine optimized in the aqueous phase at the B3LYP/6-311+G(d)/SMD level of theory. Relative energies (kcal/mol) are provided at the same level of theory. H, C, N and O atoms are represented by white, green, blue and red spheres, respectively.

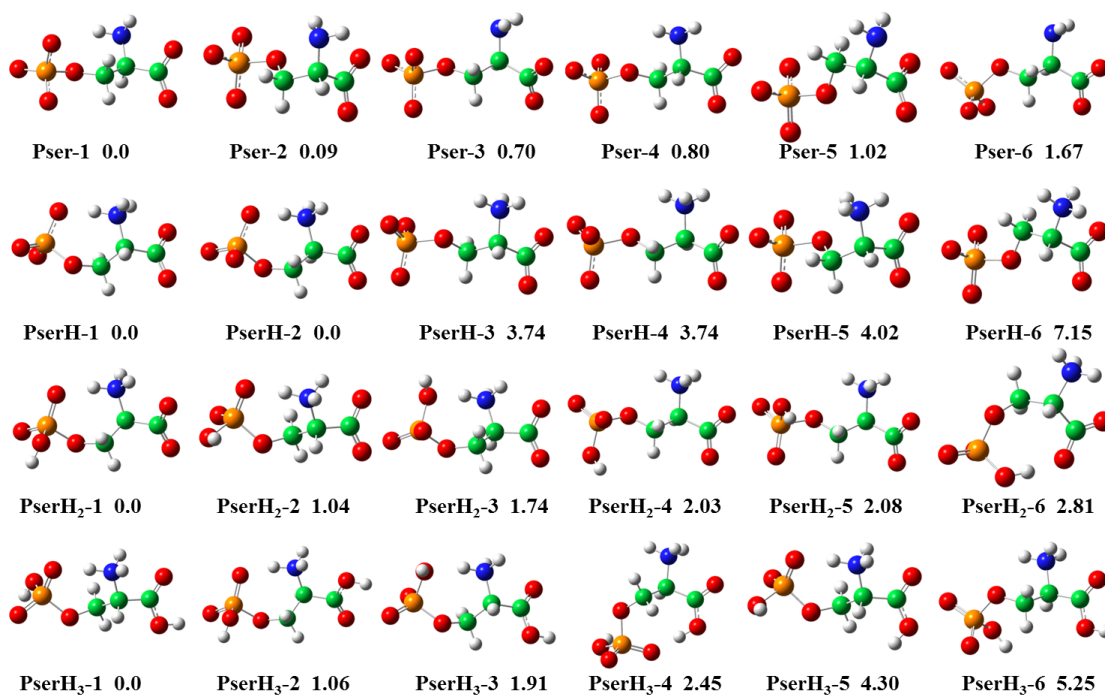
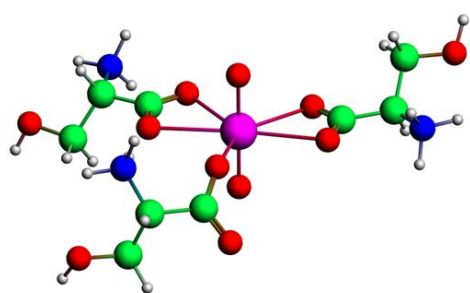
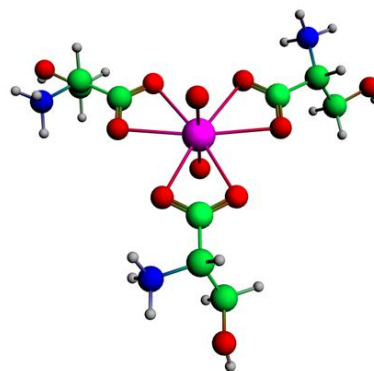


Fig. S2. Structures of the most stable neutral (pSerH₃), mono-anionic (pSerH₂⁻), di-anionic (pSerH²⁻) and tri-anionic (pSer³⁻) phosphoserine optimized in the aqueous phase at the B3LYP/6-311+G(d)/SMD level of theory. Relative energies (kcal/mol) are provided at the same level of theory. H, C, N, O and P atoms are represented by white, green, blue, red and orange spheres, respectively.



$[\text{UO}_2(\text{SerH})_3]^{2+-1}$ 0.0



$[\text{UO}_2(\text{SerH})_3]^{2+-2}$ 0.79

Fig. S3. Structures of the 1:3 type complexes of uranyl ion with zwitterionic (SerH) serine optimized at the B3LYP/ECP60MWB-SEG/6-311+G(d)/SMD level of theory in the aqueous phase. H, C, N, O and U atoms are represented by white, green, blue, red and purple spheres, respectively.

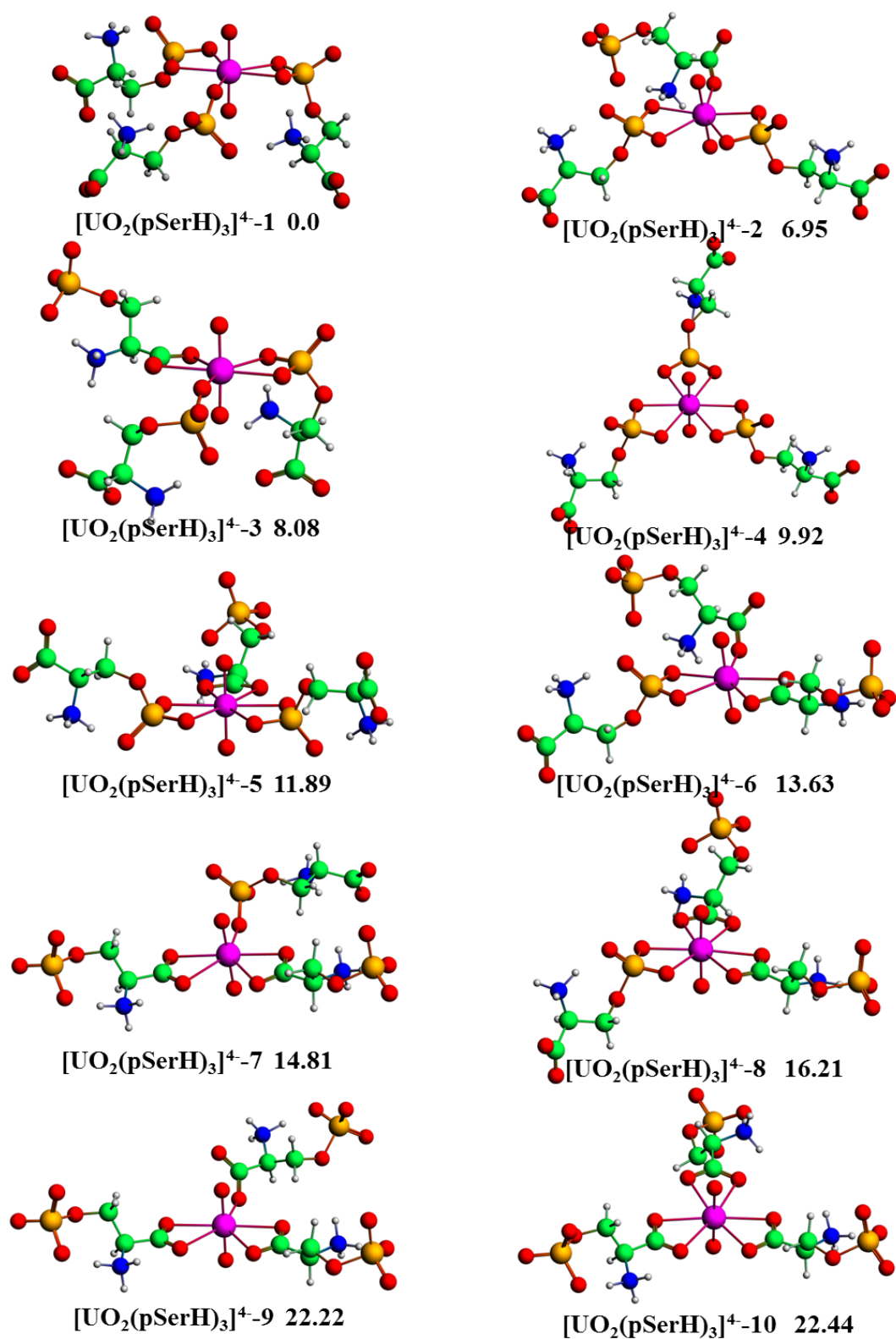


Fig. S4. Structures of the 1:3 type complexes of uranyl ion with dianionic phosphoserine (pSerH^{2-}) optimized in the aqueous phase at the B3LYP/ECP60MWB-SEG/6-311+G(d)/SMD level of theory. H, C, N, O, P and U atoms are represented by white, green, blue, red, orange and purple spheres, respectively.

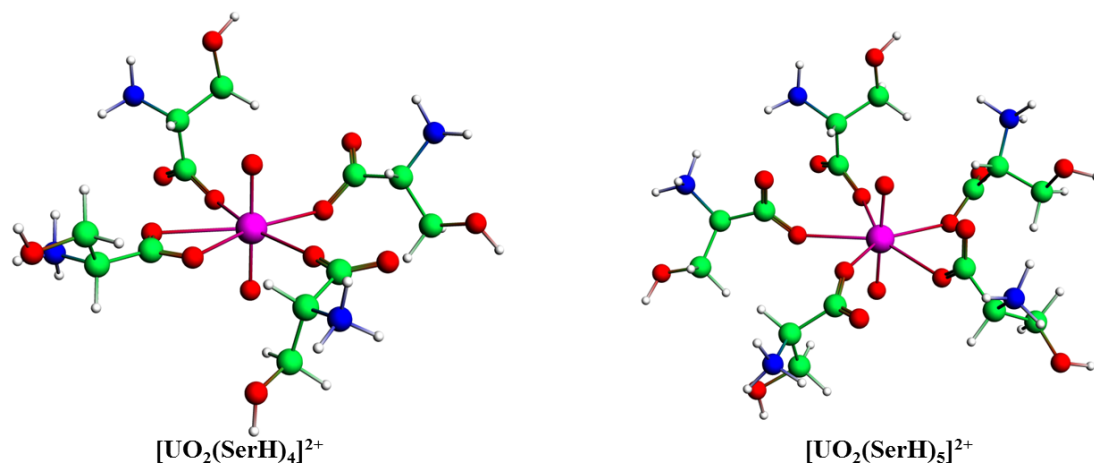


Fig. S5. Structures of the 1:4 and 1:5 type complexes of uranyl ion with zwitterionic (SerH) serine optimized at the B3LYP/ECP60MWB-SEG/6-311+G(d)/SMD level of theory in the aqueous phase. H, C, N, O and U atoms are represented by white, green, blue, red and purple spheres, respectively.

Table S1. Average U-O bond distances (Å), O=U=O angles (degree) and the UO_2^{2+} harmonic vibrational frequencies (ν_s and ν_{as} , cm^{-1}) for the $[\text{UO}_2(\text{H}_2\text{O})_3]^{+2}$ complex optimized in the aqueous solution at the different level of theory.

Level of theory	U=O	U-O _C	U-O _W	$\angle\text{O}=\text{U}=\text{O}$	ν_s	ν_{as}
B3LYP/6-311+G(d)/SMD	1.770	2.561	2.490	178.75	865	906
B3LYP/6-31+G(d)/SMD	1.772	2.537	2.514	178.68	876	920
B3LYP-D3/6-311+G(d)/SMD	1.769	2.544	2.491	178.74	867	908
B3LYP-D3/6-31+G(d)/SMD	1.771	2.519	2.518	178.60	878	922
BP86/6-311+G(d)/SMD	1.796	2.531	2.477	178.35	814	867
BP86/6-31+G(d)/SMD	1.797	2.504	2.502	178.01	824	879
PBE/6-311+G(d)/SMD	1.791	2.530	2.480	178.32	820	873
PBE/6-31+G(d)/SMD	1.793	2.503	2.506	177.98	830	885
M06/6-311+G(d)/SMD	1.741	2.569	2.481	178.87	909	936
M06/6-31+G(d)/SMD	1.744	2.551	2.504	178.84	919	952

Table S2. Electron Density (ρ , au) of U-O Bond Critical Point and Its Laplacian ($\nabla^2\rho$, au) as well as Wiberg Bond Indices (WBIs) of U-O bonds for the 1:2 Type Complexes at the B3LYP/ECP60MWB-SEG/6-311+G(d) Level of Theory.^a

Complexes	U-O _C			U-O _P			U-O _W		
	ρ	$\nabla^2\rho$	WBIs	ρ	$\nabla^2\rho$	WBIs	ρ	$\nabla^2\rho$	WBIs
$[\text{UO}_2(\text{SerH})_2(\text{H}_2\text{O})]^{2+}-1$	0.048	0.157	0.368	-	-	-	0.052	0.203	0.403
$[\text{UO}_2(\text{SerH})_2(\text{H}_2\text{O})]^{2+}-2$	0.048	0.157	0.367	-	-	-	0.054	0.214	0.413
$[\text{UO}_2(\text{pSerH}_2)_2(\text{H}_2\text{O})]-1$	0.049	0.161	0.373	-	-	-	0.052	0.203	0.405
$[\text{UO}_2(\text{pSerH}_2)_2(\text{H}_2\text{O})]-2$	0.048	0.157	0.370	0.044	0.145	0.382	0.052	0.200	0.404
$[\text{UO}_2(\text{pSerH}_2)_2(\text{H}_2\text{O})]-3$	-	-	-	0.045	0.151	0.399	0.055	0.213	0.425
$[\text{UO}_2(\text{pSerH})_2(\text{H}_2\text{O})]^{2-}-1$	-	-	-	0.058	0.192	0.511	0.048	0.186	0.397
$[\text{UO}_2(\text{pSerH})_2(\text{H}_2\text{O})]^{2-}-2$	0.045	0.149	0.364	0.061	0.199	0.515	0.050	0.192	0.394
$[\text{UO}_2(\text{pSerH})_2(\text{H}_2\text{O})]^{2-}-3$	0.048	0.157	0.371	-	-	-	0.051	0.199	0.396

^aThe O_C, O_P and O_W denote the oxygen atom of the carboxyl and phosphate groups and water molecule, respectively.

Table S3. Average U-O Bond Distances (Å), O=U=O Angles (degree) and the UO_2^{2+} Harmonic Vibrational Frequencies (ν_s and ν_{as} , cm^{-1}) for the 1:3 Type Complexes Optimized in the Aqueous Phase at the B3LYP/ECP60MWB-SEG/6-311+G(d) Level of Theory.

complexes	^a modes	U=O	^b U-O _{C_{bi}}	^b U-O _{P_{bi}}	^b U-O _{C_m}	^b U-O _{P_m}	∠O=U=O	ν_s	ν_{as}
$[\text{UO}_2(\text{SerH})_3]^{2+}-1$	2C _{bi} 1C _m	1.775	2.570	-	2.321	-	179.69	847	893
$[\text{UO}_2(\text{SerH})_3]^{2+}-3$	3C _{bi}	1.773	2.591	-	-	-	179.76	850	896
$[\text{UO}_2(\text{pSerH}_2)_3]^{-1}$	2C _{bi} 1P _m	1.776	2.561	-	-	2.331	178.66	849	894
$[\text{UO}_2(\text{pSerH}_2)_3]^{-2}$	2C _{bi} 1C _m	1.776	2.558	-	2.369	-	179.38	849	890
$[\text{UO}_2(\text{pSerH}_2)_3]^{-3}$	3C _{bi}	1.775	2.568	-	-	-	179.56	854	896
$[\text{UO}_2(\text{pSerH}_2)_3]^{-4}$	1C _{bi} 1P _{bi} 1P _m	1.775	2.592	2.589	-	2.328	178.46	849	895
$[\text{UO}_2(\text{pSerH}_2)_3]^{-5}$	1C _{bi} 1P _{bi} 1C _m	1.774	2.549	2.596	2.328	-	179.10	849	890
$[\text{UO}_2(\text{pSerH}_2)_3]^{-6}$	2C _{bi} 1P _{bi}	1.774	2.595	2.630	-	-	178.81	853	895
$[\text{UO}_2(\text{pSerH}_2)_3]^{-7}$	2P _{bi} 1P _m	1.773	-	2.593	-	2.336	179.11	854	902
$[\text{UO}_2(\text{pSerH}_2)_3]^{-8}$	2P _{bi} 1C _m	1.775	-	2.591	2.342	-	179.60	849	896
$[\text{UO}_2(\text{pSerH}_2)_3]^{-9}$	1C _{bi} 2P _{bi}	1.773	2.557	2.631	-	-	179.06	855	898
$[\text{UO}_2(\text{pSerH}_2)_3]^{-10}$	3P _{bi}	1.767	-	2.643	-	-	179.81	856	898
$[\text{UO}_2(\text{pSerH})_3]^{4-}-1$	2P _{bi} 1P _m	1.795	-	2.503	-	2.324	179.62	800	845
$[\text{UO}_2(\text{pSerH})_3]^{4-}-2$	2P _{bi} 1C _m	1.791	-	2.491	2.368	-	179.21	808	848
$[\text{UO}_2(\text{pSerH})_3]^{4-}-3$	1C _{bi} 1P _{bi} 1P _m	1.789	2.602	2.472	-	2.275	177.59	809	856
$[\text{UO}_2(\text{pSerH})_3]^{4-}-4$	3P _{bi}	1.792	-	2.563	-	-	179.87	810	852
$[\text{UO}_2(\text{pSerH})_3]^{4-}-5$	1C _{bi} 2P _{bi}	1.789	2.655	2.520	-	-	178.12	822	864
$[\text{UO}_2(\text{pSerH})_3]^{4-}-6$	1C _{bi} 1P _{bi} 1C _m	1.784	2.570	2.467	2.359	-	178.08	828	869
$[\text{UO}_2(\text{pSerH})_3]^{4-}-7$	2C _{bi} 1P _m	1.784	2.574	-	-	2.250	178.37	819	872
$[\text{UO}_2(\text{pSerH})_3]^{4-}-8$	2C _{bi} 1P _{bi}	1.784	2.597	2.483	-	-	178.19	832	872
$[\text{UO}_2(\text{pSerH})_3]^{4-}-9$	2C _{bi} 1C _m	1.777	2.565	-	2.358	-	179.32	847	888
$[\text{UO}_2(\text{pSerH})_3]^{4-}-10$	3C _{bi}	1.776	2.573	-	-	-	179.80	850	892

^aThe bidentate carboxyl (C_{bi}) and phosphate (P_{bi}) group, the mono-dentate carboxyl (C_m) and phosphate (P_m) group

^bThe O_{C_{bi}}, O_{P_{bi}}, O_{C_m} and O_{P_m} denote the oxygen atom of the bidentate carboxyl and phosphate groups and mono-dentate carboxyl and phosphate groups, respectively.

Table S4. Average U-O Bond Distances (Å), O=U=O Angles (degree) and the UO_2^{2+} Harmonic Vibrational Frequencies (ν_s and ν_{as} , cm^{-1}) for the 1:4 and 1:5 Type Complexes Optimized in the Aqueous Phase at the B3LYP/ECP60MWB-SEG/6-311+G(d) Level of Theory.

complexes	^a modes	U=O	^b U-O _{C_{bi}}	^d U-O _{C_m}	∠O=U=O	ν_s	ν_{as}
$[\text{UO}_2(\text{SerH})_4]^{2+}$	1C _{bi} 4C _m	1.782	2.604	2.386	178.90	832	879
$[\text{UO}_2(\text{SerH})_5]^{2+}$	5C _m	1.782	-	2.451	179.30	828	874

^aThe bidentate carboxyl (C_{bi}) and mono-dentate carboxyl (C_m)

^bThe O_{C_{bi}} and O_{C_m} denote the oxygen atom of the bidentate carboxyl and mono-dentate carboxyl group, respectively.

Table S5. Calculated changes of the Gibbs free energy (ΔG_{sol} , kcal/mol) for the reactions between the uranyl Ion and the serine at the B3LYP/ECP60MWB-SEG/6-311+G(d)/SMD level of theory in the aqueous solution.

Reactions	ΔG_{sol}
$\text{SerH} + [\text{UO}_2(\text{H}_2\text{O})_5]^{2+} = [\text{UO}_2\text{SerH}(\text{H}_2\text{O})_3]^{2+} + 2\text{H}_2\text{O}$	-10.99
$2\text{SerH} + [\text{UO}_2(\text{H}_2\text{O})_5]^{2+} = [\text{UO}_2(\text{SerH})_2(\text{H}_2\text{O})]^{2+} + 4\text{H}_2\text{O}$	-18.78
$3\text{SerH} + [\text{UO}_2(\text{H}_2\text{O})_5]^{2+} = [\text{UO}_2(\text{SerH})_3]^{2+} + 5\text{H}_2\text{O}$	-20.24
$4\text{SerH} + [\text{UO}_2(\text{H}_2\text{O})_5]^{2+} = [\text{UO}_2(\text{SerH})_4]^{2+} + 5\text{H}_2\text{O}$	-15.67
$5\text{SerH} + [\text{UO}_2(\text{H}_2\text{O})_5]^{2+} = [\text{UO}_2(\text{SerH})_5]^{2+} + 5\text{H}_2\text{O}$	-4.50

Geometrical Results for the Complexes of 1:3 Uranyl Ion and Serine/Phosphoserine

The selected U-O bond distances, O=U=O bond angles for the 1:3 type complexes are listed in Table S2, SI. The U=O bond distances in the two types of complex $[\text{UO}_2(\text{SerH})_3]^{2+}$ and $[\text{UO}_2(\text{pSerH}_2)_3]^-$ are $\sim 1.77 \text{ \AA}$, which are shorter than those in the complexes $[\text{UO}_2(\text{pSerH})_3]^{4+}$. It can be seen that the U-O_{Cbi} bond distances between the uranium atom and the oxygen atom of the bidentate carboxyl groups in conformer $[\text{UO}_2(\text{SerH})_3]^{2+}$ -1 are 2.570 \AA , which are somewhat 0.02 longer than those of the hexa-coordinated conformers and $[\text{UO}_2(\text{SerH})_3]^{2+}$ -2. Obviously, the distances of U-O_{Cbi} bonds in the complexes $[\text{UO}_2(\text{SerH})_3]^{2+}$ are $\sim 0.30 \text{ \AA}$ longer than that of U-O_{Cm} bond between the uranium atom and the oxygen atom of mono-dentate carboxyl group. For the 1:3 type mono-anionic phosphoserine complexes, the distances of U-O_{Cbi} bonds are ~ 2.55 - 2.60 \AA , which are also longer compared to those of U-O_{Cm} bonds. Notably, the distances of U-O_{Pbi} bonds between the uranium atom and the oxygen atom of bidentate phosphate group are $\sim 2.59 \text{ \AA}$ for the complexes $[\text{UO}_2(\text{pSerH}_2)_3]^-$ with penta-coordination mode, while the corresponding values are $\sim 2.63 \text{ \AA}$ for the complexes with hexa-coordination mode. And the distances of U-O_{Pbi} bonds are longer compare to those of U-O_{Pm} bonds between the uranium and the oxygen atom of the mono-dentate phosphate group. For the 1:3 type dianionic phosphoserine complexes, the distances of U-O_{Cbi} bonds have obvious difference, with the longest and shortest bond distance of 2.655 and 2.565 \AA in the conformers $[\text{UO}_2(\text{pSerH})_3]^{4-}$ -5 and $[\text{UO}_2(\text{pSerH})_3]^{4-}$ -9, respectively. Obviously, the distances of U-O_{Cbi} bonds are somewhat longer compared to those of U-O_{Pbi} bonds in the 1:3 type

complexes $[\text{UO}_2(\text{pSerH})_3]^{4-}$. It can be seen that the distances of U-O_{Cm} bonds are $\sim 2.36 \text{ \AA}$, while those of U-O_{Pm} bonds decrease with the decreasing number of bidentate phosphate groups in the complexes $[\text{UO}_2(\text{pSerH})_3]^{4-}$. For example, the distance of U-O_{Pm} bond is 2.324 \AA in conformer $[\text{UO}_2(\text{pSerH})_3]^{4-}$ -1 with two bidentate phosphate groups, and the corresponding value decreases to 2.275 \AA in conformer $[\text{UO}_2(\text{pSerH})_3]^{4-}$ -3 with a bidentate phosphate and carboxyl group, it changes to 2.250 \AA in conformer $[\text{UO}_2(\text{pSerH})_3]^{4-}$ -9 without bidentate phosphate group. It is worthy to notice that the distances of U-O_{Pbi} and U-O_{Pm} bonds in the complexes $[\text{UO}_2(\text{pSerH})_3]^{4-}$ are somewhat shorter than those in the complexes $[\text{UO}_2(\text{pSerH}_2)_3]^-$, which also indicates that the binding affinity of $-\text{PO}_4^{2-}$ group toward the uranyl ion is stronger than that of $-\text{PO}_4\text{H}^-$ group. Additionally, compared to the 1:1 and 1:2 type complexes, the $\text{O}=\text{U}=\text{O}$ angles in all the 1:3 type complexes are even more close to linearity with the maximum disparity of 2.4° for conformer $[\text{UO}_2(\text{pSerH})_3]^{4-}$ -3.