Stability and Structure of Doubly N-Confused Porphyrins

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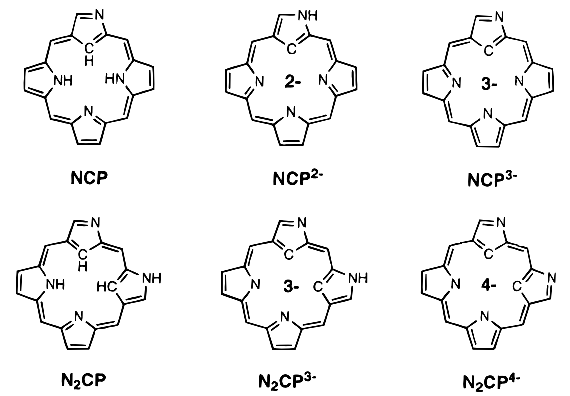
1. Introduction

“N-Confused porphyrin” (NCP) or “inverted porphyrin” is a porphyrin isomer wherein one of the pyrrolic rings is inverted.[1,2] Owing to the inner core carbon and the outward pointing nitrogen at the peripheral, the unique properties different from normal porphyrins have been accumulated gradually.[3−6] For an example, NCP can serve as both divalent (NCP^{2-}) and trivalent (NCP^{3-}) ligands with d^8 metals such as Ni^{2+} and Ag^{3+}.[2,4d] The chameleon-like change of the ligand valency is simply attained by removing the hydrogen from the outer NH of the confused pyrrole ring. Recently, we have synthesized “doubly N-confused porphyrin (N_2CP)” as the first example of multiply N-confused porphyrins, and disclosed the formation of Cu^{3+} and Ag^{3+} metal complexes which are really difficult to make with porphyrins.[7] Structurally, NCP forms a family with many “confused mutants”, which differ in the position and the number of the confused pyrrole ring. In N_2CP case, five regioisomers could exist with respect to the relative location of the confused pyrroles. If the multiple valency is general in NCP family, N_2CP^{3-} or N_2CP^{4-} type coordination could be expected with N_2CP isomers (Chart 1). The aim of this paper is to evaluate the stability of each N_2CP isomer by the density functional theory (DFT) calculation. These calculations will provide insightful information for the synthesis of other N_2CP isomers and the use of N_2CP tautomers as prearranged ligands for the coordination of M^{3+} or M^{4+}.

Chart 1



2. Method

Ab initio calculations were carried out with Gaussian 98 program[8] for the skeleton of N_2CP. All the structures were optimized with HF/6-31G**, and following B3LYP/6-31G**. The final estimation of the total electronic energies were performed at the B3LYP level with the 6-31G** basis set using B3LYP/6-31G** reference structures.

3. Results and Discussion

Five regioisomers of N_2CP are grouped into two types, ***cis*** and ***trans***, according to the relative position of the confused rings. Two confused pyrroles are neighboring in ***cis*** (**1**, **2**, and **3**) and countered in ***trans*** (**4** and **5**). Each isomer has three NH tautomers, inner 4H type (**PH_4**) and inner 3H (**PH_3**) type (Figure 1).

3A. Energies of N_2CP Isomers. The relative energies of the optimized structures for the regioisomers including all the tautomers (**1**−**5**; **a**−**c**) were shown in Table 1. In B3LYP/6-31G**//B3LYP/6-31G** level, the most stable isomers are **2-c** in ***cis*** and **4-a** and **5-a** in ***trans*** (Figure 2). The energy differences between these three isomers are within 0.06 kcal/mol. Interestingly, the relative stability of the postulated tautomers is opposite for the ***cis-trans*** isomers. The stability decreases in the order of **PH_3** > **PH_4** in ***cis*** but **PH_4** > **PH_3** in ***trans***.

Coincidentally, the most stable isomeric form is **2-c**, which is the same type of N_2CP really synthesized.[7] The calculated energy for **2-c** is 37.5 kcal/mol higher than that of porphin and 20.3 kcal/mol higher than NCP.[9] Part of

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(9) The optimized structures for porphin and NCP were shown in Supporting Information.

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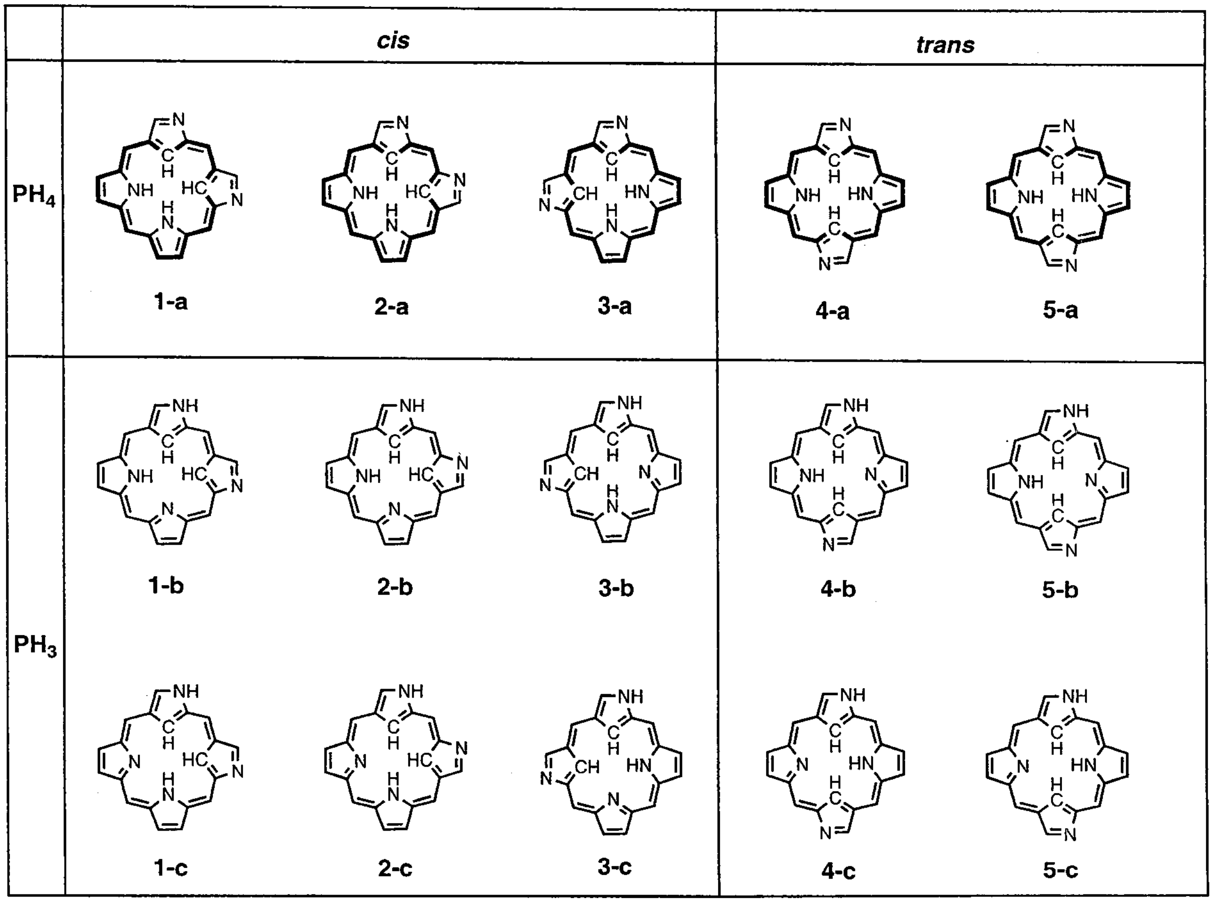


Figure 1. Structures of N_2CP (**1**−**5**). [18]-Annulenic substructures are indicated in bold.

Table 1. Calculated Relative Electronic Energies[a]

	HF/6-31G** //HF/6-31G**	B3LYP/6-31G** //HF/6-31G**	B3LYP/6-31G** //B3LYP/6-31G**
1-a	12.2	8.94	5.67
1-b	4.48	4.28	3.66
1-c	2.85	2.31	1.93
2-a	13.4	9.97	5.89
2-b	0.959	1.44	1.28
2-c	0	0	0
3-a	14.3	10.3	6.04
3-b	2.46	2.05	1.86
3-c	2.63	3.59	3.18
4-a	10.9	5.18	0.06
4-b	10.8	7.99	6.15
4-c	5.59	5.44	4.78
5-a	10.7	3.72	0.04
5-b	7.79	6.71	5.42
5-c	8.26	6.91	5.68
porphin	−	−	−37.5
NCP	−	−	−20.3

[a] In kcal/mol with respect to the energy of **2-c**.

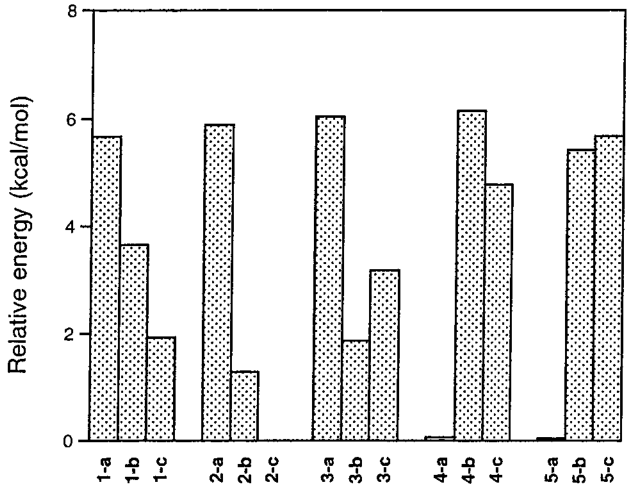
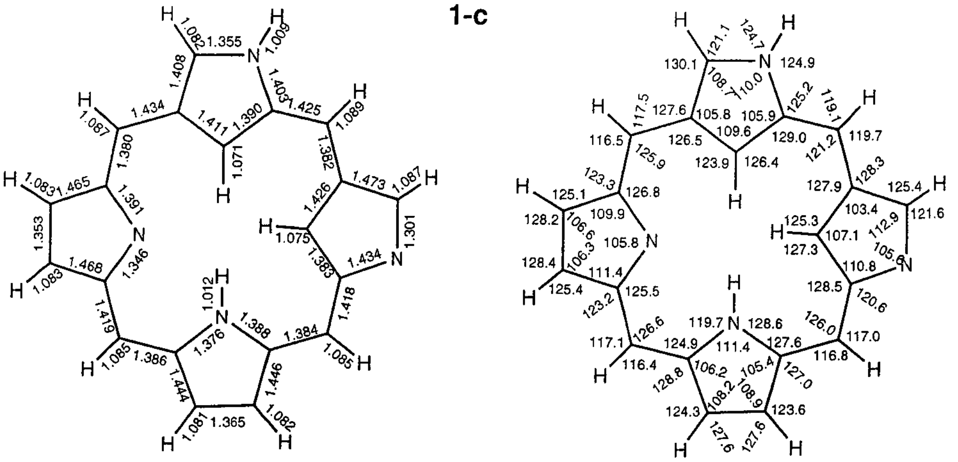


Figure 2. Calculated relative B3LYP energies of N_2CP (**1**−**5**).

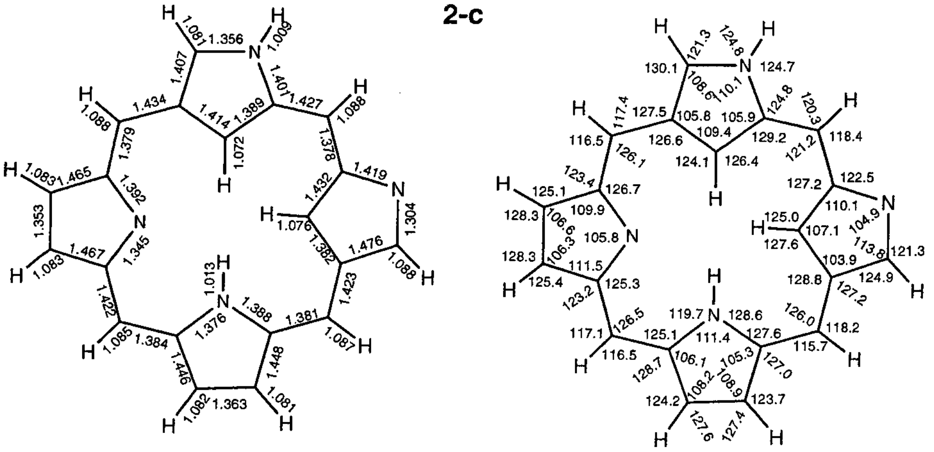
this energy changes must be ascribed to the steric repulsion among the central hydrogens and the weakened 18π aromaticity of N_2CP. Although the repulsion of the inner core NH and CH in **PH_4** is larger than **PH_3**, the complete [18]-annulenic substructure can be drawn only with **PH_4** but **PH_3**, since the circuit is structurally disconnected at the confused pyrrole ring in **PH_3**. Thus, it is probable that steric repulsion and the aromaticity are important factors to determine the relative stability of each isomer.

In ***cis***-type, the stable **PH_3** (**1-c**, **2-c**, and **3-b**) has 4−6 kcal/mol lower energy than the corresponding **PH_4** (**1-a**, **2-a**, and **3-a**). The inner NH of ***cis*-PH_3** can form hydrogen bonding to the neighboring unprotonated nitrogen, which could be an additional stabilization factor of ***cis*-PH_3**. Thus, the steric repulsion among the four central hydrogens overwhelms the resonance stabilization in ***cis*-PH_4**. On the other hand, in ***trans***-type, **PH_4** (**4-a** and **5-a**) has 5−6 kcal/mol lower energy than **PH_3** (**4-b,c** and **5-b,c**). The increased ***trans*-PH_3** energy apparently reflects the absence of inner NH- - -N hydrogen bonding due to the long distance of two pyrrolic N's in the core (ca. 4.5 Å). The decreased ***trans*-PH_4** energy may be accountable by the enhanced aromaticity due to

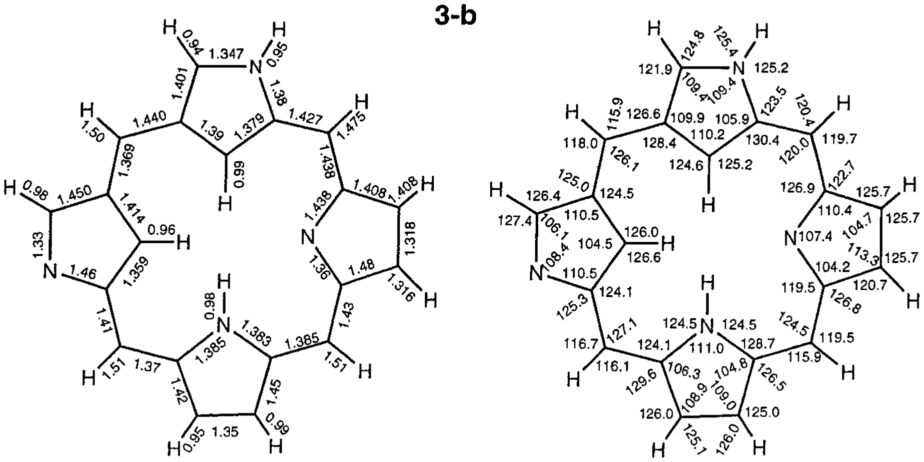
1-c



2-c



3-b



the less-crowded conformation. In fact, the optimized structures of **4-a** and **5-a** show the planarity more than **1-a**, **2-a**, and **3-a**. The arrangements of the inner core hydrogens of ***trans*-PH$_4$** are up (CH), in-plane (NH), down (CH), and in-plane (NH); on the other hand, those of ***cis*-PH$_4$** are up (CH), down (CH), down (NH), and up (NH) from the mean plane.[10] Therefore, the repulsion between the inner hydrogens seems relatively larger in ***cis*-PH$_4$** and the aromaticity is enhanced in the more flattened ***trans*-PH$_4$** isomer.

3B. Optimized Structures of N$_2$CP Isomers. Figure 3 shows the optimized structures of the most stable tautomer for each regioisomer (**1**−**5**) and the X-ray structure of the free base **N$_2$CP**−**C$_6$F$_5$** obtained[7] (Chart 2). Other isomers and tautomers are summarized in Supporting Information. Despite the lack of pentafluorophenyl and ethoxy groups, the discrepancies of the bond distances and angles between calculated (**2-c**) and experimental (**N$_2$CP**−**C$_6$F$_5$**) are very small: the maximum deviations are within 0.026 Å and 2.2°, respectively.[11] The NH containing pyrroles shows wider angles ∠C−N−C,

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[10] For examples, the tilting angles (deg) of each of the pyrroles are +18.6 (CH), 0.00 (NH), −18.5 (CH), 0.00 (NH) for **5-a**, and 20.4 (CH), −20.4 (CH), −7.9 (NH), +7.9 (NH) for **2-a**.

[11] The calculation with ethoxy group on **2-c** (**2-d**) showed almost same structure as **2-c**. See Supporting Information.

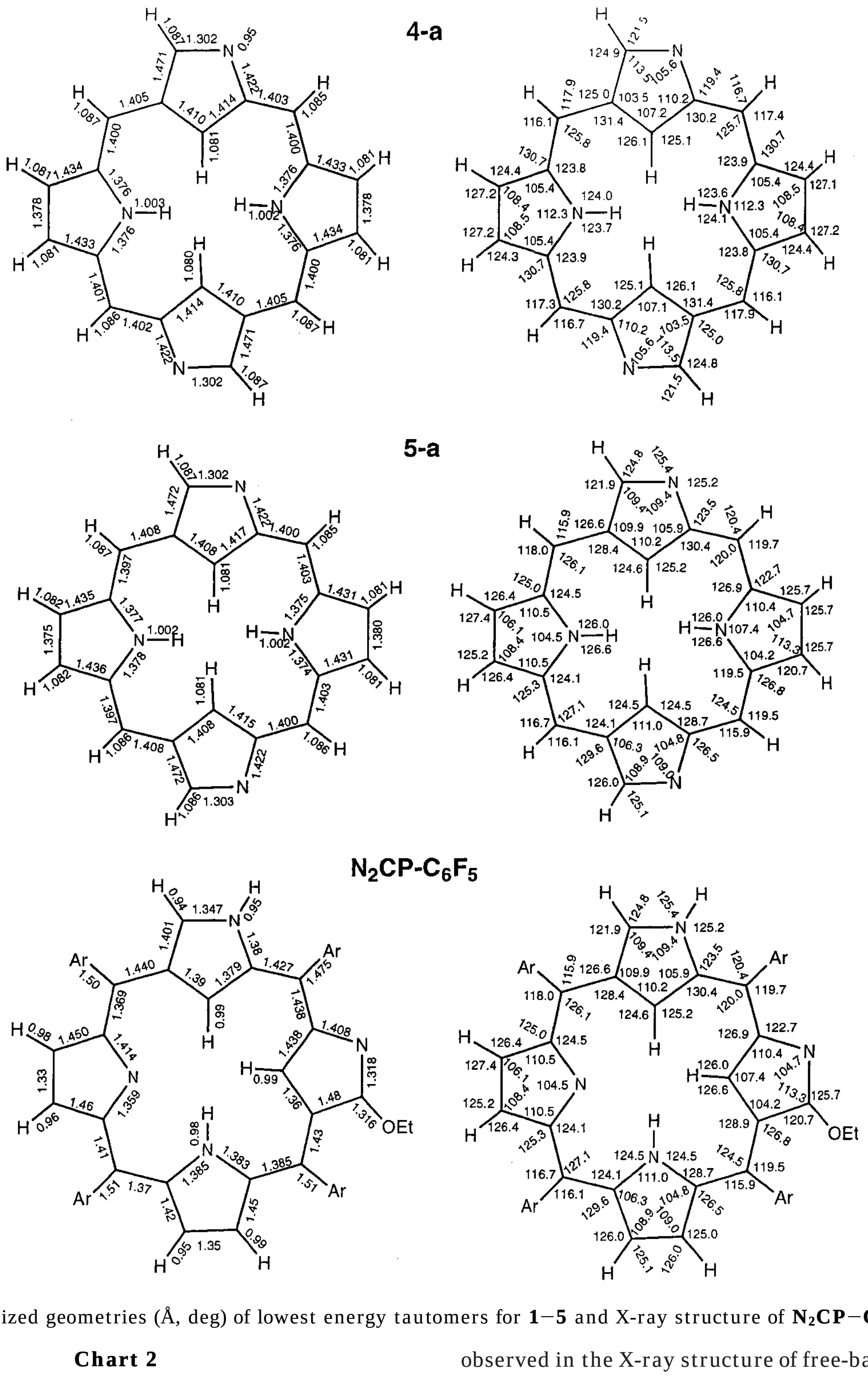
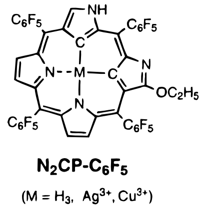


Figure 3. Optimized geometries (Å, deg) of lowest energy tautomers for **1**−**5** and X-ray structure of **N_2CP−C_6F_5**.

Chart 2



N_2CP-C_6F_5
(M = H_3, Ag^{3+}, Cu^{3+})

111.0° (111.4°) and 109.4° (110.2°), than that of unprotonated pyrroles, 104.5° (105.8°) and 104.7° (104.9°), in **N_2CP−C_6F_5** (and **2-c**). Such a tendency is frequently observed in the X-ray structure of free-base porphyrins.[12] Reflecting the weak aromaticity of **N_2CP−C_6F_5**,[13] the bond alternation, single and double (e.g., 1.440 and 1.369 Å), is observed except the NH bearing confused pyrrole ring, where the [18]-annulenic substructure is disrupted.

In ***trans*-PH_4**, the optimized distances between CH- - -

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[12] Senge, M. O. In *The Porphyrin Handbook*; Kadish, K. M., Smith, K. M., Guilard, R., Eds.; Academic Press: San Diego, 1999; Vol. 10, Chapter 61.

[13] ^1H NMR of free base **N_2CP−C_6F_5** in $CDCl_3$ shows the signals derived from inner NH and two inner CHs at 6.38, 3.50, and 3.20 ppm, respectively, which indicate the disruption of 18π fully annulenic substructure and weak hydrogen-bonding interaction between NH- - - -N in the solvent such as $CDCl_3$. See, ref 7.

HC for **4-a** and **5-a** are 2.609 and 2.622 Å, and those of the shorter NH- - -HC are 1.807 and 1.810 Å, respectively. On the other hand, the distances between the neighboring CH- - -HC for **1-c**, **2-c**, and **3-b** are 2.011, 2.057 and 1.965 Å, and those of the trans NH- - -HC are 2.305, 2.341, and 2.336 Å, respectively, in ***cis*-PH$_3$**. These data show that the two confused pyrrole rings are tilted largely in the opposite direction to avoid the CH- - -HC repulsion in ***trans*-PH$_4$** type.[10] In ***cis*-PH$_3$** type, the structure is relatively flat due to the hydrogen bonding in a porphyrin core. Supporting this, the short N- - -HN distances, 2.207, 2.203, and 2.186 Å,[14] and the unsymmetrical angles $\angle C_\alpha-N-H$, (119.7 vs 128.6°), (119.7 vs 128.6°), and (119.5 vs 128.9°) for **1-c**, **2-c**, and **3-b**, respectively, are observed.

The different strength of the aromaticity between **PH$_3$** and **PH$_4$** is also reflected on the bond lengths along the π-circuit. For **PH$_4$**, the bond lengths between the *meso* carbons and the connecting pyrrolic carbons are within the range of 1.400 to 1.405 Å in **4-a** and 1.397 to 1.408 Å in **5-a**. On the other hand, those bonds are alternated with **PH$_3$**, for example, 1.380 to 1.434 Å in **1-c**. Thus, as shown in Figure 1, the [18]-annulenic substructure can be drawn only for **PH$_4$** type. The similar aromaticity change according to the tautomeric form has been reported with the calculation on NCP.[15]

Although the relation between the prearranged structures and metal oxidation states is not clearly demonstrated, the results discussed above seem indicative for the consideration of M^{4+} complexation with N$_2$CP. At present, the only example of N$_2$CP is ***cis*-PH$_3$**, which serves actually as trivalent N$_2$CP^{3-} ligand, and is known to coordinate with Ag^{3+} or Cu^{3+}. Attempts to isolate the stable complex with M^{4+} metal such as Pt^{4+} or Pd^{4+} have not been succeeded yet. If ***trans*-PH$_4$** were to be subjected to such coordination, increased stability of the corresponding complex could be expected. We believe that synthesis of a series of N$_2$CP isomers and examination of the stability of each metal complex reveal the ligand property of NCP in general.

4. Conclusion

We have calculated the geometry and the energy of 15 N$_2$CP isomers including the tautomeric forms by DFT method. Among them, **2-c** in ***cis*-PH$_3$** type and **4-a** and **5-a** in ***trans*-PH$_4$** type are most stable. Inner core NH- - -N hydrogen bonding is significant in **PH$_3$**, and the resonance effect is dominant in **PH$_4$**. The comparably stable energies of **4-a** and **5-a** in ***trans*-PH$_4$** suggest the possibility of M^{4+} coordination. The syntheses toward the ***trans*** isomers is in progress.

Supporting Information Available: Optimized structures and their Cartesian coordinates of each of the tautomers, NCP, and porphin. This material is available free of charge via the Internet at http://pubs.acs.org.

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