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ORIGINAL PAPER

Macrocyclic conjugation in N-fused porphyrins and related species

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Abstract Macrocyclic aromaticity is the most important concept in porphyrin chemistry. We propose a general graph-theoretical procedure for predicting the main macrocyclic conjugation pathway in porphyrinoids. This procedure, based on calculated bond resonance energies (BREs), can be applied not only to natural and expanded porphyrins but also to porphyrinoids with fused rings. Main macrocyclic conjugation pathways predicted with this procedure are exactly the same as those proposed by porphyrin chemists. Macrocyclic aromaticity can be estimated readily from the BRE for any of the π-bonds linking adjacent pyrrolic rings. It was found that N-fusion often gives rise to anti-aromatic tripentacyclic subunits with negative BREs. Thus, our procedure properly characterizes macrocyclic conjugation and macrocyclic aromaticity in a wide variety of porphyrinoids.

Keywords N-Fused porphyrins · Macrocyclic aromaticity · Macrocyclic conjugation pathway · Superaromatic stabilization energy · Bond resonance energy

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Introduction

Many porphyrinoid macrocycles have been prepared and characterized, including regular, contracted, expanded, confused, and inverted porphyrins [1–16]. Free-base porphine (**1** in Fig. 1) has been described as bridged diaza[18] annulene [1–3]. This picture emphasizes that a cyclic 18π conjugation pathway must represent macrocyclic conjugation in **1**. Annulene-like main macrocyclic conjugation pathways have since been chosen from many porphyrinoid species [1–4]. Franck and Nonn proposed that porphyrinoid species should be classified according to the number of π-electrons that reside in the main macrocyclic conjugation pathway [2]. In this paper, aromaticity arising from macrocyclic conjugation is referred to as macrocyclic aromaticity or superaromaticity.

During the last decade, some research groups have re-examined the global aromaticity of free-base porphine [17–21]. They pointed out that not only macrocyclic conjugation but also four pyrrolic rings contribute significantly to global aromaticity. However, it remains true that proton chemical shifts and kinetic stability are determined primarily by macrocyclic conjugation [17–21]. We recently proposed a graph-theoretical procedure for choosing the main macrocyclic conjugation pathway from natural and expanded porphyrins [21]. The essence of this procedure is to choose π-bonds with larger bond resonance energies (BREs) at every bifurcation of the macrocycle [22–24]. Main macrocyclic conjugation pathways predicted in this manner are exactly the same as those predicted by porphyrin chemists.

Several porphyrinoids with fused rings, such as those with internally fused tripentacyclic subunits, have recently been synthesized [4–16]. These constitute a new type of porphyrinoids. However, the above procedure cannot be

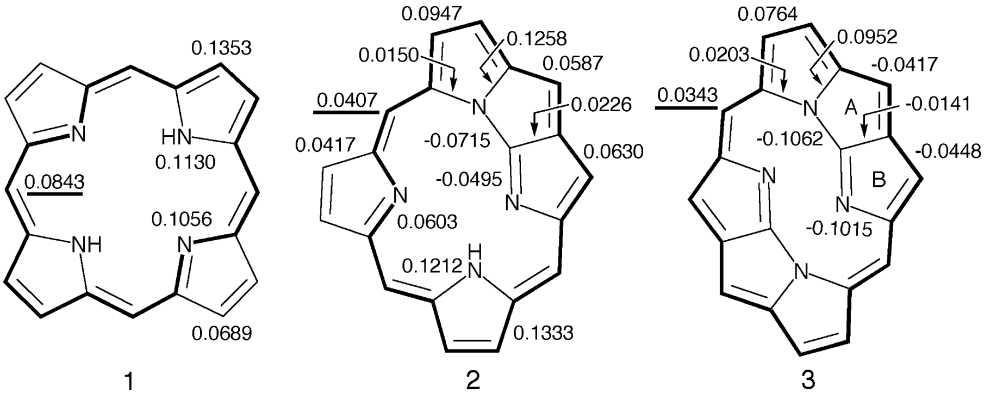

Fig. 1 Bond resonance energies (BREs) in units of |β| for free-base porphine and N-fused porphines. Superaromatic stabilization energy (SSEs) are underlined

used to properly investigate macrocyclic conjugation in these species. In addition, some of these species apparently have two or more main macrocyclic conjugation pathways. The aim of the present study was to devise a more general procedure for predicting the main macrocyclic conjugation pathway in these porphyrinoids, and then to explore macrocyclic conjugation and aromaticity in these π-systems.

Theoretical background

As stated explicitly by Dewar and others [25–29], the term 'aromatic' describes molecules that benefit energetically from the delocalization of π electrons in closed circuits. We deal with global and macrocyclic aromaticity of porphyrinoids within the framework of Hückel molecular orbital theory [20, 21, 28, 29]. Topological resonance energy (TRE) is used as an energetic criterion of global aromaticity [27, 28]. Van-Catledge's Hückel parameters are employed for amine- and imine-type nitrogen atoms [30].

The definition of BRE is outlined here for the benefit of the reader [22–24]. A hypothetical π system, in which a given π bond (e.g., a π bond formed between the *p*th and *q*th atoms) interrupts cyclic conjugation at that point, is constructed by multiplying $\beta_{p,q}$ by i and $\beta_{q,p}$ by $-i$, where $\beta_{p,q}$ and $\beta_{q,p}$ are the resonance integral between the two conjugated atoms and i is the square root of −1. In this π system, no π circulation is expected along the circuits that share the *p*–*q* π bond in common. BRE for the *p*–*q* π bond is given as a destabilization energy of this hypothetical π-system. In other words, BRE for a given π bond represents the contribution of all circuits that share the bond to global aromaticity [22–24]. Computational details for beginners have been described elsewhere [31]. BRE was originally defined to justify the isolated pentagon rule for fullerenes [22].

Superaromatic stabilization energy (SSE), which constitutes part of TRE, represents the degree of macrocyclic aromaticity [20, 21, 32]. For all porphyrinoids, SSE is equal to the BRE for any of the C–C bonds that link adjacent pyrrolic rings [20, 21]. We found that calculated BREs can be utilized for predicting or finding main macrocyclic conjugation pathways in porphyrins [21]. When a given macrocyclic π-system has a positive SSE, the main macrocyclic conjugation pathway can be predicted by choosing a π-bond with a larger BRE at every bifurcation of the π-network. The main macrocyclic conjugation pathway responsible for a negative SSE can be traced by choosing a π-bond with a smaller BRE at every bifurcation of the π-network. As will be seen later, this procedure must be modified to some extent when applied to porphyrinoids with fused rings.

Results and discussion

The 12 porphyrinoids studied are presented in Figs. 1–3; 9 of them are porphyrinoids with fused rings. They are one singly N-fused porphyrin (**2**), one doubly N-fused porphyrin (**3**), four singly N-fused pentaphyrins (**5**–**8**), one doubly N-fused pentaphyrin (**9**), one N-fused pentaphyrin (**11**), and benzo-annelated sapphyrin (**12**) [5–16]. H. Furuta and coworkers prepared all the N-fused porphyrins. Table 1 lists TREs and SSEs for these porphyrinoids, together with those for three parent porphyrins (**1**, **4**, **10**). All these species are moderately aromatic with positive TREs. BREs for **1**–**12** are summarized graphically in Figs. 1–3. Free-base porphine (**1**), pentaphyrin (**4**), and two sapphyrins (**10**, **12**) have no π bonds with negative BREs, whereas some π bonds in N-fused porphyrins (**2**, **3**, **5**–**9**, **11**) are anti-aromatic with negative BREs. Five-membered rings created by N-fusion are the least aromatic rings in each N-fused system; even in species with positive SSEs (i.e., **2**, **3**, **5**, **7**, **11**), at least one of the π-bonds that constitute such fused ring subsystems has a negative BRE.

In Figs. 1–3, BREs that represent SSEs are underlined. Positive and negative SSEs are associated with macrocyclic aromaticity and anti-aromaticity, respectively. Like free-base porphyrins (**1**, **4**, **10**), **2**, **3**, **6**, **8**, **11**, and **12** have

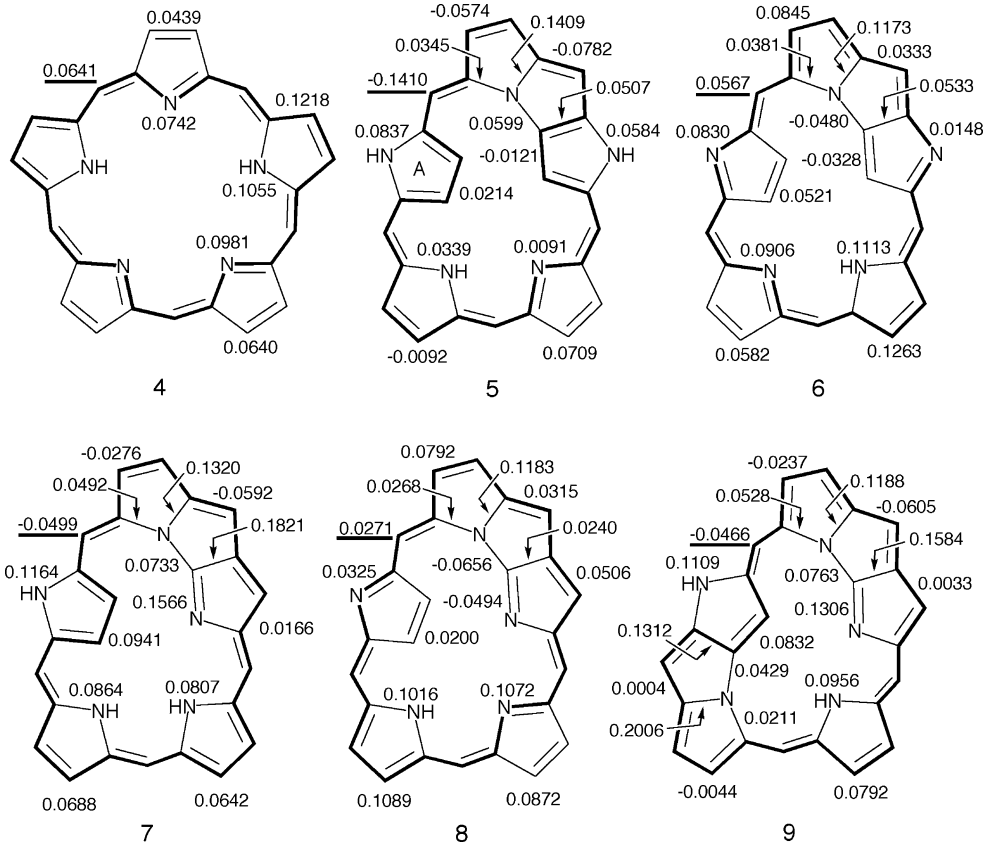

Fig. 2 BREs in units of |β| for free-base pentaphyrin and N-fused pentaphyrins. SSEs are underlined

positive SSEs. In support of these positive SSEs, the proton NMR spectra are consistent with aromatic ring current effects [5–16]. In contrast to these superaromatic species, **5**, **7**, and **9** have negative SSEs. Proton NMR spectra of **5** and **9** actually display anti-aromatic ring current effects [7–11, 13]. As a result, differences in chemical shifts of the inner protons between **5** and **6** are as much as 10–12 ppm [11]. Bond-length alternation is observed clearly in **7** [9], which further supports the super-anti-aromatic character of this macrocycle. However, the proton NMR spectrum of **5** does not show any anti-aromatic ring current effect [9].

We have pointed out that, if the minimum BRE (min BRE) in a given cyclic π system is less than −0.100 |β|, the molecule will be kinetically unstable or chemically reactive [22–24]. In this sense, **3** and **5** must be kinetically unstable. As for the fairly planar π-system of **3**, rings A and B are the origin of local anti-aromaticity; in all there are three π-bonds with BREs < −0.100 |β| and eight π-bonds with negative BREs, all of which belong to these two rings. Toganoh et al. [15] noted that, whereas this species is stable in the solid state and in solution under an inert atmosphere, it gradually decomposes to an open-ring N-confused N-fused porphyrin derivative on exposure to air in solution.

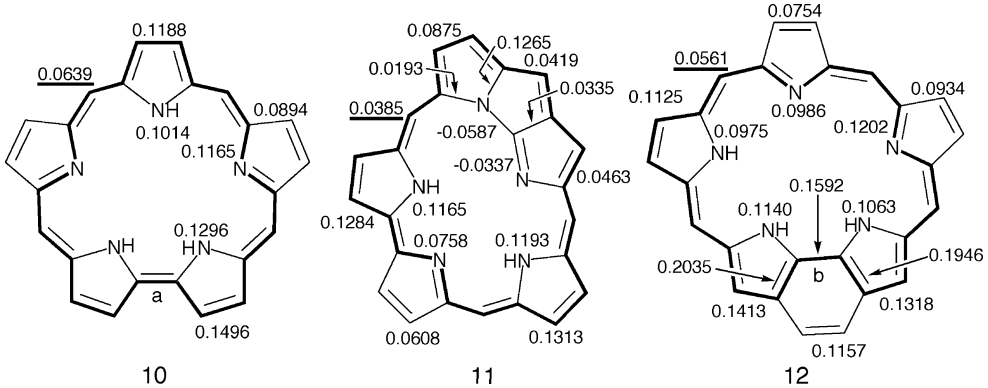

Fig. 3 BREs in units of |β| for three sapphyrins. SSEs are underlined

Table 1 Topological resonance energy (TRE) and superaromatic stabilization energy (SSE) in units of |β| for porphyrinoids studied and related annulenes

Species	TRE	SSE
1	0.4322	0.0843
2	0.2988	0.0407
3	0.1436	0.0343
4	0.4489	0.0641
5	0.4364	−0.1410
6	0.3560	0.0567
7	0.4711	−0.0499
8	0.3322	0.0271
9	0.4870	−0.0466
10	0.5904	0.0639
11	0.4653	0.0385
12	0.6447	0.0561
[18]annulene	0.0877	–
[20]annulene	−0.2360	–
[22]annulene	0.0716	–
[24]annulene	−0.1966	–

Such reactivity may be associated with large negative BREs. They also attributed the bathochromic shift of the electronic spectrum of **3** to the presence of two internally fused tripentacyclic subunits [15]. We found that these tripentacyclic subunits are very anti-aromatic in nature, which must diminish the highest occupied molecular orbital (HOMO)–lowest unoccupied molecular orbital (LUMO) energy separation. TRE for **3** is the smallest of all species studied.

The SSE for **5** is smaller than −0.100 |β|, which represents the min BRE assumed for the planar π-system. In fact, **5**–**9** have greatly strained macrocycles irrespective of their macrocyclic aromaticity, so that they must be stabilized effectively by canting one or more rings from the mean plane of the macrocycle [7–11, 13]. The same must be true for **6**–**9** regardless of their macrocyclic aromaticity. It then follows that **5** cants ring A significantly to suppress macrocyclic anti-aromaticity. Mori et al. observed that one of the expanded porphyrins with negative SSEs, [24]hexaphyrin(1.1.1.1.1.1), is atropic but becomes paratropic when metalated with one or two gold(III) ions [33, 34]. It is obvious that the planarity enforced by metalation is crucial to the manifestation of macrocyclic anti-aromaticity in this porphyrinoid.

As suggested earlier, our original procedure for predicting a main macrocyclic conjugation pathway [21] must be modified when applied to porphyrinoids with fused rings. We first classify π-bonds in these porphyrinoids into four groups: π-bonds linking two adjacent five-membered rings, outer π-bonds (π-bonds that belong to five-membered rings but are located along the outer rim of the macrocycle), inner π-bonds (those that belong to five-membered rings but are located along the inner rim of the macrocycle), and π-bonds shared by two five-membered rings. π-Bonds linking two adjacent rings always constitute part of a main macrocyclic conjugation pathway (e.g., **9a** in Fig. 4); all macrocyclic circuits pass through these π-bonds [35]. Whether π bonds shared by two rings should be chosen as part of a main macrocyclic conjugation pathway or not depends on the circumstances surrounding them.

When a given macrocycle has a positive SSE, one should next choose an inner or outer π-bond with a larger BRE from each five-membered ring. As local circuits contribute equally to the BREs for the inner and outer π-bonds, inner or outer π-bonds with a larger BRE represent the larger contribution of the macrocyclic circuits to it. In the case of a macrocycle with a negative SSE, one should choose an inner or outer π-bond with a smaller BRE from each five-membered ring (e.g., **9b** in Fig. 4). This step is justified by the fact that all macrocyclic circuits always pass through the outer or inner π-bond in each ring [20, 35]. Note that, if macrocyclic contributions were disregarded, BREs for inner π-bonds belonging to five-membered rings would be the same as those for the outer π-bonds in the same ring [20, 21]. Finally, choose π bonds shared by two five-membered rings if necessary to complete the macrocyclic pathway (e.g., **9c** in Fig. 4). BREs for such

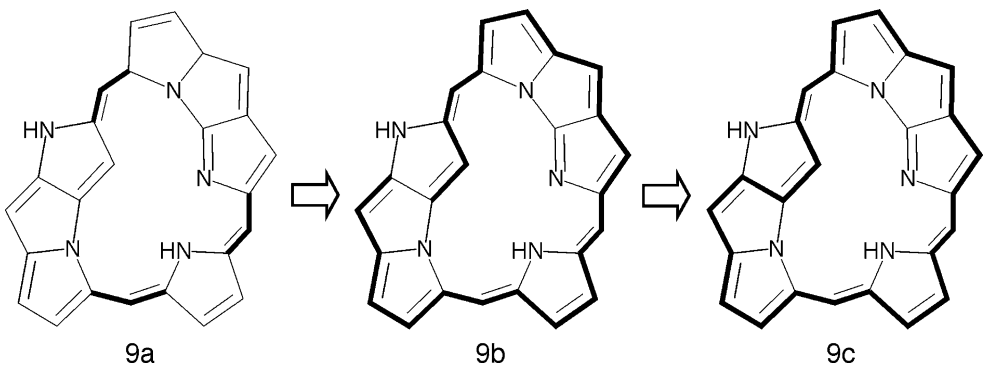

Fig. 4 Prediction of a main macrocyclic conjugation pathway in **9**. The final pathway in **9c** is identical with the main macrocyclic conjugation pathway of **9** in Fig. 1

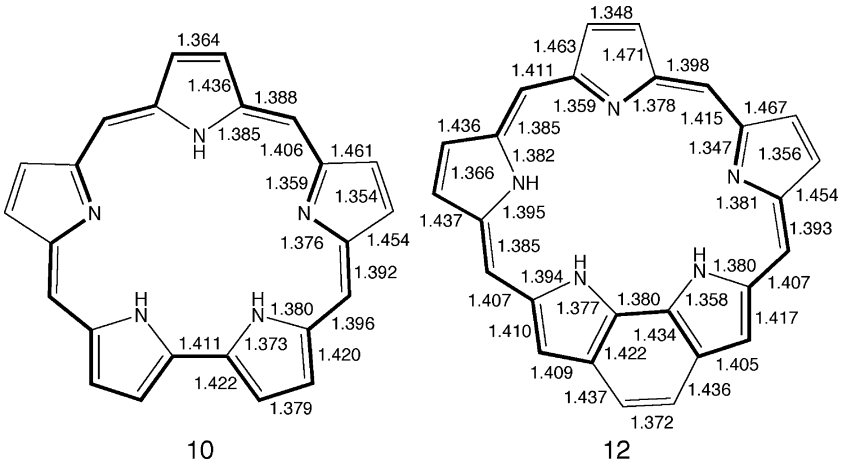

Fig. 5 B3LYP/6-31G**-optimized geometries of two sapphyrins. π-Bond lengths are given in Ångströms

π bonds are often relatively large because local aromaticity due to adjacent pyrrolic rings contributes to the increase in BRE [23].

Main macrocyclic conjugation pathways thus predicted for **1**–**12** are shown in bold lines in Figs. 1–3. Those in **5**, **9**, and **12** pass through π bonds shared by two rings, snaking somewhat along the macrocycles. Note that formal double bonds can be written for these π bonds. Main macrocyclic conjugation pathways in other porphyrinoids do not pass though any such π-bonds. As far as **1**–**12** are concerned, a main macrocyclic conjugation pathway always avoids all amine nitrogens. It is noteworthy that main macrocyclic conjugation pathways in **2**, **3, 7**–**9,** and **11** do not pass through all imine nitrogens. Such a situation never occurs in natural and expanded porphyrins without fused rings.

A main macrocyclic conjugation pathway in **1** is identical with an aromatic [18]annulene pathway [20]. Main macrocyclic conjugation pathways in **2** and **3** are also identical with aromatic [18]annulene. Those in **4**, **6**, **8**, and **10**–**12** turned out to be aromatic [22]annulenes, whereas **5**, **7**, and **9** possess anti-aromatic [24]annulene pathways. It is interesting to note that the annulene pathways in **3** and **9** avoid all nitrogen atoms. All these macrocyclic pathways are fully consistent with the annulene model for porphyrins [5–16]. Therefore, we can safely say that, as in the case of regular, contracted, expanded, confused, and inverted porphyrins [21], π-bonds located along a main aromatic conjugation pathway are intensified with larger BREs than those located along the bypasses, whereas those located along a main anti-aromatic conjugation pathway are weakened with smaller BREs. TREs for annulenes relevant to the present case have been added to Table 1. In general, the absolute magnitude of the SSE for a given porphyrinoid is smaller to a greater or lesser extent than the TRE for the corresponding annulene. For example, SSEs for **1**–**3** are all smaller than the TRE of [18] annulene, whereas SSEs for **4**, **6**, **8**, and **10**–**12** are all smaller than that for [22]annulene. Five-membered rings fused to the main macrocyclic conjugation pathway may possibly suppress macrocyclic aromaticity. As has been

Table 2 SSEs in units of |β| for the molecular ions of porphyrinoids studied

Species	Molecular dication	Neutral molecule	Molecular dianion
1	−0.0942	0.0843	−0.1384
2	−0.0181	0.0407	−0.0571
3	−0.0041	0.0343	−0.0225
4	−0.0508	0.0641	−0.1149
5	0.0610	−0.1410	0.0626
6	−0.0374	0.0567	−0.0852
7	0.0268	−0.0499	0.0419
8	−0.0116	0.0271	−0.0422
9	0.0239	−0.0466	0.0411
10	−0.0705	0.0639	−0.1627
11	−0.0160	0.0385	−0.0338
12	−0.0477	0.0561	−0.0742

shown, Hückel's 4n+2 rule of aromaticity, applicable only to monocyclic π-systems, can formally be applied to the main macrocyclic conjugation pathways in porphyrinoids.

Benzo-annelated sapphyrin **12** is not an N-fused species but is considered here for the sake of comparison. Like other sapphyrins (**10**, **11**), this species exhibits diamagnetic ring current effects in proton NMR spectra. However, a main macrocyclic conjugation pathway cannot be chosen intuitively from this π-system, because two [22]annulene pathways, those passing through the inner and outer rims of the benzene ring, can be chosen from it. On the basis of the present BRE-based approach, the [22]annulene pathway that passes through the inner rim of the benzene ring (i.e., bond **b**) is chosen as the best macrocyclic conjugation pathway. The B3LYP/6-31G** optimized geometry of **12** in Fig. 5 supports this choice. As seen from this figure, the outer rim of the benzene ring suffers from distinct bond-length alternation. Bond **b** in **12** is considerably shorter than bond **a** in **10**. Thus, our approach is of particular use when the annulene model cannot be used without ambiguity.

Randić defined a conjugated circuit as follows [36]. First, delete all atoms that lie along a given circuit from the π-system. If one or more classical resonance structures can be written for the residual π-system, the circuit is classified as a conjugated circuit. All of the main macrocyclic conjugation pathways in **1**–**12** correspond to the smallest macrocyclic conjugated circuits. One should note that all (4n+2)π and 4nπ conjugated circuits are the main origin of aromaticity and anti-aromaticity, respectively, even in a polycyclic π system [37]. All (4n+2)π and 4nπ conjugated circuits sustain diamagnetic and paramagnetic π-electron currents, respectively [37]. No non-conjugated macrocyclic circuits serve as main macrocyclic conjugation pathways in porphyrinoids with and without fused rings.

Electronic structure of expanded para-cyclophanes, in which more than three para-phenylene rings are linked to form a macrocyclic π-system, has been characterized by means of proton NMR spectroscopy [38, 39]. The Hückel-like rule of macrocyclic aromaticity holds for these macrocycles [32, 38, 39]. This rule states that, if a neutral macrocyclic molecule has a positive SSE, both the molecular dianion with two more π electrons and the molecular dication with two less π electrons will have negative SSEs. Conversely, if a neutral molecule has a negative SSE, the molecular dianion and dication will have positive SSEs. Many porphyrinoid species formally satisfy this Hückel-like rule [21]. N-Fused porphyrins are also expected to conform to this rule. We then calculated SSEs for the molecular dianions and dications of **1**–**12** and listed them in Table 2. It is clear from this table that the Hückel-like rule of macrocyclic aromaticity holds for **1**–**12**. For example, the neutral molecule of **6** has a negative SSE, whereas the molecular dianion and dication have positive SSEs. It follows that both the HOMO and the LUMO are the determinants of macrocyclic aromaticity in these porphyrinoids.

Concluding remarks

Macrocyclic aromaticity and ring-current magnetism are determined primarily by macrocyclic conjugation [20, 21]. In this paper, we presented a generalized procedure for predicting main macrocyclic conjugation pathways in porphyrinoids with fused rings, and firmly established the concepts of macrocyclic conjugation and macrocyclic aromaticity in N-fused and benzo-annelated porphyrins. It is now clear that not only regular porphyrinoids but also porphyrinoid species with fused-ring subsystems can naïvely be viewed as large bridged annulenes. Annulene-like delocalization pathways represent well the essence of macrocyclic aromaticity or anti-aromaticity in which many macrocyclic circuits participate. For example, doubly N-fused species **9** has as many as 128 macrocyclic circuits. The present BRE-based approach to macrocyclic conjugation will be useful not only for deepening our understanding of electronic structure of many different macrocyclic π-systems but also for designing novel macrocyclic structures.

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