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Investigating the (Poly)Radicaloid Nature of Real-World Organic Compounds with DFT-Based Methods

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11 Investigating the (poly)radicaloid nature
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Abstract

Recent advances in the synthesis of stable organic (open-shell) polyradicaloids have opened their application as active compounds for emerging technologies. These systems typically exhibit small energy differences between states with different spin multiplicities, which are intrinsically difficult to calculate by theoretical methods. We thus apply here some DFT-based variants (FT-DFT, SF-DFT, and SF-TDDFT) on a test set of large and real-world molecules, as test systems for which such energy differences are experimentally available, also comparing systematically with RAS-SF results to infer if shortcomings of previous DFT applications are corrected. Additionally, we explore the spin-spin contribution to the ZFS tensor, of high interest for EPR spectroscopy, and derive the spatial extent of the corresponding (photoexcited) triplet state.

Key words: organic (poly)radicals, low- and high-spin states, finite-temperature DFT, spin-flip (TD)DFT, ZFS tensor.

1 Introduction

Studying the (poly)radical character of organic molecules is a long-standing field of research due to the many envisioned applications of these compounds.^{1,2} Recent experimental developments, in ultrahigh-vacuum surfaces or using non-standard synthetic routes, have propelled the synthesis of highly challenging species including classically studied carbon-rich radicals³ like triangulenes,⁴ graphene nanoribbons with zigzag edges,^{5,6} kekulenes,⁷ long acenes,^{8,9} cyclic nanobelts,^{10,11} etc. All these systems share a complicated electronic structure, with (near-)degenerated orbitals lying within the gap between occupied and virtual ones, leading to small exchange interactions and thus close in energy low- (e.g. singlet or doublet) and high-spin (e.g. triplet or quartet) many-body states.¹² Furthermore, C-based magnetism is gaining attention for nanographene fragments since long time ago,¹³ and it has been recently demonstrated for well-defined geometrical C-based structures, like those arising from planar conjugated hydrocarbons, how to anticipate the spin multiplicity and energy ordering of the corresponding states,¹⁴ thus complementing the Ovchinnikov's rule¹⁵ and the Lieb theorem.¹⁶ However, for more general situations, one should rely on robust, accurate, and cost-effective theoretical methods, which is still a difficult task not exempted from computational limitations, especially for large systems.¹⁷

On the other hand, the application of standard Density Functional Theory (DFT) methods to these (poly)radical systems is known to be affected by some pitfalls and/or artifacts: the intrinsic one-determinantal nature of Kohn-Sham (KS) DFT precludes to deal with orbital degeneracies, thus neglecting non-dynamical or static correlation effects, and the use of a Broken-

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8 Symmetry (BS) solution for open-shell systems introduces spin-contamination
9 (also scaling with size¹⁸) issues mostly affecting the energy of the low-spin
10 solution.¹⁹ This situation has historically prompted the development of non-
11 standard methods able to cope with these subtle electronic effects, namely
12 based on the two-body on-top pair density²⁰⁻²⁹ with a revisited interest
13 nowadays,³⁰⁻³³ the balanced coupling of *ab initio* and density functional
14 expressions,³⁴⁻³⁷ the use of natural orbitals³⁸⁻⁴⁰ or the specific *ensemble*
15 of pure spin states,⁴¹⁻⁴³ to name just a few of the existing non-standard
16 methods. Another possible route is the use of fractional spin⁴⁴ or orbital
17 occupation,^{45,46} mimicking the situation when multiconfigurational *ab ini-*
18 *tio* methods are instead employed, or spin-flip techniques,⁴⁷⁻⁴⁹ describing
19 target states from a high-spin reference state.
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31 To further explore (*vide infra*) the applicability and accuracy of modern
32 DFT variants, in the search for the best trade-off between accuracy and
33 computational cost, we have chosen a set of large (and real-world) organic
34 radical compounds recently synthesized and crystallized with diverse struc-
35 tural motifs (see Figure 1). Note that for all of the systems selected, their
36 stability has allowed the original authors to perform experimental measure-
37 ments such as Electron Spin Resonance (ESR) or Superconducting QUan-
38 tum Interference Device (SQUID), among others, to extract e.g., the energy
39 difference between low- and high-spin states, thus allowing to bracket the
40 accuracy of the theoretical methods employed after the comparison with ex-
41 perimental results. The systems selected here (and their short names used
42 in the following) are: (i) substituted Blatter-like radicals^{50,51} (Diradical
43 I and II); (ii) [6]cyclo-para-phenylmethine⁵² (6CPPM-Mes); (iii) [n]cyclo-
44 para-biphenylmethines⁵³ ([n]CPBM-Ant) with $n = 3 - 6$; (iv) ethynylene-
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bridged fluorenyl macrocycle⁵⁴ (MC-F3A3); and (v) cyclopenta-ring-fused oligo(m-phenylene) macrocyclic⁵⁵ (8MC). Note that the DFT-based results will also be compared with those from the Restricted-Active-Space Spin-Flip (RAS-SF) method,⁵⁶ to bracket their accuracy also for magnitudes for which experimental results are not available.

2 Theoretical Methods

2.1 The FT-DFT method

The Finite-Temperature DFT (FT-DFT) method relies on the fractional occupation of molecular orbitals induced by (near-)degeneracy effects, with the associated density written as:

$$\rho(\mathbf{r}) = \sum_i^{\infty} f_i |\phi_i(\mathbf{r})|^2, \quad (1)$$

where $\phi_i(\mathbf{r})$ is a molecular spin-orbital and f_i its fractional electron occupation numbers ($0 \leq f_i \leq 1$). The self-consistency of the procedure is achieved by minimizing the Gibbs electronic free energy ($G_{el} = E_{el} - T_{el}S_{el}$) of the system at a fictitious pseudo-temperature (i.e., electronic) called T_{el} , with the f_i values obtained by a Fermi-Dirac distribution around the Fermi level E_F :

$$f_i = \frac{1}{1 + e^{(\epsilon_i - E_F)/\theta}}, \quad (2)$$

depending on $\theta = k_B T_{el}$. The corresponding energy difference between the low-spin (LS) and high-spin (HS) solutions can be calculated after imposing the desired spin multiplicity, $\Delta E(\text{LS} - \text{HS}) = E(\text{LS}) - E(\text{HS})$, with $\Delta E(\text{LS} - \text{HS}) < 0$ indicating a favoured low-spin ground-state (antiferromagnetic). Note the similarities between this method and the Thermally-Assisted-Occupation (TAO) DFT method of Chai *et al.*^{46,57}

2.1.1 Characterization of the radical character

Additionally, the set $\{f_i, \phi_i(\mathbf{r})\}$ can be used to define a density of unpaired electrons, that is the Fractional Orbital Density (FOD)^{58,59} as:

$$\rho^{FOD}(\mathbf{r}) = \sum_i^M (\delta_1 - \delta_2 f_i) |\phi_i(\mathbf{r})|^2, \quad (3)$$

where δ_1 and δ_2 are chosen to become $(1, 1)$ if the single-particle energy level (ϵ_i) associated with the orbital ϕ_i is lower than the energy of the Fermi level, E_F , or $(0, -1)$ otherwise. This density also leads upon integration to a measure of the number of strongly correlated electrons, $N_{FOD} = \int \rho^{FOD}(\mathbf{r}) d\mathbf{r}$, which is a concept equivalent to the (linear) metrics introduced by Head-Gordon,⁶⁰ typically labelled as N_U and obtained from natural orbital occupation numbers (NOONs), i.e., the eigenvalues of the one-electron reduced density matrix.

Complementarily, the radical character of electronic states can be quantified by means of the radical indices $0 \leq y_i \leq 1$ ($i = 0, 1, 2, 3$). Within the FT-DFT methodology, they can be directly assigned to the electronic occupations above the Fermi level as $y_i = f_{LUMO+i}^\alpha + f_{LUMO+i}^\beta$, with f_{LUMO+i}^σ the fractional occupation number of the lowest unoccupied LUMO+ i spin-orbital (since approximately $f_{LUMO+i}^\sigma + f_{HOMO-i}^\sigma = 1$). For systems with a significant (poly)radical nature, the indices y_i can be used to estimate their di- or tri- (y_0), tetra- or penta- (y_1), hexa- or hepta- (y_2), and octa- or nonradical (y_3) character, respectively. Large indices ($y_i \approx 1$) indicate high radical character, while intermediate values are indicative of moderate (poly)radicaloid character. The similarity of these fractional occupation numbers with the NOONs has been recently confirmed for polycyclic aromatic hydrocarbons,⁶¹ as well as the trend between N_{FOD} and global

biradical values arising from experimental measurements.^{62,63}

2.2 The SF-DFT method

The Spin-Flip DFT (SF-DFT) method relies on the exchange of the α and β spin blocks of the density on certain user-defined centers, thus generating a Broken-Symmetry (BS) solution after converging the high-spin wavefunction. The energy difference between both considered configurations is given by $\Delta E(\text{BS} - \text{HS}) = E(\text{BS}) - E(\text{HS})$, which can be used as a first approximation to the energy difference between LS and HS solutions. Energy differences between pure spin states can be estimated by the Yamaguchi’s procedure:^{64–66}

$$\Delta E(\text{LS} - \text{HS}) = \frac{n_S}{\langle \hat{S}^2 \rangle_{\text{HS}} - \langle \hat{S}^2 \rangle_{\text{BS}}} \Delta E(\text{BS} - \text{HS}), \quad (4)$$

where n_S corresponds to the $\langle \hat{S}^2 \rangle$ difference between the ideal spin multiplicities, e.g., $n_S = 2$ for a LS singlet and a HS triplet, $n_S = 3$ for a LS doublet and a HS quartet, etc.

2.3 The SF-TDDFT method

The Spin-Flip Time-Dependent DFT (SF-TDDFT) method is recognized to uniformly describe excited states of single, double, and mixed excitation character in molecular systems,⁶⁷ and more specifically in conjugated molecules featuring diradical or (poly)radical character,^{68,69} starting from a high-spin (e.g., triplet) reference state. The formalism is based on the (linear response) TDDFT equations for excitation energies:

$$\begin{bmatrix} \mathbf{A} & \mathbf{B} \\ \mathbf{B}^* & \mathbf{A}^* \end{bmatrix} \begin{bmatrix} \mathbf{X} \\ \mathbf{Y} \end{bmatrix} = \Omega \begin{bmatrix} \mathbf{1} & \mathbf{0} \\ \mathbf{0} & -\mathbf{1} \end{bmatrix} \begin{bmatrix} \mathbf{X} \\ \mathbf{Y} \end{bmatrix}, \quad (5)$$

with \mathbf{X} (\mathbf{Y}) the set of (de-)excitation amplitudes, \mathbf{A} and \mathbf{B} the linear-response matrices, and Ω the excitation energies. In SF-TDDFT, Eq. (5) is solved for the subspace of spin-flip ($\alpha \rightarrow \beta$) operators.⁴⁷ For this case, the general expression for \mathbf{A} and \mathbf{B} elements simplify to $A_{i\bar{a},j\bar{b}} = \delta_{ij}\delta_{\bar{a},\bar{b}}(\epsilon_{\bar{a}} - \epsilon_i) - C_x(ij|\bar{a}\bar{b})$ and $B_{i\bar{a},j\bar{b}} = -C_x(ib|\bar{a}\bar{j})$, with C_x the weight of exact exchange of the density functional used, i, j (a, b) refer to occupied (virtual) orbitals (the overbar on orbital indices indicates β -spin), ϵ_p is the energy associated to the KS p -spin-orbital, and $(pq|st)$ is the two electron interaction integral given in Mülliken's notation:

$$(pq|st) = \int \phi_p^*(\mathbf{x})\phi_q(\mathbf{x})\frac{1}{|\mathbf{x} - \mathbf{x}'|}\phi_t^*(\mathbf{x}')\phi_s(\mathbf{x}')d\mathbf{x}d\mathbf{x}' \quad (6)$$

2.4 The RAS-SF method

Spin-flip methods with single spin-flip excitations^{70–72} are not capable to properly describe low-spin states of molecular systems with more than three unpaired electrons, e.g., tetraradicals. This limitation can be overcome through the generalization of the excitation operator to multiple spin-flip excitations, as in the RAS-SF method. In RAS-SF the orbital space of the high-spin reference is split in three subspaces: doubly occupied (RAS1), singly occupied (RAS2), and virtual (RAS3). The eigenstates of the RAS-SF Hamiltonian are obtained as n -spin-flip excitations expanded in terms of the number of holes (electrons) in the doubly (virtual) spaces:

$$\hat{R}^{n\text{SF}} = \hat{r}_0^{n\text{SF}} + \hat{r}_h^{n\text{SF}} + \hat{r}_p^{n\text{SF}} + \hat{r}_{hp}^{n\text{SF}} + \hat{r}_{2h}^{n\text{SF}} + \hat{r}_{2p}^{n\text{SF}} + \dots, \quad (7)$$

where $\hat{r}_0^{n\text{SF}}$ performs all possible spin-flip excitations within RAS2 and h and p subindices indicate the number of holes and electrons in RAS1 and

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8 RAS3, respectively.
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10 11 12 **2.5 Computational details** 13

14 We use a semi-local (TPSS⁷³) and a pair of hybrid⁷⁴ (TPSS0 and TPSSHH)
15 exchange-correlation meta-GGA functionals differing in the weight (C_x) of
16 the EXact-eXchange (EXX) introduced (i.e., 0% for TPSS, 25% for TPSS0,
17 and 50% for TPSSHH) for the FT-DFT and SF-DFT calculations reported
18 here. Note that the original FT-DFT method employed the TPSS functional,
19 which will be respected here, but we will also complementarily explored the
20 dependence of the results with respect to the EXX weight. The electronic
21 temperature (T_{el}) was fixed for the FT-DFT calculations following the rec-
22 ommended expression $T_{el}/K = 5000 + 20000 C_x$ as a function of the EXX
23 weight C_x .
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33 We use the cost-effective 6-31G** (SF-DFT) and the large def2-TZVP⁷⁵
34 (FT-TPSS) basis sets for those calculations, together with the RIJCOSX
35 technique⁷⁶ (with the def2/JK auxiliary basis sets⁷⁷) to reduce the increase
36 in computational cost associated to the TPSS0 and TPSSHH functionals.
37 The plots of the $\rho^{\text{FOD}}(\mathbf{r})$ density were generated by the UCSF Chimera⁷⁸
38 (version 1.12) package. The FT-DFT and SF-DFT calculations were done
39 with the ORCA (version 4.0.1.2) quantum-chemical package⁷⁹ employing
40 ultrafine numerical integration grids (i.e., Grid6, NoFinalGrid) in all cases.
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50 The SF-TDDFT calculations employed the collinear approximation as
51 implemented in the GAMESS package,⁸⁰ together with the BHHLYP func-
52 tional⁸¹ and the cost-effective 6-31G* basis set. Note that the use of a
53 functional with a high $C_x = 0.50$ value is recommended for this kind of
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8 calculations,^{47,82} and that the accuracy is not expected to vary using an-
9 other exchange-correlation functional like TPSSHH of PBEHH (both with
10 the same $C_x = 0.50$ value than BHHLYP).⁸³
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15 The RAS-SF calculations have been done within the hole and electron
16 approximation, that is including the three first terms in the rhs of Eq. (5)
17 using a ROHF (Restricted Open-Shell) high-spin reference: triplet (Blatter-
18 like diradicals), quartet ([3]CPBM), quintet ([4]CPBM), sextet ([5]CPBM),
19 septet ([6]CPPM and [6]CPBM), and nonet (8MC). Further details can be
20 found at the Supporting Information and elsewhere.⁵²⁻⁵⁵ These calculations
21 have been done with the Q-Chem (version 5.2) program⁸⁴ and the 6-31G**
22 basis set.
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31 Finally, the Zero-Field-Splitting (ZFS) calculations were performed with
32 the ω B97X-D functional⁸⁵ and the IGLO-II basis set,⁸⁶ intended for com-
33 puting magnetic properties with high accuracy,⁸⁷ together with the 'Au-
34 toAux' generation procedure for auxiliary basis sets.⁸⁸ The ZFS tensor was
35 self-consistently calculated on the basis on spin-Unrestricted Natural Or-
36 bitals (UNO)⁸⁹ as recommended.⁹⁰ The ZFS calculations were done with
37 the ORCA (version 4.0.1.2) quantum-chemical package⁷⁹ employing a tight
38 threshold for convergence (i.e., TightSCF) and ultrafine numerical integra-
39 tion grids (i.e., Grid6, NoFinalGrid) in all cases.
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3 Results and discussion

3.1 Quantification of the (poly)radicaloid character.

First, we aim to evaluate the extent of the radical character, i.e., the number of unpaired electrons (N_{FOD}), of the considered molecular species by means of FT-DFT calculations. The N_{FOD} values obtained by FT-TPSS, FT-TPSS0, and FT-TPSSHH methods are presented in Table 1 for both the low- and high-spin states of all studied compounds. Complementarily, Figure 2 compares the calculated N_{FOD} values for the low-spin state of all compounds, from which we can recognize a close agreement between RAS-SF and FT-TPSS results. The results discussed along this section will thus limit to those obtained at the FT-TPSS level, with FT-TPSS0 slightly (FT-TPSSHH largely) overestimating the RAS-SF results. Moreover, all molecules present significant N_{FOD} values, indicating their open-shell (poly)radical character. The radical character is also preserved for the high-spin states, i.e. qualitatively similar $N_{FOD}(\text{LS})$ and $N_{FOD}(\text{HS})$ values are found except for Diradical I and II systems. Because fractional occupation is induced by near degeneracy, the smaller values of N_{FOD} for the HS state of Diradical I and II can be rationalized by their HOMO-1/HOMO and LUMO/LUMO+1 gaps, considerably larger than those of the other systems investigated. Interestingly, the series of [n]CPBM-Ant ($n = 3 - 6$) compounds is predicted to increase their radical character as a function of their increasing size, in perfect agreement with experimental and RAS-SF results.⁵³

Following the agreement found between N_{FOD} values at the FT-TPSS and RAS-SF levels, see also Table S1, we represent in Figure 3 the topology (real-space distribution) of the corresponding density, $\rho^{FOD}(\mathbf{r})$, at the FT-TPSS level and using the recommended threshold^{58,59} for the isocon-

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 8 tour values ($\sigma = 0.005 \text{ e/bohr}^3$). For the Blatter-like radicals, the FOD
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 10 density concentrates on the N atoms of the conjugated backbone, and on
 11
 12 the nitrosyl substituents, in agreement with what one would expect from the
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 14 resonance Lewis structures of the molecules. For 6CPPM-Mes, [n]CPBM-
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 16 Ant ($n = 3 - 6$), and MC-F3A3 compounds we can observe how the FOD
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 18 density locates mainly at those C atoms bringing the mesityl and anthracene
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 20 substituents, respectively, acting effectively as protective synthons. For the
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 22 8MC compound we observe a delocalization of the FOD density on the non-
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 24 bridging C atoms, resembling the results found for other systems with cyclic
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 26 topologies as cyclacenes (i.e. cyclic oligoacenes⁹¹).
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3.1.1 Radical(oid) indices.

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 30 In order to get a deeper insight into the radical nature of these com-
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 32 pounds, in the following we explore them by means of their $\{y_i\}$ indices.
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 34 Table 2 presents the y_0 , y_1 , y_2 , and y_3 values for all the systems studied at
 35
 36 the FT-TPSS level. The Blatter-like diradicals exhibit nearly ideal diradical
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 38 character, with $y_0 \simeq 1.0$ and $y_{i>0} \simeq 0$ for the low and high-spin T_0 states.
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 40 Note that this is in agreement with the smaller N_{FOD} values discussed in
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 42 the previous section for the HS state of these two systems. The 6CPPM-Mes
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 44 molecule holds a sizable tetraradicaloid character, with moderate y_0 and y_1
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 46 values for the ground-state singlet. For the [n]CPBM-Ant ($n = 3 - 6$) sys-
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 48 tems, we observe an increase of the number of strongly correlated electrons
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 50 as a function of their size, in agreement with the trend found for the N_{FOD}
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 52 values. Inspection of their y_i values allows to classify them as tri-, tetra-
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 54 , penta- and hexaradicaloid molecules, respectively. Finally, for the 8MC
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 56 molecule we obtain moderate values for all the y_{0-3} indices, indicating a
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 58 moderate octaradicaloid behaviour. Tables S2-S3 present the y_i values ob-
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8 tained at the FT-TPSS0 and FT-TPSSHH levels, respectively, which follow
9 the same trend found for FT-TPSS, but with $\{y_i\}$ indices being systemati-
10 cally larger, like for N_{FOD} values.
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15 3.2 Energy difference between low- and high-spin states.

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18 Table 3 presents the energy difference $\Delta E(\text{LS} - \text{HS})$ between the low-
19 and high-spin states of all the systems considered, calculated at the FT-
20 TPSS, FT-TPSS0, and FT-TPSSHH levels. Note that, except for the Blatter-
21 like diradicals considered, the electronic ground-state of these systems is al-
22 ways the one with the lowest spin-multiplicity, thus denoted as S_0 (singlet) or
23 D_0 (doublet). Therefore, $\Delta E(\text{LS} - \text{HS})$ refers to the S_0 - T_1 or D_0 - Q_1 energy
24 difference, respectively, and will hold a negative sign: $\Delta E(\text{LS} - \text{HS}) < 0$.
25 For the Blatter-like diradicals, the triplet electronic ground-state is instead
26 favoured, and in these cases it should be $\Delta E(\text{LS} - \text{HS}) > 0$ accordingly.
27 First of all, inspecting the evolution of values in Table 3, we can see how the
28 relative stabilization of the HS state with respect to the LS solution increases
29 with the amount of Hartree-Fock exchange, i.e., upon going from FT-TPSS
30 to FT-TPSS0, and to FT-TPSSHH, with the latter being systematically
31 closer to experimental energy gaps. However, the agreement with experi-
32 mental results largely differs among the set of compounds, even looking at
33 the FT-TPSSHH results (i.e. best estimates) providing the lowest MSE and
34 MUE values. For [6]CPBM or 8MC, employing any of the FT-DFT variants
35 will lead to an error close or even less than 1 kcal/mol, commonly known
36 as the chemical accuracy threshold. On the other hand, for [3]CPBM and
37 MC-F3A3 compounds the computed gaps are a few kcal/mol too negative,
38 even with the FT-TPSSH method. Figure 4 compares the FT-DFT cal-
39 culated values with the experimental results, for which we can also easily
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8 observe a different behaviour for odd and even $[n]$ CPBM compounds. These
9 facts, together with the spread of the results for MC-F3A3, allow us to con-
10 clude that the FT-DFT (with the default electronic temperatures) tends to
11 overestimate the relative stability of low-spin (singlet or doublet) state with
12 respect to the next higher spin state (triplet or quartet). Energy differences
13 can be systematically improved, to some extent, by increasing the amount
14 of exact exchange.
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22 We compare next the SF-DFT and the experimental results in Table
23 4, also using the TPSS, TPSS0, and TPSSHH functionals to disclose the
24 effect of linearly increasing the exact-exchange weight. First of all, we con-
25 sider the FOD density as the criteria to select those atoms to flip, with the
26 highest density localized on them, which could also be roughly estimated by
27 inspecting the corresponding spin density. In this case, spin contamination
28 becomes a key factor and results progressively deteriorates upon increas-
29 ing the exact-exchange weight, contrarily to what happened with FT-DFT
30 methods. The (spin-corrected) energy gaps $\Delta E(\text{LS} - \text{HS})$ keep an accuracy
31 similar to that obtained for the uncorrected $\Delta E(\text{BS} - \text{HS})$ values, still with
32 the SF-TPSS or SF-TPSS0 methods providing the closest agreement with
33 experimental results (e.g., MUEs of 6.0 and 4.0–5.0 kcal/mol, respectively).
34 Remarkably, the SF-TPSS method provides the correct lowest-energy spin-
35 state for all the molecules considered, contrarily to SF-TPSS0 and especially
36 SF-TPSSHH. Inspecting now the SF-TDDFT results in Table 5, done with
37 the BHHLYP and thus comparable with TPSSHH in terms of having a sim-
38 ilar exact exchange proportion, we observe larger averaged errors than for
39 previous FT-DFT or SF-DFT methods, with a reverse state ordering for
40 Diradicals I and II. The method yields too large energy differences for the
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set of $[n]$ CPBM compounds, but it keeps the correct trend of decreasing the ΔE values with increasing size.

For the sake of comparison of all these results, RAS-SF gives a MSE (MUE) of -0.55 (0.85) kcal/mol with respect to experimental results, with a maximum deviation of 3.2 kcal/mol and producing thus more accurate relative energies than the investigated DFT-based methods. Actually, this method is able to provide the chemical accuracy sought for the whole set of compounds. Discarding the case of $[6]$ CPPM-Mes, the MSE (MUE) would decrease to -0.22 (0.56) kcal/mol, and thus being considerably low.

3.3 Zero-field splitting interactions

The magnetic dipole-dipole (i.e., spin-spin) interaction leads to the splitting of the triplet sublevels ($M_s = 0, \pm 1$) even in the absence of any external field; a physical effect described by the Zero-Field Splitting (ZFS) Hamiltonian:

$$\hat{H}_{ZFS} = \hat{\mathbf{S}} \cdot \hat{\mathbf{D}} \cdot \hat{\mathbf{S}} = D_{xx} \hat{S}_x^2 + D_{yy} \hat{S}_y^2 + D_{zz} \hat{S}_z^2 = D \left(\hat{S}_z^2 - \frac{1}{3} \hat{\mathbf{S}}^2 \right) + E \left(\hat{S}_x^2 - \hat{S}_y^2 \right), \quad (8)$$

with D_{ii} the principal values of the ZFS diagonal tensor $\hat{\mathbf{D}}$, which by convention are recasted as $D = D_{zz} - \frac{1}{2} (D_{xx} + D_{yy})$ and $E = \frac{1}{2} (D_{xx} - D_{yy})$. For systems having $S > 1/2$, the ZFS usually dominates the spectral shape of the Electron Paramagnetic Resonance (EPR) spectra, and thus the absolute values of D and the E/D ratio determine the energies of the three magnetic sublevels.⁹² Additionally, provided that the point-dipole approximation holds, D also relates with the averaged distance (Δr) between ideally localized spin densities, and can be thus used to estimate the size of the photoexcited triplet exciton⁹³ (see the Supporting Information for further

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8 details). Note that in the following we will restrict the study to those sys-
9 tems possessing ground-state or low-lying triplet states, i.e., with an even
10 number of electrons.
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15 First of all, we have thoroughly assessed the accuracy of DFT methods
16 to calculate the D and E parameters for the pair of systems (Diradicals
17 I and II) for which experimental measurements are available.⁵¹ For both
18 compounds it is clear that $D/hc < 0$ from the experimental EPR spec-
19 tra, thus indicating a prolate-like distribution of the spin density for the
20 triplet state. The sign of D indicates whether the $M_s = 0$ ($D > 0$) or
21 $M_s = \pm 1$ ($D < 0$) spin substrates are the lowest energy states at zero ex-
22 ternal fields. However, previous results at the B3LYP/EPR-II level,⁵¹ and
23 with different exchange-correlation functionals and basis sets (see Tables S4-
24 S5), predicted the wrong sign for Diradical II ($D/hc > 0$), which is properly
25 characterized only by certain range-separated functionals (i.e., ω B97X-D⁸⁵
26 and LC-BLYP⁹⁴) together with basis sets suited for electric and magnetic
27 properties, i.e. IGLO-II or EPR-II, previously applied⁹⁵ to the study of
28 spin-spin contributions to the ZFS tensor in organic radicals too.
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42 This deficiency of DFT methods has also been documented before^{96,97}
43 and prompted us to apply in the following the ω B97X-D functional for con-
44 sistency. Note also that the range-separated CAM-B3LYP functional⁹⁹ was
45 also used but did not bring the correct sign of D for Diradical II. The main
46 difference between the ω B97X-D/LC-BLYP and CAM-B3LYP schemes is a
47 relatively large (35%) fixed DFT exchange contribution in the latter, and
48 thus a maximum screened exact exchange of 65%, which seems to corrob-
49 orate the importance of that variable part (80% and 100% for ω B97X-D
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8 and LC-BLYP, respectively). On the other hand, looking again at Tables
9 S4-S5, the relative error for the calculation of E was found larger than for
10 D , in agreement with previous applications to heavy-atoms coordination
11 complexes.⁹⁸
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17 Table 6 presents the D , E , and Δr calculated values (at the ω B97X-
18 D/IGLO-II level) for the lowest triplet state of the set of compounds studied.
19 Interestingly, for the Diradicals I and II, a high-spin ground-state together
20 with a negative D could lead to effective molecular magnets.¹³ In the case
21 of 8MC, we can see how $E = 0$ due to the perfect axial symmetry of this
22 compound, with E being considerably lower than D as expected in all other
23 cases. Inspecting the Δr values, i.e., the mean inter-spin distance in a dipole-
24 dipole approximation, see the Supporting Information for further details
25 about the explicit derivation, we can see how it decreases with the system
26 size; a fact also documented before for linear polyenes and polyacenes.¹⁰⁰
27 This is rationalized by the dependence $D \propto r^{-3}$ with r the distance between
28 the spins of the unpaired electrons. We can also compare these results with
29 the estimated exciton size (Δr) for the triplet ground-state of 2,6,10-Tri-
30 *tert*-Butyltriangulene,¹⁰¹ around 5.6 Å, or for the photoexcited triplet state
31 of tetracene and pentacene,¹⁰² around 3.8 Å, or for the photoexcited triplet
32 state of B- and N-doped nanographenes,¹⁰³ around 4.4-5.2 Å depending on
33 their size.
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50 4 Conclusions

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53 We report here a benchmark study of a set of real-world (poly)radicaloids,
54 focusing on the extent of the radical character, spatial distribution of the
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8 unpaired electrons, and singlet-triplet (or doublet-quartet) energy difference
9 obtained with different electronic structure methods. Current research on
10 organic (poly)radicaloid character and its applications has prompted the ap-
11 plication here of both (cost-effective) DFT-based and RAS-SF methods, with
12 the latter method behaving more accurately than the others as compared
13 with reference experimental results. Complementarily, we have systemati-
14 cally compared finite-temperature (FT-DFT) and spin-flip approaches (SF-
15 DFT and SF-TDDFT) with various exchange-correlation functionals, mostly
16 differing in their exact exchange weight, to disentangle the effect of the un-
17 derlying expression as well as the effect of the spin-contamination intro-
18 duced. Evidently, the use of any of these approaches with a GGA form (i.e.,
19 TPSS) is less costly than using a hybrid expression. Finally, we have also
20 calculated the ZFS parameters for the triplet states of the compounds, as
21 well as their exciton size. Overall, we have shown how the cost-effective char-
22 acterization of (poly)radicaloid nature in conjugated organic compounds is
23 still a challenging issue, precluding the blind application of DFT variants.
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48 Supplementary Material

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51 The Supplementary Material contains in this order: (i) the metrics er-
52 ror used to compare the performance of the different methods; (ii) N_U and
53 $\Delta E(\text{LS} - \text{HS})$ values obtained at the RAS-SF level for all the compounds;
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(iii) calculated radical indices (y_i) at the FT-TPSS0 and FT-TPSSHH levels for all the compounds; (iv) comparison between calculated and experimental EPR parameters for Diradicals I and II; (v) notes on the theoretical estimates of the exciton size and the sign of the D-tensor; (vi) cartesian coordinates of all the compounds.

References

- [1] Hu, X.; Wang, W.; Wang, D.; Zheng, Y. The electronic applications of stable diradicaloids: present and future. *Journal of Materials Chemistry C* **2018**, *6*, 11232–11242.
- [2] Badía-Domínguez, I.; Pérez-Guardiola, A.; Sancho-García, J. C.; Lopez Navarrete, J. T.; Hernandez Jolin, V.; Li, H.; Sakamaki, D.; Seki, S.; Rúaiz Delgado, M. C. Formation of Cyclophane Macrocycles in Carbazole-Based Biradicaloids: Impact of the Dicyanomethylene Substitution Position. *ACS Omega* **2019**, *4*, 4761–4769.
- [3] Morita, Y.; Suzuki, S.; Sato, K.; Takui, T. Synthetic organic spin chemistry for structurally well-defined open-shell graphene fragments. *Nature chemistry* **2011**, *3*, 197.
- [4] Pavlíček, N.; Mistry, A.; Majzik, Z.; Moll, N.; Meyer, G.; Fox, D. J.; Gross, L. Synthesis and characterization of triangulene. *Nature Nanotechnology* **2017**, *12*, 308.
- [5] Wang, S.; Talirz, L.; Pignedoli, C. A.; Feng, X.; Müllen, K.; Fasel, R.; Ruffieux, P. Giant edge state splitting at atomically precise graphene zigzag edges. *Nature Communications* **2016**, *7*, 11507.
- [6] Li, J.; Sanz, S.; Corso, M.; Choi, D. J.; Peña, D.; Frederiksen, T.;

- 1
2
3
4
5
6
7
8 Pascual, J. I. Single spin localization and manipulation in graphene
9 open-shell nanostructures. *Nature Communications* **2019**, *10*, 200.
10
11
12 [7] Pozo, I.; Majzik, Z.; Pavliček, N.; Melle-Franco, M.; Guitián, E.;
13 Peña, D.; Gross, L.; Perez, D. Revisiting kekulene: synthesis and
14 single-molecule imaging. *Journal of the American Chemical Society*
15 **2019**, *141*, 15488–15493.
16
17
18 [8] Mondal, R.; Shah, B. K.; Neckers, D. C. Photogeneration of heptacene
19 in a polymer matrix. *Journal of the American Chemical Society* **2006**,
20 *128*, 9612–9613.
21
22
23 [9] Tönshoff, C.; Bettinger, H. F. Photogeneration of octacene and
24 nonacene. *Angewandte Chemie International Edition* **2010**, *49*, 4125–
25 4128.
26
27
28 [10] Segawa, Y.; Yagi, A.; Matsui, K.; Itami, K. Design and Synthesis of
29 carbon nanotube segments. *Angewandte Chemie International Edition*
30 **2016**, *55*, 5136–5158.
31
32
33 [11] Povie, G.; Segawa, Y.; Nishihara, T.; Miyauchi, Y.; Itami, K. Synthesis
34 of a carbon nanobelt. *Science* **2017**, *356*, 172–175.
35
36
37 [12] Stuyver, T.; Chen, B.; Zeng, T.; Geerlings, P.; De Proft, F.; Hoff-
38 mann, R. Do Diradicals Behave Like Radicals? *Chemical Reviews*
39 **2019**,
40
41
42 [13] Perumal, S.; Minaev, B.; Ågren, H. Spin-spin and spin-orbit inter-
43 actions in nanographene fragments: A quantum chemistry approach.
44 *The Journal of Chemical Physics* **2012**, *136*, 104702.
45
46
47 [14] Ortiz, R.; Boto, R. Á.; García-Martínez, N.; Sancho-García, J. C.;
48
49
50
51
52
53
54
55
56
57
58
59
60

- 1
2
3
4
5
6
7
8 Melle-Franco, M.; Fernández-Rossier, J. Exchange rules for diradical
9 *pi*-conjugated hydrocarbons. *Nano Letters* **2019**, *19*, 5991–5997.
- 10
11
12 [15] Ovchinnikov, A. A. Multiplicity of the ground state of large alternant
13 organic molecules with conjugated bonds. *Theoretica Chimica Acta*
14 **1978**, *47*, 297–304.
- 15
16
17
18 [16] Lieb, E. H. Two theorems on the Hubbard model. *Physical Review*
19 *Letters* **1989**, *62*, 1201.
- 20
21
22
23 [17] Das, A.; Muller, T.; Plasser, F.; Lischka, H. Polyradical Character
24 of Triangular Non-Kekulé Structures, Zethrenes, p-Quinodimethane-
25 Linked Bisphenalenyl, and the Clar Goblet in Comparison: An Ex-
26 tended Multireference Study. *The Journal of Physical Chemistry A*
27 **2016**, *120*, 1625–1636.
- 28
29
30
31
32 [18] Hajgató, B.; Deleuze, M. S. Quenching of magnetism in hexago-
33 nal graphene nanoflakes by non-local electron correlation. *Chemical*
34 *Physics Letters* **2012**, *553*, 6–10.
- 35
36
37
38 [19] Illas, F.; Moreira, I. P.; De Graaf, C.; Barone, V. Magnetic coupling
39 in biradicals, binuclear complexes and wide-gap insulators: a survey
40 of ab initio wave function and density functional theory approaches.
41 *Theoretical Chemistry Accounts* **2000**, *104*, 265–272.
- 42
43
44
45 [20] Moscardó, F.; San-Fabián, E. Density-Functional Formalism and the
46 Two-Body Problem. *Physical Review A* **1991**, *44*, 1549.
- 47
48
49
50
51 [21] Perdew, J. P.; Savin, A.; Burke, K. Escaping the Symmetry Dilemma
52 through a Pair-Density Interpretation of Spin-Density Functional The-
53 ory. *Physical Review A* **1995**, *51*, 4531.
- 54
55
56
57
58
59
60

- 1
2
3
4
5
6
7
8 [22] Miehllich, B. B.; Stoll, H.; Savin, A. A Correlation-Energy Density
9 Functional for Multideterminantal Wavefunctions. *Molecular Physics*
10 **1997**, *91*, 527–536.
11
12
13
14 [23] Moscardó, F.; Pérez-Jiménez, A. J. Self-Consistent Field Calculations
15 Using Two-Body Density Functionals for Correlation Energy Compo-
16 nent: I. Atomic Systems. *Journal of Computational Chemistry* **1998**,
17 *19*, 1887–1898.
18
19
20
21
22 [24] Moscardó, F.; Pérez-Jiménez, A. J.; Cjuno, J. A. Self-Consistent Field
23 Calculations Using Two-Body Density Functionals for Correlation
24 Energy Component: II. Small Molecules. *Journal of Computational*
25 *Chemistry* **1998**, *19*, 1899–1908.
26
27
28
29
30 [25] McDouall, J. J. Combining Two-Body Density Functionals with
31 Multiconfigurational Wavefunctions: Diatomic Molecules. *Molecular*
32 *Physics* **2003**, *101*, 361–371.
33
34
35
36 [26] Sancho-García, J. C.; Moscardó, F. Usefulness of the Colle–Salvetti
37 Model for the Treatment of the Nondynamic Correlation. *The Journal*
38 *of Chemical Physics* **2003**, *118*, 1054–1058.
39
40
41
42 [27] Takeda, R.; Yamanaka, S.; Yamaguchi, K. Approximate On-Top Pair
43 Density into One-Body Functions for CAS-DFT. *International Journal*
44 *of Quantum Chemistry* **2004**, *96*, 463–473.
45
46
47
48 [28] Gusarov, S.; Malmqvist, P.-Å.; Lindh, R. Using On-Top Pair Den-
49 sity for Construction of Correlation Functionals for Multideterminant
50 Wave Functions. *Molecular Physics* **2004**, *102*, 2207–2216.
51
52
53
54 [29] Toulouse, J.; Colonna, F.; Savin, A. Long-Range–Short-Range Sepa-
55
56
57
58
59
60

1
2
3
4
5
6
7
8 ration of the Electron-Electron Interaction in Density-Functional The-
9 ory. *Physical Review A* **2004**, *70*, 062505.

10
11
12 [30] Li Manni, G.; Carlson, R. K.; Luo, S.; Ma, D.; Olsen, J.; Truh-
13 lar, D. G.; Gagliardi, L. Multiconfiguration Pair-Density Functional
14 Theory. *Journal of Chemical Theory and Computation* **2014**, *10*,
15 3669–3680.

16
17
18
19
20 [31] Gagliardi, L.; Truhlar, D. G.; Li Manni, G.; Carlson, R. K.;
21 Hoyer, C. E.; Bao, J. L. Multiconfiguration Pair-Density Functional
22 Theory: A New Way to Treat Strongly Correlated Systems. *Accounts*
23 *of Chemical Research* **2016**, *50*, 66–73.

24
25
26
27
28 [32] Hoyer, C. E.; Ghosh, S.; Truhlar, D. G.; Gagliardi, L. Multiconfig-
29 uration Pair-Density Functional Theory is as Accurate as CASPT2
30 for Electronic Excitation. *The Journal of Physical Chemistry Letters*
31 **2016**, *7*, 586–591.

32
33
34
35
36 [33] Ghosh, S.; Cramer, C. J.; Truhlar, D. G.; Gagliardi, L. Generalized-
37 Active-Space Pair-Density Functional Theory: An Efficient Method
38 to Study Large, Strongly Correlated, Conjugated Systems. *Chemical*
39 *Science* **2017**, *8*, 2741–2750.

40
41
42
43
44 [34] Grimme, S.; Waletzke, M. A Combination of Kohn–Sham Density
45 Functional Theory and Multi-Reference Configuration Interaction
46 Methods. *The Journal of Chemical Physics* **1999**, *111*, 5645–5655.

47
48
49
50 [35] Gräfenstein, J.; Cremer, D. The Combination of Density Func-
51 tional Theory with Multi-Configuration Methods–CAS-DFT. *Chemical*
52 *Physics Letters* **2000**, *316*, 569–577.

53
54
55
56 [36] Nakata, K.; Ukai, T.; Yamanaka, S.; Takada, T.; Yamaguchi, K.

CASSCF Version of Density Functional Theory. *International Journal of Quantum Chemistry* **2006**, *106*, 3325–3333.

- [37] Pijeau, S.; Hohenstein, E. G. Improved Complete Active Space Configuration Interaction Energies with a Simple Correction from Density Functional Theory. *Journal of Chemical Theory and Computation* **2017**, *13*, 1130–1146.
- [38] Pérez-Jiménez, Á. J.; Pérez-Jordá, J. M.; Sancho-García, J. C. Combining Two-Body Density Correlation Functionals with Multiconfigurational Wave Functions Using Natural Orbitals and Occupation Numbers. *The Journal of Chemical Physics* **2007**, *127*, 104102.
- [39] Piris, M.; Lopez, X.; Ruipérez, F.; Matxain, J.; Ugalde, J. A Natural Orbital Functional for Multiconfigurational States. *The Journal of Chemical Physics* **2011**, *134*, 164102.
- [40] Piris, M.; Ugalde, J. M. Perspective on Natural Orbital Functional Theory. *International Journal of Quantum Chemistry* **2014**, *114*, 1169–1175.
- [41] Filatov, M.; Shaik, S. A Spin-Restricted Ensemble-Referenced Kohn–Sham Method and its Application to Diradicaloid Situations. *Chemical Physics Letters* **1999**, *304*, 429–437.
- [42] Kazaryan, A.; Heuver, J.; Filatov, M. Excitation Energies from Spin-Restricted Ensemble-Referenced Kohn–Sham Method: A State-Average Approach. *The Journal of Physical Chemistry A* **2008**, *112*, 12980–12988.
- [43] Filatov, M. Spin-Restricted Ensemble-Referenced Kohn–Sham Method: Basic Principles and Application to Strongly Correlated

- 1
2
3
4
5
6
7
8 Ground and Excited States of Molecules. *Wiley Interdisciplinary*
9 *Reviews: Computational Molecular Science* **2015**, *5*, 146–167.
- 10
11
12 [44] Ess, D. H.; Johnson, E. R.; Hu, X.; Yang, W. Singlet- Triplet Energy
13 Gaps for Diradicals from Fractional-Spin Density-Functional Theory.
14 *The Journal of Physical Chemistry A* **2010**, *115*, 76–83.
- 15
16
17
18 [45] Grimme, S. Towards First Principles Calculation of Electron Impact
19 Mass Spectra of Molecules. *Angewandte Chemie International Edition*
20 **2013**, *52*, 6306–6312.
- 21
22
23
24 [46] Chai, J.-D. Density Functional Theory with Fractional Orbital Occu-
25 pations. *The Journal of Chemical Physics* **2012**, *136*, 154104.
- 26
27
28
29 [47] Shao, Y.; Head-Gordon, M.; Krylov, A. I. The spin-flip approach
30 within time-dependent density functional theory: Theory and appli-
31 cations to diradicals. *The Journal of Chemical Physics* **2003**, *118*,
32 4807–4818.
- 33
34
35
36 [48] Wang, F.; Ziegler, T. Time-dependent density functional theory based
37 on a noncollinear formulation of the exchange-correlation potential.
38 *The Journal of Chemical Physics* **2004**, *121*, 12191–12196.
- 39
40
41
42 [49] Wang, F.; Ziegler, T. The performance of time-dependent density func-
43 tional theory based on a noncollinear exchange-correlation potential
44 in the calculations of excitation energies. *The Journal of Chemical*
45 *Physics* **2005**, *122*, 074109.
- 46
47
48
49
50
51 [50] Gallagher, N. M.; Bauer, J. J.; Pink, M.; Rajca, S.; Rajca, A. High-
52 spin organic diradical with robust stability. *Journal of the American*
53 *Chemical Society* **2016**, *138*, 9377–9380.
- 54
55
56
57
58
59
60

- 1
2
3
4
5
6
7
8 [51] Gallagher, N.; Zhang, H.; Junghoefer, T.; Giangrisostomi, E.; Ovsyan-
9 nikov, R.; Pink, M.; Rajca, S.; Casu, M. B.; Rajca, A. Thermally
10 and magnetically robust triplet ground state diradical. *Journal of the*
11 *American Chemical Society* **2019**, *141*, 4764–4774.
12
13
14
15
16 [52] Li, Z.; Gopalakrishna, T. Y.; Han, Y.; Gu, Y.; Yuan, L.; Zeng, W.;
17 Casanova, D.; Wu, J. [6]Cyclo-para-phenylmethine: an analog of ben-
18 zene showing global aromaticity and open-shell diradical character.
19 *Journal of the American Chemical Society* **2019**, *141*, 16266–16270.
20
21
22
23 [53] Ni, Y.; Sandoval-Salinas, M. E.; Tanaka, T.; Phan, H.; Heng, T. S.;
24 Gopalakrishna, T. Y.; Ding, J.; Osuka, A.; Casanova, D.; Wu, J.
25 [n]Cyclo-para-biphenylmethine polyradicaloids: [n]annulene analogs
26 and unusual valence tautomerization. *Chem* **2019**, *5*, 108–121.
27
28
29
30
31 [54] Lu, X.; Lee, S.; Hong, Y.; Phan, H.; Gopalakrishna, T. Y.;
32 Heng, T. S.; Tanaka, T.; Sandoval-Salinas, M. E.; Zeng, W.; Ding, J.;
33 Casanova, D.; Osuka, A.; Kim, D.; Wu, J. Fluorenyl based macrocyclic
34 polyradicaloids. *Journal of the American Chemical Society* **2017**, *139*,
35 13173–13183.
36
37
38
39
40
41 [55] Liu, C.; Sandoval-Salinas, M. E.; Hong, Y.; Gopalakrishna, T. Y.;
42 Phan, H.; Aratani, N.; Heng, T. S.; Ding, J.; Yamada, H.; Kim, D.;
43 Casanova, D.; Wu, J. Macrocyclic polyradicaloids with unusual super-
44 ring structure and global aromaticity. *Chem* **2018**, *4*, 1586–1595.
45
46
47
48 [56] Casanova, D.; Head-Gordon, M. Restricted active space spin-flip con-
49 figuration interaction approach: theory, implementation and exam-
50 ples. *Physical Chemistry Chemical Physics* **2009**, *11*, 9779–9790.
51
52
53
54 [57] Lin, C.-Y.; Hui, K.; Chung, J.-H.; Chai, J.-D. Self-Consistent De-
55 termination of the Fictitious Temperature in Thermally-Assisted-
56
57
58
59
60

- 1
2
3
4
5
6
7
8 Occupation Density Functional Theory. *RSC Advances* **2017**, *7*,
9 50496–50507.
- 10
11
12 [58] Grimme, S.; Hansen, A. A practicable real-space measure and visual-
13 ization of static electron-correlation effects. *Angewandte Chemie In-*
14 *ternational Edition* **2015**, *54*, 12308–12313.
- 15
16
17
18 [59] Bauer, C. A.; Hansen, A.; Grimme, S. The fractional occupation num-
19 ber weighted density as a versatile analysis tool for molecules with
20 a complicated electronic structure. *Chemistry-A European Journal*
21 **2017**, *23*, 6150–6164.
- 22
23
24
25
26 [60] Head-Gordon, M. Characterizing unpaired electrons from the one-
27 particle density matrix. *Chemical Physics Letters* **2003**, *372*, 508–511.
- 28
29
30
31 [61] Yeh, C.-N.; Chai, J.-D. Role of Kekulé and non-Kekulé structures in
32 the radical character of alternant polycyclic aromatic hydrocarbons:
33 a TAO-DFT study. *Scientific Reports* **2016**, *6*, 30562.
- 34
35
36
37 [62] Nakano, M.; Kishi, R.; Ohta, S.; Takahashi, H.; Kubo, T.; Ka-
38 mada, K.; Ohta, K.; Botek, E.; Champagne, B. Relationship between
39 third-order nonlinear optical properties and magnetic interactions in
40 open-shell systems: a new paradigm for nonlinear optics. *Physical Re-*
41 *view Letters* **2007**, *99*, 033001.
- 42
43
44
45
46 [63] Pérez-Guardiola, A.; Sandoval-Salinas, M. E.; Casanova, D.; San-
47 Fabián, E.; Pérez-Jiménez, A.; Sancho-García, J.-C. The role of topol-
48 ogy in organic molecules: origin and comparison of the radical char-
49 acter in linear and cyclic oligoacenes and related oligomers. *Physical*
50 *Chemistry Chemical Physics* **2018**, *20*, 7112–7124.
- 51
52
53
54
55
56 [64] Yamaguchi, K.; Fukui, H.; Fueno, T. Molecular orbital (MO) theory
57
58
59
60

1
2
3
4
5
6
7
8 for magnetically interacting organic compounds. Ab-initio MO calcu-
9 lations of the effective exchange integrals for cyclophane-type carbene
10 dimers. *Chemistry Letters* **1986**, *15*, 625–628.

- 11
12
13
14 [65] Yamaguchi, K.; Takahara, Y.; Fueno, T.; Houk, K. N. Extended
15 Hartree-Fock (EHF) theory of chemical reactions. *Theoretica Chim-*
16 *ica Acta* **1988**, *73*, 337–364.
- 17
18
19
20 [66] Yamanaka, S.; Okumura, M.; Nakano, M.; Yamaguchi, K. EHF the-
21 ory of chemical reactions Part 4. UNO CASSCF, UNO CASPT2 and
22 R(U)HF coupled-cluster (CC) wavefunctions. *Journal of Molecular*
23 *Structure: THEOCHEM* **1994**, *310*, 205–218.
- 24
25
26
27
28 [67] Rinkevicius, Z.; Vahtras, O.; Ågren, H. Spin-flip time dependent den-
29 sity functional theory applied to excited states with single, double, or
30 mixed electron excitation character. *The Journal of Chemical Physics*
31 **2010**, *133*, 114104.
- 32
33
34
35
36 [68] Canola, S.; Casado, J.; Negri, F. The double exciton state of con-
37 jugated chromophores with strong diradical character: insights from
38 TDDFT calculations. *Physical Chemistry Chemical Physics* **2018**, *20*,
39 24227–24238.
- 40
41
42
43
44 [69] Canola, S.; Dai, Y.; Negri, F. The Low Lying Double-Exciton State
45 of Conjugated Diradicals: Assessment of TDUDFT and Spin-Flip
46 TDDFT Predictions. *Computation* **2019**, *7*, 68.
- 47
48
49
50 [70] Krylov, A. I. Spin-flip configuration interaction: an electronic struc-
51 ture model that is both variational and size-consistent. *Chemical*
52 *Physics Letters* **2001**, *350*, 522–530.
- 53
54
55
56 [71] Krylov, A. I. Spin-flip equation-of-motion coupled-cluster electronic
57
58
59
60

1
2
3
4
5
6
7
8 structure method for a description of excited states, bond breaking,
9 diradicals, and triradicals. *Accounts of Chemical Research* **2006**, *39*,
10 83–91.
11

12
13
14 [72] Casanova, D.; Krylov, A. I. *Physical Chemistry Chemical Physics*,
15 2020, DOI: 10.1039/C9CP06507E.
16

17
18 [73] Tao, J.; Perdew, J. P.; Staroverov, V. N.; Scuseria, G. E. Climbing
19 the density functional ladder: Nonempirical meta-generalized gradi-
20 ent approximation designed for molecules and solids. *Physical Review*
21 *Letters* **2003**, *91*, 146401.
22
23

24
25
26 [74] Staroverov, V. N.; Scuseria, G. E.; Tao, J.; Perdew, J. P. Comparative
27 assessment of a new nonempirical density functional: Molecules and
28 hydrogen-bonded complexes. *The Journal of Chemical Physics* **2003**,
29 *119*, 12129–12137.
30
31

32
33
34 [75] Weigend, F.; Ahlrichs, R. Balanced basis sets of split valence, triple
35 zeta valence and quadruple zeta valence quality for H to Rn: De-
36 sign and assessment of accuracy. *Physical Chemistry Chemical Physics*
37 **2005**, *7*, 3297–3305.
38
39

40
41
42 [76] Kossmann, S.; Neese, F. Comparison of two efficient approximate
43 Hartree–Fock approaches. *Chemical Physics Letters* **2009**, *481*, 240–
44 243.
45
46

47
48 [77] Weigend, F. Hartree–Fock exchange fitting basis sets for H to Rn.
49 *Journal of Computational Chemistry* **2008**, *29*, 167–175.
50
51

52
53 [78] Pettersen, E. F.; Goddard, T. D.; Huang, C. C.; Couch, G. S.; Green-
54 blatt, D. M.; Meng, E. C.; Ferrin, T. E. UCSF Chimera: A Visu-
55
56
57
58
59
60

- 1
2
3
4
5
6
7
8 alization System for Exploratory Research and Analysis. *Journal of*
9 *Computational Chemistry* **2004**, *25*, 1605–1612.
- 10
11
12 [79] Neese, F. Software update: the ORCA program system, version 4.0.
13 *Wiley Interdisciplinary Reviews: Computational Molecular Science*
14 **2018**, *8*, e1327.
- 15
16
17
18 [80] Schmidt, M. W.; Baldridge, K. K.; Boatz, J. A.; Elbert, S. T.; Gor-
19 don, M. S.; Jensen, J. H.; Koseki, S.; Matsunaga, N.; Nguyen, K. A.;
20 Su et al., S. General atomic and molecular electronic structure system.
21 *Journal of Computational Chemistry* **1993**, *14*, 1347–1363.
- 22
23
24
25
26 [81] Becke, A. D. A new mixing of Hartree–Fock and local density-
27 functional theories. *The Journal of Chemical Physics* **1993**, *98*, 1372–
28 1377.
- 29
30
31
32 [82] Orms, N.; Krylov, A. I. Singlet–triplet energy gaps and the degree
33 of diradical character in binuclear copper molecular magnets char-
34 acterized by spin-flip density functional theory. *Physical Chemistry*
35 *Chemical Physics* **2018**, *20*, 13127–13144.
- 36
37
38
39 [83] Bernard, Y. A.; Shao, Y.; Krylov, A. I. General formulation of spin-flip
40 time-dependent density functional theory using non-collinear kernels:
41 Theory, implementation, and benchmarks. *The Journal of Chemical*
42 *Physics* **2012**, *136*, 204103.
- 43
44
45
46
47 [84] Shao et al., Y. Advances in molecular quantum chemistry contained in
48 the Q-Chem 4 program package. *Molecular Physics* **2015**, *113*, 184–
49 215.
- 50
51
52
53
54 [85] Chai, J.-D.; Head-Gordon, M. Long-range corrected hybrid density
55
56
57
58
59
60

- 1
2
3
4
5
6
7
8 functionals with damped atom–atom dispersion corrections. *Physical*
9 *Chemistry Chemical Physics* **2008**, *10*, 6615–6620.
- 11
12 [86] Schindler, M.; Kutzelnigg, W. Theory of magnetic susceptibilities and
13 NMR chemical shifts in terms of localized quantities. II. Application
14 to some simple molecules. *The Journal of Chemical Physics* **1982**, *76*,
15 1919–1933.
- 17
18
19
20 [87] Jensen, F. Basis set convergence of nuclear magnetic shielding con-
21 stants calculated by density functional methods. *Journal of Chemical*
22 *Theory and Computation* **2008**, *4*, 719–727.
- 24
25
26 [88] Stoychev, G. L.; Auer, A. A.; Neese, F. Automatic generation of aux-
27 iliary basis sets. *Journal of Chemical Theory and Computation* **2017**,
28 *13*, 554–562.
- 30
31
32 [89] Neese, F. Calculation of the zero-field splitting tensor on the basis
33 of hybrid density functional and Hartree-Fock theory. *The Journal of*
34 *Chemical Physics* **2007**, *127*, 164112.
- 36
37
38 [90] Jost, P.; van Wüllen, C. Why spin contamination is a major problem
39 in the calculation of spin–spin coupling in triplet biradicals. *Physical*
40 *Chemistry Chemical Physics* **2013**, *15*, 16426–16427.
- 42
43
44 [91] Pérez-Guardiola, A.; Ortiz-Cano, R.; Sandoval-Salinas, M. E.;
45 Fernández-Rossier, J.; Casanova, D.; Pérez-Jiménez, A.; Sancho-
46 Garcia, J.-C. From cyclic nanorings to single-walled carbon nanotubes:
47 disclosing the evolution of their electronic structure with the help of
48 theoretical methods. *Physical Chemistry Chemical Physics* **2019**, *21*,
49 2547–2557.
- 51
52
53
54
55
56 [92] Richert, S.; Tait, C. E.; Timmel, C. R. Delocalisation of photoexcited
57
58
59
60

triplet states probed by transient EPR and hyperfine spectroscopy. *Journal of Magnetic Resonance* **2017**, *280*, 103–116.

- [93] Buta, M. C.; Toader, A. M.; Frecus, B.; Oprea, C. I.; Cimpoesu, F.; Ionita, G. Molecular and Supramolecular Interactions in Systems with Nitroxide-Based Radicals. *International Journal of Molecular Sciences* **2019**, *20*, 4733.
- [94] Tawada, Y.; Tsuneda, T.; Yanagisawa, S.; Yanai, T.; Hirao, K. A long-range-corrected time-dependent density functional theory. *The Journal of Chemical Physics* **2004**, *120*, 8425–8433.
- [95] Sinnecker, S.; Neese, F. Spin-Spin Contributions to the Zero-Field Splitting Tensor in Organic Triplets, Carbenes and Biradicals A Density Functional and Ab Initio Study. *The Journal of Physical Chemistry A* **2006**, *110*, 12267–12275.
- [96] Perumal, S. S. Zero-field splitting of compact trimethylenemethane analogue radicals with density functional theory. *Chemical Physics Letters* **2011**, *501*, 608–611.
- [97] Ye, S.; Neese, F. How do heavier halide ligands affect the signs and magnitudes of the zero-field splittings in halogenonickel (II) scorpiionate complexes? A theoretical investigation coupled to ligand-field analysis. *Journal of Chemical Theory and Computation* **2012**, *8*, 2344–2351.
- [98] Duboc, C.; Ganyushin, D.; Sivalingam, K.; Collomb, M.-N.; Neese, F. Systematic theoretical study of the zero-field splitting in coordination complexes of Mn (III). Density functional theory versus multireference wave function approaches. *The Journal of Physical Chemistry A* **2010**, *114*, 10750–10758.

- 1
2
3
4
5
6
7
8 [99] Yanai, T.; Tew, D. P.; Handy, N. C. A new hybrid exchange–
9 correlation functional using the Coulomb-attenuating method (CAM-
10 B3LYP). *Chemical Physics Letters* **2004**, *393*, 51–57.
11
12
13
14 [100] Ganyushin, D.; Gilka, N.; Taylor, P. R.; Marian, C. M.; Neese, F.
15 The resolution of the identity approximation for calculations of spin-
16 spin contribution to zero-field splitting parameters. *The Journal of*
17 *Chemical Physics* **2010**, *132*, 144111.
18
19
20
21
22 [101] Inoue, J.; Fukui, K.; Kubo, T.; Nakazawa, S.; Sato, K.; Shiomi, D.;
23 Morita, Y.; Yamamoto, K.; Takui, T.; Nakasuji, K. The first detection
24 of a Clar’s hydrocarbon, 2,6,10-tri-tert-butyltriangulene: a ground-
25 state triplet of non-Kekulé polynuclear benzenoid hydrocarbon. *Jour-*
26 *nal of the American Chemical Society* **2001**, *123*, 12702–12703.
27
28
29
30
31 [102] Bayliss, S. L.; Chepelianskii, A. D.; Sepe, A.; Walker, B. J.; Ehrler, B.;
32 Bruzek, M. J.; Anthony, J. E.; Greenham, N. C. Geminate and
33 nongeminate recombination of triplet excitons formed by singlet fis-
34 sion. *Physical Review Letters* **2014**, *112*, 238701.
35
36
37
38
39 [103] Pershin, A.; Hall, D.; Lemaire, V.; Sancho-Garcia, J.-C.; Muccioli, L.;
40 Zysman-Colman, E.; Beljonne, D.; Olivier, Y. Highly emissive excitons
41 with reduced exchange energy in thermally activated delayed fluores-
42 cent molecules. *Nature Communications* **2019**, *10*, 597.
43
44
45
46
47
48
49
50
51
52
53
54
55
56
57
58
59
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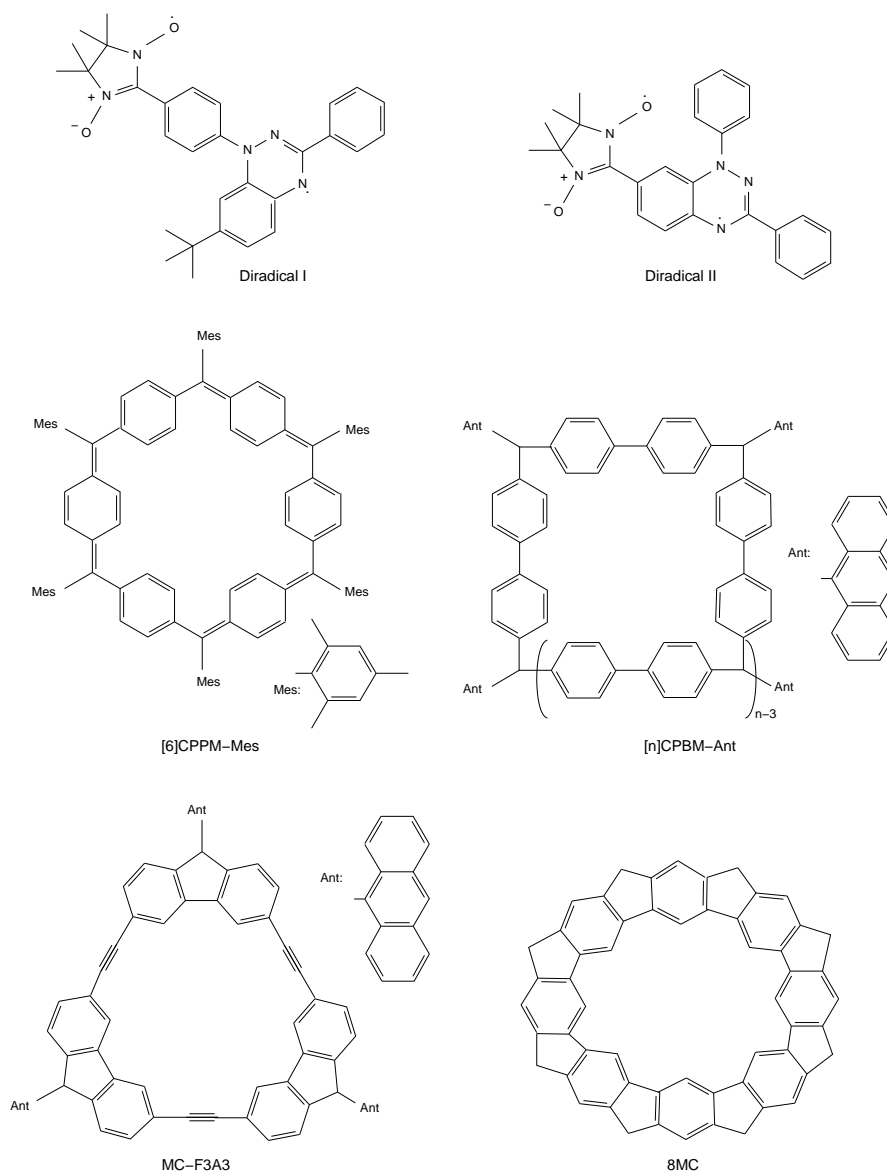


Figure 1: Chemical structures of the investigated compounds

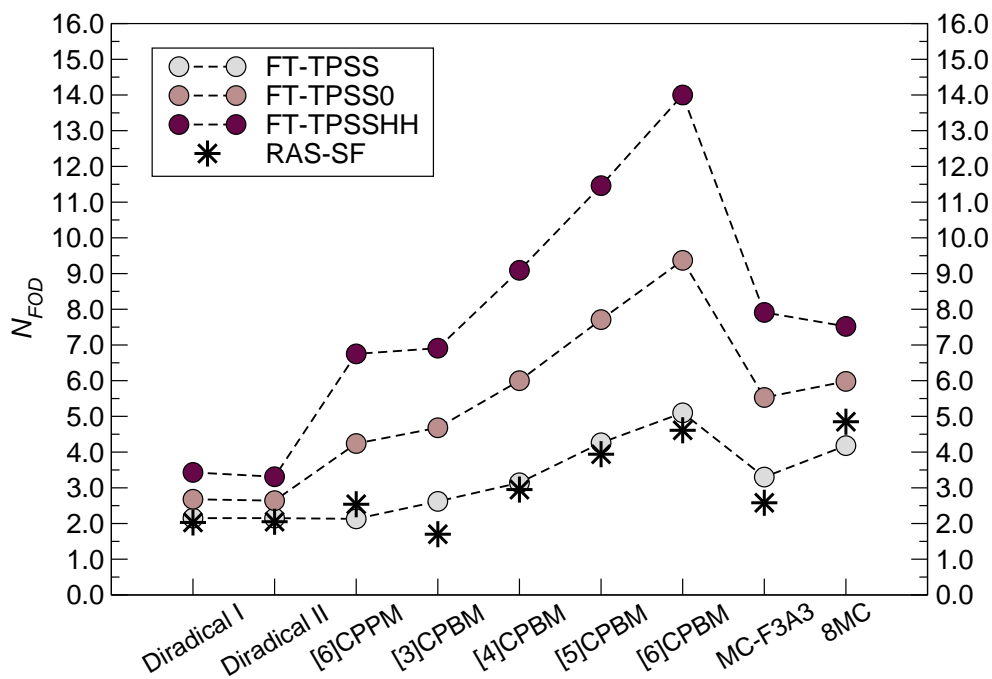


Figure 2: Comparison between FT-DFT and RAS-SF N_{FOD} values for the low-spin state of the set of studied compounds.

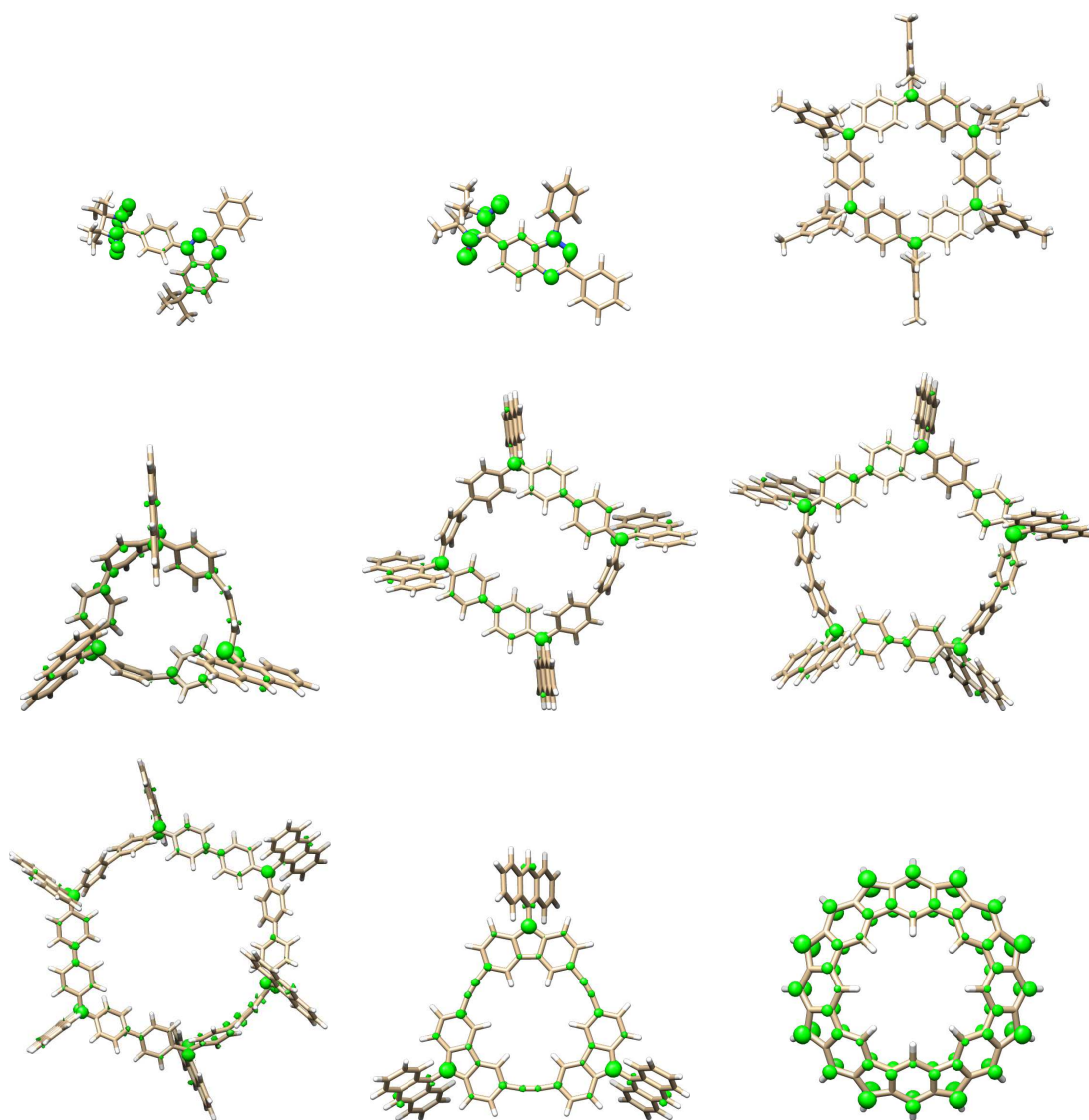


Figure 3: FOD density plots ($\sigma = 0.005 \text{ e/bohr}^3$) obtained from the FT-TPSS/def2-TZVP method for the set of studied compounds.

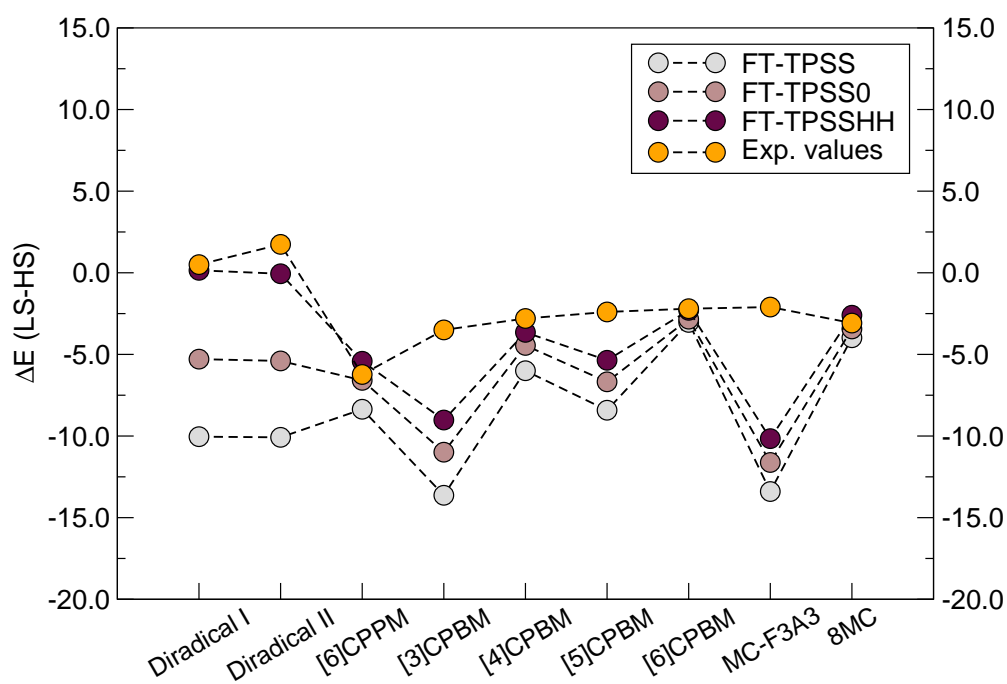


Figure 4: Comparison between $\Delta E(\text{LS} - \text{HS})$ (kcal/mol) computed (FT-DFT) and experimental values for the set of studied compounds.

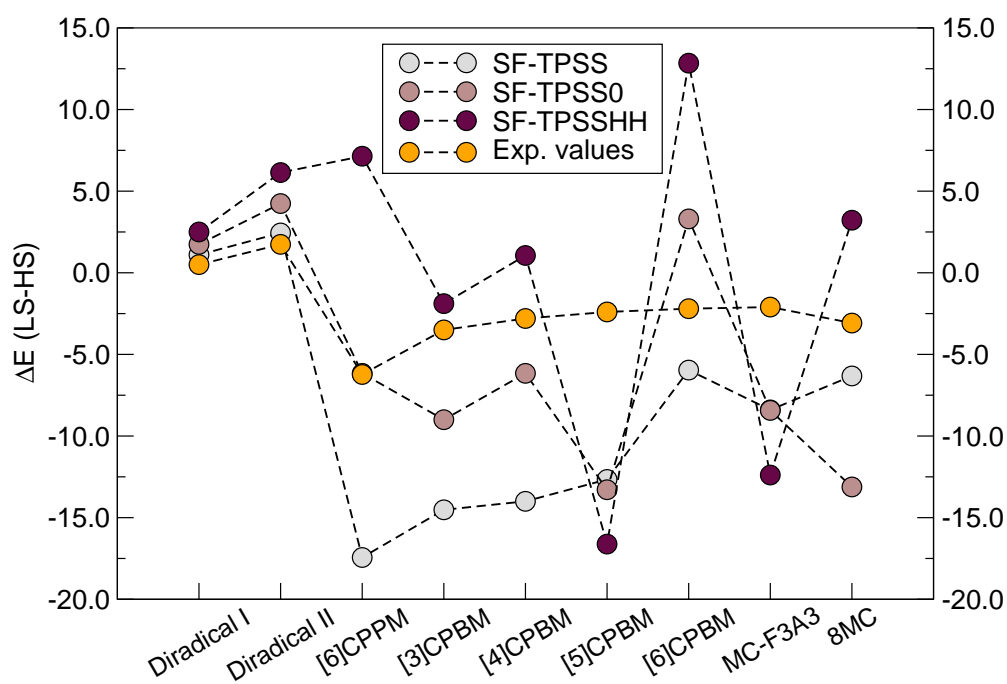


Figure 5: Comparison between $\Delta E(\text{LS} - \text{HS})$ (kcal/mol) computed (SF-DFT) and experimental values for the set of studied compounds.

Table 1: N_{FOD} values obtained at different theoretical levels.

Compound	GS	FT-TPSS		FT-TPSS0		FT-TPSSH	
		$N_{FOD}(\text{LS})$	$N_{FOD}(\text{HS})$	$N_{FOD}(\text{LS})$	$N_{FOD}(\text{HS})$	$N_{FOD}(\text{LS})$	$N_{FOD}(\text{HS})$
Diradical I ^a	T ₀	2.15	0.81	2.68	1.44	3.43	2.23
Diradical II ^a	T ₀	2.15	0.79	2.64	1.42	3.31	2.10
[6]CPPM-Mes	S ₀	2.13	2.90	4.24	4.82	6.75	7.24
[3]CPBM-Ant	D ₀	2.62	2.78	4.68	4.78	6.91	6.99
[4]CPBM-Ant	S ₀	3.14	3.70	6.00	6.43	9.09	9.44
[5]CPBM-Ant	D ₀	4.26	4.61	7.71	7.95	11.46	11.66
[6]CPBM-Ant	S ₀	5.10	5.50	9.37	9.63	14.00	14.17
MC-F3A3	D ₀	3.30	3.13	5.53	5.37	7.91	7.73
8MC	S ₀	4.18	4.34	5.98	5.93	7.52	7.36

^a Note that for these systems the header classification do not apply, since the ground-state is already the T₀ and thus the HS state.

Table 2: Calculated radical indices (y_i^α) by the FT-DFT method at the TPSS/def2-TZVP level.

Compound	y_0^α	y_1^α	y_2^α	y_3^α
Diradical I	0.49	0.03	0.02	0.00
Diradical II	0.49	0.03	0.00	0.00
[6]CPPM-Mes	0.24	0.22	0.04	0.00
[3]CPBM-Ant	0.35	0.08	0.08	0.08
[4]CPBM-Ant	0.28	0.21	0.06	0.06
[5]CPBM-Ant	0.31	0.29	0.08	0.08
[6]CPBM-Ant	0.34	0.28	0.21	0.06
MC-F3A3	0.46	0.07	0.07	0.06
8MC	0.30	0.30	0.21	0.21

Table 3: Energy difference (kcal/mol) between the low-spin (LS) and high-spin (HS) states, $\Delta E(\text{LS} - \text{HS})$, obtained at the FT-DFT level.

Compound	GS	FT-TPSS	FT-TPSS0	FT-TPSSHH	Exp.
Diradical I	T ₀	-10.04	-5.29	0.15	0.50±0.02
Diradical II	T ₀	-10.08	-5.40	-0.06	1.74±0.07
[6]CPPM-Mes	S ₀	-8.36	-6.50	-5.42	-6.23±0.78
[3]CPBM-Ant	D ₀	-13.63	-10.99	-9.02	-3.5
[4]CPBM-Ant	S ₀	-6.00	-4.45	-3.65	-2.8
[5]CPBM-Ant	D ₀	-8.42	-6.68	-5.36	-2.4
[6]CPBM-Ant	S ₀	-3.54	-2.84	-2.30	-2.2
MC-F3A3	D ₀	-13.40	-11.62	-10.16	-2.10
8MC	S ₀	-3.98	-3.44	-2.60	-3.08
	MSE	-6.4	-4.1	-2.0	
	MUE	6.4	4.1	2.3	
	MIN	0.9	0.4	0.4	
	MAX	11.8	9.5	8.1	

Table 4: Energy difference (kcal/mol) between the Broken-Symmetry (BS) and high-spin (HS) states, $\Delta E(\text{BS} - \text{HS})$, and the corresponding $\Delta E(\text{LS} - \text{HS})$ corrected, obtained at the SF-DFT level.

Compound	GS	SF-TPSS		SF-TPSS0		SF-TPSSHH		Exp.
		$\Delta E(\text{BS} - \text{HS})$	$\Delta E(\text{LS} - \text{HS})$	$\Delta E(\text{BS} - \text{HS})$	$\Delta E(\text{LS} - \text{HS})$	$\Delta E(\text{BS} - \text{HS})$	$\Delta E(\text{LS} - \text{HS})$	
Diradical I	T ₀	0.55	1.10	0.88	1.74	1.32	2.50	0.50±0.02
Diradical II	T ₀	1.23	2.44	2.18	4.24	3.34	6.14	1.74±0.07
[6]CPPM-Mes	S ₀	-18.44	-17.44	-8.61	-6.16	12.94	7.14	-6.23±0.78
[3]CPBM-Ant	D ₀	-14.61	-14.52	-9.21	-9.00	-2.05	-1.89	-3.5
[4]CPBM-Ant	S ₀	-14.07	-14.00	-8.62	-6.16	1.27	1.06	-2.8
[5]CPBM-Ant	D ₀	-12.60	-12.66	-10.16	-13.29	-11.41	-16.62	-2.4
[6]CPBM-Ant	S ₀	-6.29	-5.96	3.48	3.30	15.85	12.84	-2.2
MC-F3A3	D ₀	-7.89	-8.40	-5.97	-8.43	-7.47	-12.39	-2.10
8MC	S ₀	-6.72	-6.32	-8.06	-13.12	1.93	3.22	-3.08
	MSE	-6.5	-6.2	-2.7	-3.0	4.0	2.4	
	MUE	6.5	6.5	4.1	5.0	7.2	7.9	
	MIN	0.0	0.6	0.4	0.1	0.8	1.6	
	MAX	12.2	11.2	7.8	10.9	19.2	15.0	

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Table 5: Energy difference (kcal/mol) between the low-spin (LS) and high-spin (HS) states, $\Delta E(\text{LS} - \text{HS})$, obtained at the SF-TDDFT level.

Compound	GS	SF-TDBHLYP	Exp.
Diradical I	T ₀	-9.34	0.50±0.02
Diradical II	T ₀	-9.94	1.74±0.07
[6]CPPM-Mes	S ₀	-3.37	-6.23±0.78
[3]CPBM-Ant	D ₀	-17.99	-3.5
[4]CPBM-Ant	S ₀	-17.80	-2.8
[5]CPBM-Ant	D ₀	-15.86	-2.4
[6]CPBM-Ant	S ₀	-9.34	-2.2
MC-F3A3	D ₀	-6.69	-2.10
8MC	S ₀	-0.57	-3.08
	MSE	-7.9	
	MUE	9.1	
	MIN	2.5	
	MAX	15.0	

Table 6: Calculated D and E EPR parameters (D/hc and E/hc in 10^3cm^{-1}) and exciton size (Δr , in \AA) at the $\omega\text{B97X-D/IGLO-II}$ level, of the lowest triplet state of the selected compounds.

Compound	D	E	Δr
Diradical I	-5.52	-0.80	7.8
Diradical II	-11.13	-3.66	6.2
[6]CPPM-Mes	-12.60	-0.56	5.9
[4]CPBM-Ant	-13.04	-1.74	5.8
[6]CPBM-Ant	-10.05	-0.04	6.4
8MC	4.29	0.00	8.5