Research Article

Journal of Physical Organic Chemistry

Received: 23 March 2014, Revised: 27 July 2014, Accepted: 6 August 2014, Published online in Wiley Online Library: 17 September 2014

(wileyonlinelibrary.com) DOI: 10.1002/poc.3348

Aromaticities of azines relative to benzene; a theoretical approach through the dimethyldihydropyrene probe

Maria[a], Riffat U. Nisa[a], Muhammad Hanif[a], Adeem Mahmood[a†] and Khurshid Ayub[a,b*]

The aromaticities of azines relative to benzene have been estimated by fusion with 15,16-dimethyldihydropyrene. Chemical shift data for the azine-fused dihydropyrenes (calculated at GIAO HF/6-31G*//B3LYP/6-31 + G*) were used to estimate the reduction in the dihydropyrene nucleus aromaticity. Choice of the saturated reference model was quite crucial in reliable estimation of aromaticity. Reference models with partial unsaturation at azine (21,23,25–32) gave better estimate of aromaticity than the parent dimethyldihydropyrene. Aromaticities of azines through chemical shift data and geometric parameter analysis were found to be 90–100% to that of benzene, highly consistent with the aromaticity estimation by nucleus independent chemical shift$_{(0)\pi zz}$ calculations. Copyright © 2014 John Wiley & Sons, Ltd.

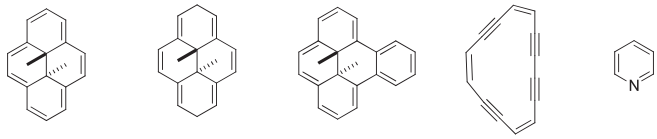
Keywords: Aromaticity quantification; Azines; Density functional theory; Dimethyldihydropyrene probe; Magnetic and geometric criteria

INTRODUCTION

Aromaticity is a general, commonly used, but quite controversial concept in organic chemistry. Qualitative description of a compound as aromatic, non-aromatic or anti aromatic is generally less contentious; however, quantitative estimation of aromaticity is not trivial and generally leads to controversies, primarily due to the quantification methods applied.[1] The aromaticity of a compound may vary considerably depending on the method used for quantitative analysis. Three major categories to quantify aromaticity are energetic, structural and magnetic, essentially all theorectical

Dewar resonance energy,[2–5] Huckel resonance energy,[6–8] Hess-Schaad resonance energy,[9–14] Schleyer isomerization stabilization energies[15] and topological resonace energies[16–18] are a few important energetic criteria. The Harmonic Oscillator Model of Aromaticity (HOMA),[19–21] Julg aromaticity index,[22] Bird's aromaticity index[23–27] and Fringuelli structural index[28,29] are the most important structure-based methods for the quantification of aromaticity.

The most common magnetic criteria include magnetic susceptibility exaltation,[30–41] nuclear magnetic resonance (NMR)[36,42–48] and nucleus independent chemical shifts (NICS).[49] NMR-based methods are generally more diverse and include chemical shift analysis of ^{3}He and ^{7}Li nuclei placed above the aromatic nucleus,[36,42–48] ^{1}H chemical shift[50,51] analysis of probe protons usually in the center of the nucleus under consideration and coupling constants[52,53] analysis in H-NMR (Gunther Q-values). However, NMR-based methods generally require that a suitable model or probe is chosen. NMR-based methods may even provide experimental scale of aromaticity for theoretical NICS values.[54] A probe of high accuracy based on ^{1}H NMR chemical shift is 15,16-dimethyldihydropyrene **1**.



1 **2** **3** **4** **5**

The internal methyl protons in 15,16-dimethyldihydropyrene **1** appear at δ −4.25 and its comparison with the non-conjugated model **2** δ 0.97 indicates large shielding of ~5.2 ppm due to a strong ring current.[50] When an aromatic ring is [a]- or [e]- fused to the dimethyldihydropyrene, the ring current in the latter is reduced. The internal protons of [e]- fused benzodihydropyrene[50] **3** appear at −1.85 ppm which means that the internal methyl protons in **3** are shielded by 2.82 ppm, and this leads to an experimental estimate of the aromaticity for **3** relative to **1** to be 52%. The greater the aromaticity of the fused ring, the greater is the reduction in the ring current of the dihydropyrene (DHP), and this concept can be used to compare the relative aromaticities of any two molecules provided the following two conditions are met: (i) the effect of fusion on the geometry of the probe

* *Correspondence to: K. Ayub, Department of Chemistry COMSATS Institute of Information Technology Abbottabad 22060, Pakistan. Email: kayub@kfu.edu.sa; khurshid@ciit.net.pk*

† *Current Address: Chemistry Department, King Saud University, Riyadh 11451, Saudi Arabia*

a *Maria, R. U. Nisa, M. Hanif, A. Mahmood, K. Ayub Department of Chemistry, COMSATS Institute of Information Technology, Abbottabad 22060, Pakistan*

b *K. Ayub Department of Chemistry, College of Science, King Faisal University, Al Ahsa 31982, Kingdom of Saudi Arabia*

Journal of Physical Organic Chemistry

molecules is negligible and the ring current around the probe molecule is only affected by the new delocalization and (ii) the chemical shift of the probe protons is not affected by through space anisotropic effects. Dimethyldihydropyrene is an excellent probe to fulfill these requirements and has successfully been used to compare aromaticities of a large number of molecules, and so far the only failure is the aromaticity quantification of **4** and is believed to be mainly due to orientation of the shielding cone of alkynes.[55]

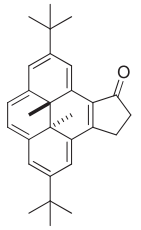
Aromaticity of azines has created some controversies in the literature. Comparison of resonance energies calculated by Wiberg[56] (benzene vs **5**: 36 vs 34 kcal mol^{-1}), by Bird[27,57,58] (benzene vs **5**: 45.8 vs 43.3 kcal mol^{-1}) and aromatic stabilization energies through homodesmotic equations[15] (benzene vs **5**:28.8 vs 31.0 kcal mol^{-1}) reveals that both benzene and pyridine are almost equally aromatic. However, Mosquera[59] based on an N-Centre delocalization index pointed out that azines are less aromatic than benzene. Another inconsistency appears in the cases of contiguous azines; contiguous azines are more aromatic than benzene based on Mosquera's n-DI[59–62] but less aromatic according to resonance energies (REs) derived from isodesmic reactions. The HOMA[60,62] aromaticity index revealed a quite divergent aromaticity order for di, tri and tetrazene; however, HOMED[63] (harmonic oscillator model for electron delocalization) indicated almost comparable aromaticities for azines to that of benzene. Very recently, Schleyer *et al.*,[64] based on NICS calculations, have also shown that azines are of comparable aromaticities to benzene regardless of the contiguous or non-contiguous nature.

To the best of our knowledge, the dimethyldihydropyrene probe has not been used in quantification of aromaticities of nitrogenous bases relative to benzene. In the present study, we set to quantify the aromaticities of azines relative to benzene by fusion to 15,16-dimethyldihydropyrene probe and then to compare with the relative aromaticities reported in the literature, especially those reported recently by Schleyer through NICS.

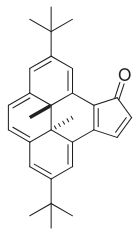
RESULTS AND DISCUSSION

Choice of the reference system

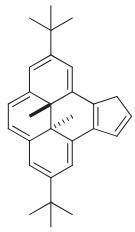
Choice of a non-aromatic model is crucial to the reliable quantification of aromaticies, in particular to the aromaticities of heteroarenes, and arenes with small ring size. The non-aromatic model should nullify other effects (such as anisotropic effects etc.). Mitchell *et al.* have shown that for the quantification of anti-aromaticity of cyclopentadieneone, compound **6** was used as a non-aromatic model for **7** in order to nullify anisotropic effect of the carbonyl group. Later, re-examination led them to conclude that compound **8** is a better non-aromatic model. Similarly, for compound **9**, compounds **10** and **11** are effective non-aromatic models because they contain suitable substitution as well as the proper ring size. In this work, we compare different reference model systems for the quantification of aromaticity of azines. Moreover, we also show here the importance of selecting a proper reference model.



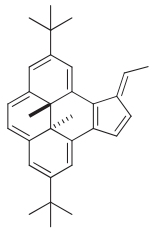
6



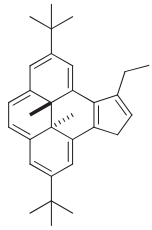
7



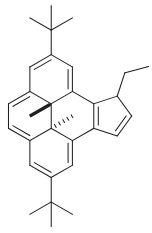
8



9

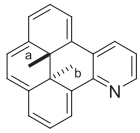


10



11

Parent DHP as a reference model



12

Mitchell and his team have spent over three decades in developing dimethyldihydropyrene as a probe to quantify aromaticity,[50,51,54,55] and in most of their reports the parent DHP **1** is used as a reference model. The change in ring current of the DHP nucleus (DHPN) on fusion with any arene (pyridine in this case) can be calculated by:

$$\frac{[\delta \text{ methyl protons of N heterocyclclic fused DHP}] - [\delta \text{ methyl protons of DHP}]}{[\delta \text{ methyl protons of non conjugated model}] - [\delta \text{ methyl protons of DHP}]}$$

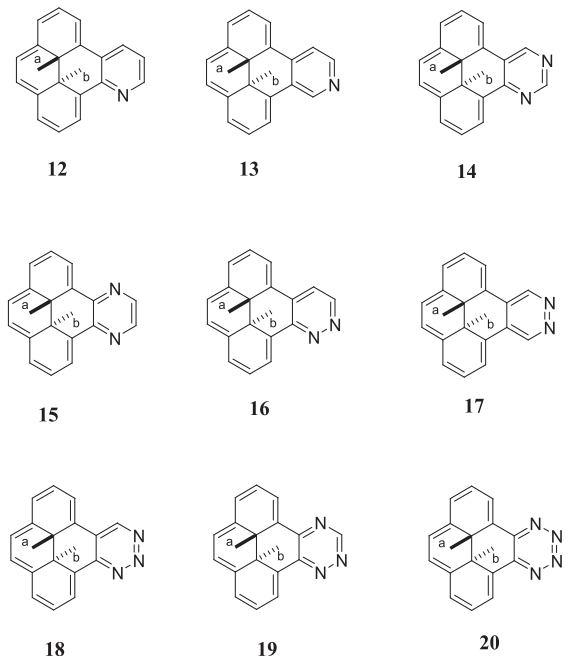
$$\frac{[\delta 12] - [\delta 1]}{[\delta 2] - [\delta 1]} \quad (1)$$

The equation above is actually a measure of bond fixation in dimethyldihydropyrene by fusion of an aromatic moiety. Based on the formula above, aromaticity of arene (pyridine) relative to benzene can be estimated by:

$$\frac{[\delta \text{ methyl protons of N heterocyclclic fused DHP}] - [\delta \text{ methyl protons of DHP}]}{[\delta \text{ methyl protons of benzo} - \text{DHP}] - [\delta \text{ methyl protons of DHP}]}$$

$$\frac{[\delta 12] - [\delta 1]}{[\delta 3] - [\delta 1]} \quad (2)$$

The majorities of examples reported in the literature for the quantification of aromaticity through DHP are based on these model and reference systems. A main reason for this choice lies in the fact that the reported examples are related to carbacycles such as benzene, naphthalene, anthracene, cyclopentadienone and cyclooctatetraene. Heterocycles present additional anisotropy effects, as well as potential conjugation effects, and so far have not been extensively studied. Our efforts in this paper are centered on azines, which, of course, do contain heteroatoms. Our calculations (explained below) of the degree of bond fixation in DHPN and of the relative aromaticities of a variety of azines to benzene, using Eqns (1) and (2), are given in Table 1.



Although experimental chemical shifts of DHPs **1** and **3** are available in the literature, to maintain consistency, theoretically calculated values of chemical shifts are used for the aromaticity quantification of benzene (row 1, Table 1). A pyridine ring can be fused to dimethyldihydropyrene to generate two isomeric species **12** and **13**, as pairs of enantiomers! Since the chemical shifts of the two different internal protons are very similar, any local anisotropic effects are very similar for both types of protons. For example, in **13**, proton "a" appears at δ −2.06 whereas proton "b" appears at δ −2.05. On the basis of calculated NMR, fusion of a pyridine ring in **13** reduces the DHPN aromaticity to 57.5%, compared with 58.3% for benzene. This indicates that both pyridine and benzene have comparable effect on reduction of the DHPN aromaticity. The internal protons in isomeric DHP **12** appear at δ −2.17 and δ −2.14 which translate into 55.9–56.3% reduction in the DHPN aromaticity. Reduction in DHPN aromaticities of 56.3 and 57.5% relative to 58.3% for benzene is indicative of comparable aromaticities of pyridine and benzene. A small difference in the reduction in DHPN aromaticities is probably due to through space anisotropic effect and bond length alternation in pyridine. However, for pyridazines, the aromaticity turns out to be 102.3% of benzene if **16** is used, or 80.4% if **17** is used for quantification (Table 1, entries 6 and7). A similar discrepancy is also observed in the case of triazine where relative aromaticities of 102.7–103% or 84–85% were observed when **19** or **18** are used, respectively (Table 1, entries 8 and 9). These significant differences between two isomeric fusions of arenes might have arisen from contiguous nature of these arenes but definitely point out the failure of the model, in particular the reference model. A benzene ring or a pyridine ring when fused to the DHP may provide quantitative estimate of local aromaiticity. The equation above does not provide global estimate of aromaticity. For a global estimate of aromaticity of benzene and azines, a method should be chosen in which both fusion provide similar quantitative estimate of aromaticity

Table 1. ^{1}H NMR chemical shifts of the internal protons of azine fused DHPs **12–20** and the calculated bond fixation and percent aromaticities relative to benzene using Eqn (2).

Entry	Arene	Comp. #	Protons	δppm calc.	% fix. DHPN	% arom. (benzene)
1	Benzene	**3**		−1.99	58.3	100
2	Pyridine	**12**	a	−2.14	56.3	95.0
			b	−2.17	55.9	94.3
3	Pyridine	**13**	a	−2.06	57.4	96.8
			b	−2.05	57.5	97.0
4	Pyrimidine	**14**	a	−2.16	56.0	94.5
			b	−2.2	55.5	93.6
5	Pyrazine	**15**	a	−2.22	55.2	93.2
			b	−2.22	55.2	93.2
6	Pyridazine	**16**	a	−1.82	60.6	102.3
			b	−1.82	60.6	102.3
7	Pyridazine	**17**	a	−2.78	47.6	80.4
			b	−2.78	47.6	80.4
8	Triazene	**18**	a	−2.59	50.2	84.7
			b	−2.61	49.9	84.2
9	Triazene	**19**	a	−1.8	60.9	102.7
			b	−1.79	61.2	103.0
10	Tetrazene	**20**	a	−2.31	54.0	91.1
			b	−2.31	54.0	91.1

%Fix = % bond fixation, %Arom. = % aromaticity relative to benzene

Journal of Physical Organic Chemistry

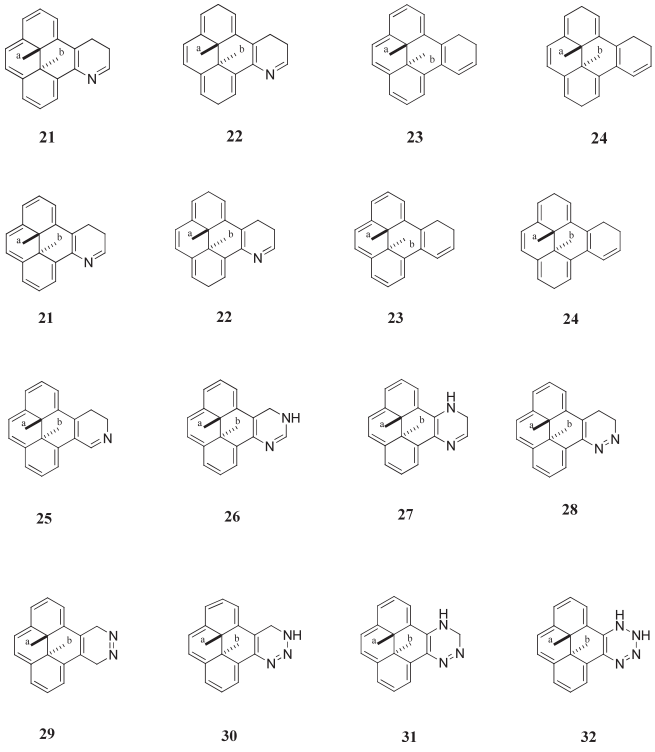
For a better estimate of aromaticity, partially saturated azine non-aromatic reference model was chosen in such that the model is very similar to the azine under study, but it lacks the aromaticity of azine. The non-aromatic model **21** for pyridine fused dimethyldihydroopyrene was chosen because it is expected to nullify all other effects except the aromaticity of pyridine. The aromaticity of azine through the reference model **21** for pyridine was calculated using the Eqn (3) shown below

$$\frac{[\delta \text{ methyl protons of N heterocyclclic fused DHP}] - [\delta \text{ methyl protons of sat. N hetero DHP}]}{[\delta \text{ methyl protons of non aromatic model}] - [\delta \text{ methyl protons of sat. N hetero DHP}]}$$

$$\frac{[\delta 12] - [\delta 21]}{[\delta 2] - [\delta 21]} \quad (3)$$

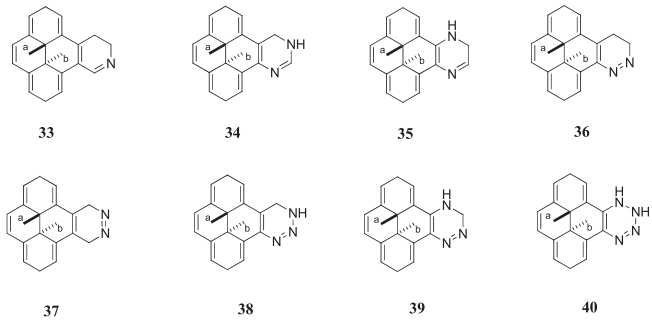
Aromaticity of azine relative to benzene can be calculated by

$$\frac{[\delta 12]-[\delta 21] \,/\, [\delta 22]-[\delta 21]}{[\delta 3]-[\delta 23] \,/\, [\delta 24]-[\delta 23]}. \quad (4)$$



As discussed earlier, the compound **21** is expected to be a better reference model compound for pyridine-DHP **12**, and similarly **22** is believed to be a better non-conjugated model for **12** than compound **2**; therefore, a better estimate of aromaticities can be obtained using the equation above (equations 3 and 4), which incorporates similar changes for the benzo fused DHP. Indeed, the modified equation and the model compounds turned out to be quite effective and free of any considerable anisotropic effects. Comparable results on the aromaticity of pyridine relative to benzene are obtained with both isomeric DHPs **12** and **13**. There exist two different types of protons in **12** and **13** ("a" and "b"), and use of chemical shifts of proton "b" in isomeric DHPs resulted in 98% aromaticity of pyridine relative to benzene. The chemical shifts of protons "a" in **12** and **13** delivered somewhat overestimated (but not very different) aromaticity values of 103.5 and 105.1%, respectively. The aromaticities of azines calculated using Eqns (3) and (4) are shown in the Table 2.

Thus, the discrepancies associated with the aromaticity of pyridazine and triazine through method 1 are mostly overcome. Pyridazine has almost 96–100% of the aromaticity of benzene calculated (through proton "b") by any of the fused DHP (Table 2, entries 6 and 7). The aromaticities of a series of azines are reported relative to benzene in the Table 2. Similarly, for triazine, the aromaticities were also found very comparable (Table 2 entries 8 and 9). Although the aromaticity values calculated by this method are quite different when protons "a" and "b" are used, very similar aromaticity values of azines were obtained for isomeric fusion when the protons of a similar label are chosen; for example protons "b". This method provides somewhat global estimate of aromaticity of azines where isomeric fusion does not impart significant effect on the aromaticity. We were able to calculate the relative aromaticities of pyridine, pyrimidine, pyrazine, pyridazine, triazine and tetrazine. However, relative aromaticities of pentazine and hexazine are not possible through this method because this would involve incorporation of nitrogen atoms in the DHPN which of course requires reinvestigation of proper non-aromatic and non-conjugated models. Relative aromaticities of different azines relative to benzene through protons "b" are within 95–100% except pyrazine, and these results are indicative of comparable aromaticities of azines with respect to benzene, quite consistent with the literature (NICS and other aromaticity indices).[64,65] Non aromatic model **27** for pyrazine fused DHP is not perfectly ideal because it contains a sp3 nitrogen atom very next to the DHPN which is expected to additionally affect the aromaticity by conjugation effect.

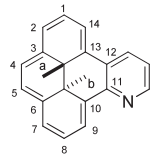


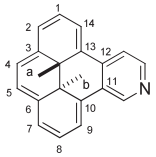
Since chemical shifts of the internal protons in **24** and **33–40** are quite similar among themselves as well as to the non-conjugated model **2**, therefore the chemical shifts of the latter can safely be applied instead of using the these individual reference compounds. In most of the calculations, two different protons are available for the quantification of aromaticities. Results of the aromaticity quantification through two different protons are shown in Table 2. Generally with protons of type "b", less

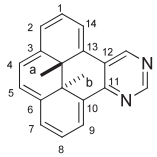
Table 2. Percent aromaticities of azines fused DHPs **12–20** relative to benzene calculated using Eqn (4)

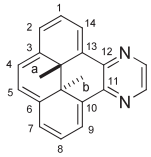
Entry	Azine	δppm	Non-ar. model	δppm	Non-conjug model	δppm	% bond fixation	% arom. (benzene)
1	Benzene	−1.99	**23**	−5.45	**24**	1.11	53.2	100
2	Pyridine	−2.14	**21**	−6.09	**22**	1.1	55.1	103.5
		−2.17		−5.99		1.17	53.9	97.9
3	Pyridine	−2.06	**25**	−6.1	**33**	1.05	56.7	105.1
		−2.05		−5.98		1.08	55.8	98.4
4	Pyrimidine	−2.16	**26**	−5.7	**34**	1.09	52.2	93.5
		−2.2		−5.78		1.02	52.3	100.1
5	Pyrazine	−2.22	**27**	−5.5	**35**	1.08	49.8	85.1
		−2.22		−5.42		0.92	48.8	98.2
6	Pyridaz.	−1.82	**28**	−6	**36**	1.06	58.5	112.0
		−1.82		−5.91		1.08	58.5	99.9
7	Pyridaz	−2.78	**29**	−6.18	**37**	1.07	47.9	98.0
		−2.78		−6.06		1.14	46.1	96.2
8	Triazine	−2.59	**30**	−6.1	**38**	1.06	48.5	105.2
		−2.61		−5.96		1.09	47.2	97.3
9	Triazine	−1.8	**31**	−4.45	**39**	1.13	47.4	100.5
		−1.79		−4.38		1.14	46.9	99.0
10	Tetrazine	−2.31	**32**	−5.88	**40**	1.14	50.8	108.4
		−2.31		−5.71		1.14	49.9	98.0

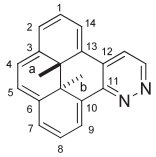
variation in the aromaticities has been observed as compared to protons "a". Intuitively one would expect the opposite results because "b" protons are closer to the heteroatoms and they are more prone to the anisotropic effects arising from these heteroatoms. To solve the problem, "which set of protons give the most reliable estimate of aromaticity", we analyzed geometric parameters of azene-fused DHPs **12–20**, and the results are summarized in Table 3.

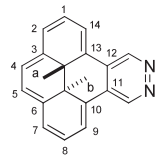

12

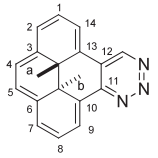

13

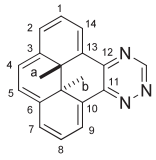

14

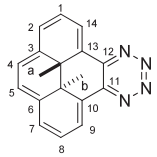

15


16


17


18


19


20

The geometric data illustrate that bond fixation for all azines is lower than that of benzene except for pyridazine fused **16**. Second, the bond fixation for all azines is within 90–100% to that of benzene, and this data is consistent with estimation of aromaticity of azines obtained when proton "b" are used. Now the question arises why the protons "b" give reliable estimate over protons "a" even though the protons "b" are close to the heteroatom and are more prone to anisotropic effect. An obvious reason for this behavior could be the planarity of the system in the region of proton "b" than proton "a" in the reference models.

A comparison of our calculated aromaticity values through the dimethyldihydropyrene probe with other methods reported in the literature[64,65] is given in Table 4. The aromaticity values obtained through our NMR and geometric method are comparable to the aromaticity values obtained through other magnetic NICS $_{(0)\pi zz}$ and energetic (ECRE) methods. Since NICS$_{(0)\pi zz}$ only takes into account the contribution of the out of plane (zz) tensor components of the π MOs directly relevant to aromaticity which is very comparable to our NMR method. The methyl protons in dimethyldihydropyrene are out of the plane and are expected to be affected by aromaticity only, and local anisotropic effects should be negligible. Aromaticity values obtained through protons "b" of dimethyldihydropyrene by using Eqns (3) and (4) are very similar to the aromaticity values through NICS$_{(0)\pi zz}$. Moreover, this data is consistent with the bond localization values in Table 3. The extra cyclic resonance energy (ECRE) values calculated through bond localized wavefunction (BLW) also give similar results. A main reason for the similar results through ECRE lies in the fact that BLW separates all electrons and basis functions into sets of localized MOs which ultimately disables intramolecular interaction among selected subgroups. Absence of any intramolecular interaction in subgroups delivers better estimate of resonance energies. In short we have shown that with a suitable model, magnetic (NMR and NICS$_{(0)\pi zz}$), energetic (ECRE through BLW) and geometric (bond fixation) give comparable estimates of aromaticities. Moreover, we have shown that the dimethyldihydropyrene nucleus can reliably be used for the quantification of aromaticity of azines provided a suitable saturated reference model and non-aromatic model are available.

Table 3. Calculated lengths for azine fused DHPs 12–20 and the associated bond fixation

	3	12	13	14	15	16	17	18	19	20
C1–C2	1.376	1.378	1.377	1.379	1.380	1.378	1.380	1.381	1.380	1.382
C2–C3	**1.417**	**1.416**	**1.416**	**1.417**	**1.417**	**1.418**	**1.414**	**1.414**	**1.418**	**1.416**
C3–C4	1.382	1.383	1.382	1.384	1.384	1.382	1.385	1.385	1.382	1.384
C4–C5	**1.419**	**1.419**	**1.419**	**1.419**	**1.420**	**1.421**	**1.416**	**1.417**	**1.421**	**1.419**
C5–C6	1.382	1.383	1.382	1.383	1.383	1.382	1.385	1.385	1.382	1.384
C6–C7	**1.417**	**1.417**	**1.417**	**1.416**	**1.417**	**1.419**	**1.414**	**1.415**	**1.419**	**1.416**
C7–C8	1.377	1.380	1.377	1.380	1.380	1.378	1.380	1.382	1.378	1.382
C8–C9	**1.428**	**1.426**	**1.428**	**1.426**	**1.427**	**1.429**	**1.424**	**1.425**	**1.429**	**1.425**
C9–C10	1.373	1.372	1.373	1.372	1.372	1.369	1.375	1.373	1.369	1.373
C10–C11	**1.454**	**1.448**	**1.451**	**1.442**	**1.445**	**1.450**	**1.443**	**1.440**	**1.448**	**1.437**
C11–C12	1.435	1.434	1.430	1.429	1.434	1.432	1.421	1.420	1.432	1.420
C12–C13	**1.454**	**1.451**	**1.450**	**1.448**	**1.445**	**1.449**	**1.443**	**1.440**	**1.441**	**1.437**
C13–C14	1.373	1.373	1.373	1.373	1.372	1.372	1.375	1.374	1.372	1.372
C14–C1	**1.428**	**1.427**	**1.427**	**1.428**	**1.426**	**1.428**	**1.424**	**1.425**	**1.427**	**1.425**
Σ(bond)Bold	1.430	1.429	1.430	1.428	1.428	1.430	1.425	1.425	1.429	1.425
Σ(bond)Plain	1.385	1.386	1.385	1.386	1.386	1.385	1.386	1.386	1.385	1.385
Bond fixation	0.0454	0.043	0.044	0.0423	0.0418	0.0457	0.039	0.0396	0.0439	0.0401

Bond fixation = Σ(bond)Bold − Σ(bond)Plain.

Table 4. Comparison of our calculated aromaticity parameters through the dimethyldihydropryene probe with other criteria for aromaticity

	NMR (%)	Bond fix.	NICS(0)πzz	ECRE[a]	BLW[a]
Benzene	100	0.0454	−36.12	29.29	61.39
Pyridine	97.9	0.043	−35.94	29.68	61.30
Pyridine	98.4	0.044	−35.94	29.68	61.30
Pyrimidine	100.1	0.0423	−35.15	29.46	60.87
Pridazine	99.9	0.0452	−36.11	32.50 25.98	63.82 53.38
Pyridazine	96.2	0.039	−36.11	32.50 25.98	63.82 53.38
Pyrazine	98.2	0.0418	−34.75	29.93	59.59
123Triazine	97.3	0.0396	−36.34	27.21	53.74
124Triazine	99.0	0.0439	−35.88	31.63 28.44	60.85
Tetrazine	98.0	0.0401	−36.36	29.80	53.02

[a]Taken from reference 65.
[b] Taken from reference 66.

COMPUTATIONAL METHODS

All calculations were performed with Gaussian 09 suite of programs.[66] Geometries of the structures were optimized without any symmetry constraints at hybrid B3LYP method using 6-31 + G* basis set.[67] The B3LYP method, which consists of parameter hybrid functional of Becke[68] three in conjunction with the correlation functional of Lee, Yang and Parr,[69] provides a nice balance between cost and accuracy, and it is known to perform very well for the prediction of geometries of a number of DHPs.[70] The 6-31 + G(d) basis set was evaluated for the prediction of geometries of dihydropryenes and compared with the results obtained from 6-31G(d) basis set (see Supporting Information). Each optimized structure was confirmed by frequency analysis at the same level (B3LYP/6-31 + G*) as a true minimum (no imaginary frequency). Predictions based on the B3LYP method for the DHPN have led to the development of robust photoswitches[71] as well. 1H NMR chemical shifts were calculated by Hartree–Fock (HF) Gauge Independent Atomic Orbital (GIAO) method at 6-31G* basis set on the B3LYP/6-31 + G* optimized geometries (GIAO-HF/6-31G*//B3LYP/6-31 + G*). GIAO-HF/6-31G* was chosen because the predicted aromaticities of a number of DHPs through this method correlate very well with the experiment.[72]

CONCLUSIONS

The aromaticities of azines relative to benzene have been estimated by fusion with dimethyldihydropyrene. Chemical shift data for azine-fused DHPs (calculated at GIAO HF/6-31G(d)//B3LYP/6-31 + G(d)) were used to estimate the reduction in the DHPN aromaticity. Aromaticities of pyridine, pyrimidine, pyridazine, pyrazine, triazine and tetrazene have been estimated with dimethyldihydropyrene probe. In the estimation of aromaticity with dimethyldihydropyrene probe, the choice of non-aromatic reference model is of vital importance. Reference models with partial unsaturation **21**, **23**, **25–32** where nitrogen atoms are part of the unsaturation provide reliable estimate of aromaticity. Aromaticities of azines were found 95–100% to benzene. Aromaticities of azines were also obtained by geometric analysis and were found 90–100% to that of benzene, consistent with magnetic shielding. Moreover the aromaticities values obtained through dimethyldihydropyrene probe are very close to those obtained from $NICS_{(0)\pi zz}$

Acknowledgements

K. A. highly acknowledges the Higher Education Commission of Pakistan (Grant # 1899 via No. 20-1899/R&D/10/8863) for financial support to the project. Support from COMSATS Institute of Information Technology and King Faisal University is also highly acknowledged.

REFERENCES

[1] A. T. Balaban, D. C. Oniciu, A. R. Katritzky, *Chemical Reviews* **2004**, *104*, 2777–2812.
[2] M. J. S. Dewar, C. De Llano, *Journal of the American Chemical Society* **1969**, *91*, 789–795.
[3] M. J. S. Dewar, G. J. Gleicher, *Journal of the American Chemical Society* **1965**, *87*, 692–696.
[4] M. J. S. Dewar, G. J. Gleicher, *Journal of Chemical Physics* **1966**, *44*, 759.
[5] L. J. Schaad, B. A. Hess, *Chemical Reviews* **2001**, *101*, 1465–1476.
[6] B. A. Hess, L. J. Schaad, C. W. Holyoke, *Tetrahedron* **1975**, *31*, 295–298.
[7] M. Randic, *Journal of the American Chemical Society* **1977**, *99*, 444–450.
[8] L. J. Schaad, B. A. Hess Jr, *Journal of Chemical Education* **1974**, *51*, 640.
[9] B. Hess, L. J. Schaad, C. W. Holyoke, *Tetrahedron* **1972**, *28*, 3657–3667.
[10] B. A. Hess, L. J. Schaad, *Journal of the American Chemical Society* **1973**, *95*, 3907–3912.
[11] B. A. Hess Jr, L. J. Schaad, *Journal of the American Chemical Society* **1971**, *93*, 2413–2416.
[12] B. A. Hess Jr, L. J. Schaad, *Journal of the American Chemical Society* **1971**, *93*, 305–310.
[13] B. A. Hess Jr, L. J. Schaad, *Journal of Organic Chemistry* **1971**, *36*, 3418–3423.
[14] L. J. Schaad, B. A. Hess Jr, *Journal of the American Chemical Society* **1972**, *94*, 3068–3074.
[15] P. von Ragué Schleyer, F. Pühlhofer, *Organic Letters* **2002**, *4*, 2873–2876.
[16] J. Aihara, *Journal of the American Chemical Society* **1976**, *98*, 2750–2758.
[17] I. Gutman, M. Milun, N. Trinajstic, *Journal of the American Chemical Society* **1977**, *99*, 1692–1704.
[18] I. Gutman, M. Milun, N. Trinajstić, *Communications in Mathematical and in Computer Chemistry* **1975**, *1*, 171–175.
[19] J. Kruszewski, T. M. Krygowski, *Tetrahedron Letters* **1972**, *13*, 3839–3842.
[20] T. M. Krygowski, *Journal of Chemical Information and Computer Sciences* **1993**, *33*, 70–78.
[21] T. M. Krygowski, M. Cyranski, *Tetrahedron* **1996**, *52*, 1713–1722.
[22] A. Julg, P. François, *Theoretica Chimica Acta* **1967**, *8*, 249–259.
[23] C. W. Bird, *Tetrahedron* **1986**, *42*, 89–92.
[24] C. W. Bird, *Tetrahedron* **1985**, *41*, 1409–1414.
[25] C. W. Bird, *Tetrahedron* **1987**, *43*, 4725–4730.
[26] C. W. Bird, *Tetrahedron* **1990**, *46*, 5697–5702.
[27] C. W. Bird, *Tetrahedron* **1992**, *48*, 1675–1682.
[28] F. Fringuelli, G. Marino, A. Taticchi, G. Grandolini, *Journal of the Chemical Society, Perkin Transactions 2* **1974**, 332–337.
[29] K. Jug, *Journal of Organic Chemistry* **1983**, *48*, 1344–1348.
[30] H. J. Dauben Jr, J. D. Wilson, J. L. Laity, *Journal of the American Chemical Society* **1968**, *90*, 811–813.
[31] H. J. Dauben Jr, J. D. Wilson, J. L. Laity, *Journal of the American Chemical Society* **1969**, *91*, 1991–1998.
[32] B. Goldfuss, P. von Ragué Schleyer, F. Hampel, *Organometallics* **1996**, *15*, 1755–1757.
[33] R. Herges, H. Jiao, P. von Ragué Schleyer, *Angewandte Chemie International Edition* **1994**, *33*, 1376–1378.
[34] H. Jiao, P. R. Schleyer, *Angewandte Chemie International Edition* **1996**, *35*, 2383–2386.
[35] H. Jiao, P. von Ragué Schleyer, *Angewandte Chemie International Edition* **1995**, *34*, 334–337.
[36] H. Jiao, P. von Ragué Schleyer, *Angewandte Chemie International Edition* **1993**, *32*, 1760–1763.
[37] H. Jiao, P. von Ragué Schleyer, *Journal of the Chemical Society, Faraday Transactions* **1994**, 90, 1559–1567.
[38] P. R. Schleyer, H. Jiao, M. N. Glukhovtsev, J. Chandrasekhar, E. Kraka, *Journal of the American Chemical Society* **1994**, *116*, 10129–10134.
[39] P. R. Schleyer, H. M. Sulzbach, H. Jiao, H. F. Schaefer III, *Journal of the American Chemical Society* **1996**, *118*, 2093–2094.
[40] H. M. Sulzbach, P. R. Schleyer, H. Jiao, Y. Xie, H. F. Schaefer III, *Journal of the American Chemical Society* **1995**, *117*, 1369–1373.
[41] P. von Ragué Schleyer, H. Jiao, B. Goldfuss, P. K. Freeman, *Angewandte Chemie International Edition* **1995**, *34*, 337–340.
[42] M. Buehl, W. Thiel, H. Jiao, P. R. Schleyer, M. Saunders, F. A. L. Anet, *Journal of the American Chemical Society* **1994**, *116*, 6005–6006.
[43] M. Bühl, A. Hirsch, *Chemical Reviews* **2001**, *101*, 1153–1183.
[44] H. Jiao, P. R. Schleyer, *Journal of the American Chemical Society* **1995**, *117*, 11529–11535.
[45] L. A. Paquette, W. Bauer, M. R. Sivik, M. Buehl, M. Feigel, P. R. Schleyer, *Journal of the American Chemical Society* **1990**, *112*, 8776–8789.
[46] M. Saunders, R. J. Cross, H. A. Jimenez-Vazquez, R. Shimshi, A. Khong, *Science* **1996**, *271*, 1693.
[47] M. Saunders, H. A. Jimenez-Vazquez, R. J. Cross, W. E. Billups, C. Gesenberg, A. Gonzalez, W. Luo, R. C. Haddon, F. Diederich, A. Herrmann, *Journal of the American Chemical Society* **1995**, *117*, 9305–9308.
[48] T. Siegrist, H. W. Zandbergen, R. J. Cava, J. J. Krajewski, W. F. Peck, *Nature* **1994**, *367*, 254–256.
[49] P. von Ragué Schleyer, C. Maerker, A. Dransfeld, H. Jiao, N. J. R. van Eikema Hommes, *Journal of the American Chemical Society* **1996**, *118*, 6317–6318.
[50] R. H. Mitchell, *Chemical Reviews* **2001**, *101*, 1301–1316.
[51] R. H. Mitchell, R. Zhang, D. J. Berg, B. Twamley, R. V Williams, *Journal of the American Chemical Society* **2008**, *131*, 189–199.
[52] D. Cremer, H. Günther, *Justus Liebigs Annalen der Chemie* **1972**, *763*, 87–108.
[53] H. Günther, A. Shyoukh, D. Cremer, K. H. Frisch, *Justus Liebigs Annalen der Chemie* **1978**, *1978*, 150–164.
[54] R. V. Williams, J. R. Armantrout, B. Twamley, R. H. Mitchell, T. R. Ward, S. Bandyopadhyay, *Journal of the American Chemical Society* **2002**, *124*, 13495–13505.
[55] D. B. Kimball, M. M. Haley, R. H. Mitchell, T. R. Ward, S. Bandyopadhyay, R. V. Williams, J. R. Armantrout, *Journal of Organic Chemistry* **2002**, *67*, 8798–8811.
[56] K. B. Wiberg, D. Nakaji, C. M. Breneman, *Journal of the American Chemical Society* **1989**, *111*, 4178–4190.
[57] C. W. Bird, *Tetrahedron* **1996**, *52*, 9945–9952.
[58] C. W. Bird, *Tetrahedron* **1997**, *53*, 13111–13118.
[59] M. Mandado, N. Otero, R. A. Mosquera, *Tetrahedron* **2006**, *62*, 12204–12210.
[60] F. Feixas, E. Matito, J. Poater, M. Solà, *Journal of Computational Chemistry* **2008**, *29*, 1543–1554.
[61] M. Mandado, M. J. González-Moa, R. A. Mosquera, *Journal of Computational Chemistry* **2007**, *28*, 127–136.
[62] M. Solà, F. Feixas, J. O. C. Jiménez-Halla, E. Matito, J. Poater, *Symmetry (Basel).* **2010**, *2*, 1156–1179.
[63] E. D. Raczyńska, M. Hallman, K. Kolczyńska, T. M. Stępniewski, *Symmetry (Basel).* **2010**, *2*, 1485–1509.
[64] Y. Wang, J. I. C. Wu, Q. Li, P. R. Schleyer, *Organic Letters* **2010**.
[65] M. Alonso, B. Herradón, *Journal of Computational Chemistry* **2010**, *31*, 917–28.
[66] M. J. Frisch, G. W. Trucks, H. B. Schlegel, G. E. Scuseria, M. A. Robb, J. R. Cheeseman, G. Scalmani, V. Barone, B. Mennucci, G. A. Petersson, Gaussian, Inc., Wallingford CT **2009**.
[67] P. C. Hariharan, J. A. Pople, *Theoretica Chimica Acta* **1973**, 28, 213–222.
[68] A. D. Becke, *Journal of Chemical Physics* **1993**, *98*, 5648.
[69] C. Lee, W. Yang, R. G. Parr, *Physical Review B* **1988**, 37, 785–789.
[70] K. Ayub, R. Zhang, S. G. Robinson, B. Twamley, R. V. Williams, R. H. Mitchell, *Journal of Organic Chemistry* **2008**, *73*, 451–456.
[71] K. Ayub, R. Li, C. Bohne, R. V. Williams, R. H. Mitchell, *Journal of the American Chemical Society* **2011**, *133*, 4040–4045.
[72] R. V. Williams, W. D. Edwards, P. Zhang, D. J. Berg, R. H. Mitchell, *Journal of the American Chemical Society* **2012**, *134*, 16742–52.

SUPPORTING INFORMATION

Additional supporting information may be found in the online version of this article at the publisher's website.