Accurate Infrared (IR) Spectra for Molecules Containing the C≡N Moiety by Anharmonic Computations with the Double Hybrid B2PLYP Density Functional

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S *Supporting Information*

ABSTRACT: Herein, we report a comprehensive benchmark of C≡N stretching vibrations computed at harmonic and anharmonic levels with the aim of proposing and validating a reliable computational strategy to get accurate results for this puzzling vibrational mode without any *ad hoc* scaling factor. Anharmonic calculations employing second-order vibrational perturbation theory provide very good results when performed using the B2PLYP double-hybrid functional, in conjunction with an extended basis set and supplemented by semiempirical dispersion contributions. For larger systems, B2PLYP harmonic frequencies, together with B3LYP anharmonic corrections, offer a very good compromise between accuracy and computational cost without the need of any empirical scaling factor.
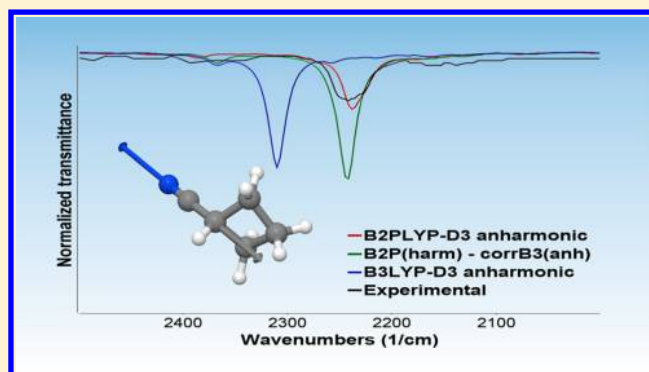
INTRODUCTION

Over the past few years, the C=N and C≡N moieties have been deeply investigated,[1−4] also in connection with their intrinsic role as intermediates in reactions involving purines and proteins,[5] not to mention the particular interest of the CN moiety for luminescent properties related to its ability to tune the phosphorescence of some transition-metal complexes. From another point of view, the simplest form of this compound, HCN, plays a remarkable role in the interstellar space as a widespread small molecule[6−8] of relevance for prebiotic chemistry.[9,10] Furthermore, cyanocarbons (i.e., organic compounds bearing enough cyano functional groups to significantly alter their chemical properties) are considered a classical example of discovery-driven research,[11] tetracyanoethylene (TCNE) and its derivatives playing a prominent role in the field of magnetic materials.[12,13] Finally, the vibration of the cyano group in organic and biological molecules has been studied as an infrared (IR) probe of the local environment in biological systems.[14,15] Several studies have shown that the CN stretching is highly localized and its frequency is very sensitive to environmental changes.[16] Therefore, a molecular level understanding of the tuning of frequency shift, peak width, and intensity change by stereoelectronic and environmental effects is of increasing importance. Thanks to the impressive development of hardware and software, quantum chemical computations are playing an increasing role toward disentanglement of intrinsic and environmental effects in determining specific spectroscopic signatures.[17−21] Methods based on

density functional theory (DFT) have been instrumental, especially for infrared and Raman spectra of medium- and large-sized molecules, because of their reliability, coupled with favorable scaling with the number of electrons.[22,23] Several benchmarks have shown that harmonic computations performed by global hybrid functionals (e.g., B3LYP),[24,25] in conjunction with medium-sized basis sets and scaled by a reduced number of empirical factors, lead to remarkable agreement with experimental frequencies and intensities of fundamental bands.[26,27] More recently, second-order vibrational perturbation theory (VPT2) generalized to include a variational treatment of leading resonances (GVPT2)[28−30] has been shown to deliver accurate frequencies and intensities for fundamentals, overtones, and combination bands without the need of any scaling factor.[23,31−33] Unfortunately, global hybrid functionals provide disappointing results for some moieties involving multiple bonds such as C≡N, unless specific scaling factors are introduced.[1,34] The recent development of double hybrid functionals[36] and of their analytical second derivatives[36] has led to more-reliable geometries and vibrational spectra for a large panel of organic and biological systems.[23,30,31] On these grounds, we decided to perform a systematic analysis of representative molecules containing the C≡N moiety by both the double-hybrid B2PLYP functional[35,36] and its parent B3LYP global hybrid.[24,25] The main objective of our

investigation is to perform direct *vis-à-vis* comparisons of computed and experimental spectra by including the leading contributions of both mechanical and electrical anharmonicity in a general and robust strategy routinely applicable to large molecules, also by nonspecialists. To this end, we will also consider the so-called hybrid approach,[23] in which harmonic and anharmonic contributions are computed at different levels of sophistication and the reduced dimensionality model,[23] in which anharmonicity is introduced only for a limited number of normal modes.

■ COMPUTATIONAL DETAILS

All calculations have been performed with a development version of the Gaussian suite of programs,[37] employing the B3LYP[24,25] global hybrid and the B2PLYP[35,36] double-hybrid density functionals, in conjunction with the m-aug-cc-pVTZ basis set,[38,39] where d functions on the hydrogens have been removed. Semiempirical dispersion contributions were also included in DFT computations by means of the D3 model of Grimme.[40,41] After full geometry optimizations with very tight convergence criteria, cubic and semidiagonal quartic force constants have been computed by finite differences of analytical Hessians and employed to obtain anharmonic frequencies with the GVPT2 model, taking possible resonances for frequencies,[29] together with IR intensities (including both mechanical and electrical anharmonicities),[31] into proper account. All calculations have been performed in the same medium employed for recording the corresponding experimental spectra (gas phase or different solvents), including bulk solvent effects, when needed, by means of the Polarizable Continuum Model (PCM).[42−44] The overall molecular symmetry and, possibly, mode degeneration were taken into full account in all computational steps including finite differentiations. All the spectra have been generated and managed by the VMS-draw graphical user interface.[45]

■ RESULTS AND DISCUSSION

As a first step, the intrinsic frequency of the C≡N stretching was investigated by employing HCN as a template. Contrary to the general trend observed for several other functional groups, the B3LYPD3 computational model overestimates the experimental value by ∼100 cm^{-1} at the harmonic level (ω_{B3}) and by ∼70 cm^{-1} at the anharmonic level (ν_{B3}). As suggested in a previous study,[34] agreement with experiment can be restored by scaling the harmonic frequency without modifying the anharmonic contribution ($\Delta_{B3} = \nu_{B3} - \omega_{B3}$), i.e.,

$$\nu_S = K\omega_{B3} + \Delta_{B3} \qquad (1)$$

For HCN, we get $K = 0.966$. On the other hand, the B2PLYPD3 computational model overestimates the experimental frequency by ∼35 cm^{-1} at the harmonic level (ω_{B2}), but the inclusion of anharmonicity (ν_{B2}) decreases the discrepancy to <5 cm^{-1}, which is a value that allows quantitative comparisons with experiment and is similar to that usually obtained by the most refined (and much more expensive) CCSD(T) approaches, including complete basis set extrapolation.[12,19] Furthermore, anharmonic corrections evaluated at the B3LYPD3 and B2PLYPD3 levels (hereafter referenced as Δ_{B3} and Δ_{B2}, respectively) are very close, thus suggesting that a hybrid method estimating the anharmonic frequency by

$$\nu_H = \omega_{B2} + \Delta_{B3} \qquad (2)$$

could represent the best compromise between accuracy and computational efficiency, while avoiding the use of any empirical scaling factor.

Starting from these results, we have then investigated the effect of different chemical environments and of coupling between several moieties in tuning the characteristic frequency of the C≡N stretching, together with the corresponding IR intensity. To this end, we have selected the seven molecules shown in Figure 1, which are representative of quite different
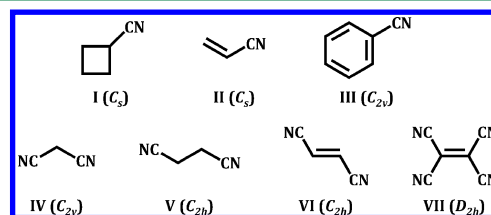

Figure 1. Investigated compounds.

situations including a single C≡N moiety in different environments (**I**, **II**, **III**), two germinal (**IV**) or vicinal (**V**, **VI**) C≡N moieties, and four coupled C≡N moieties (**VII**).

Some of the systems are particularly demanding, since they require not only a good description of inductive and conjugative effects on the C≡N vibrational frequency, but also strong couplings between different C≡N moieties. The harmonic and anharmonic vibrational wavenumbers of the C≡N stretching for all the studied molecules are compared in Table 1 with experimental data and the general trends are sketched in Figure 2.

Full Anharmonic Treatment. The experimental data (black line in Figure 2) show that the presence of more than one CN moiety increases the average vibrational frequency, but leads to negligible splitting, except for compound **VII**. Among the different computational methods, only the full B2PLYP anharmonic treatment (yellow line in Figure 2) fully reproduces this trend also from a quantitative point of view, whereas all the other methods give only qualitatively correct trends for compounds **I−VI** and fail to provide significant splittings for compound **VII**. As a matter of fact, the experimental splitting between the lowest and highest CN stretchings of **VII** amounts to 48 cm^{-1}, whereas the computed anharmonic value is 18 cm^{-1} at the B3LYPD3 level, which is increased to 30 cm^{-1} at the B2PLYP level. Furthermore, the difference between experimental and B2PLYPD3 anharmonic frequencies is constant (15 cm^{-1}) for the three highest frequencies and drops to just 3 cm^{-1} for the lowest frequency. It appears that the electronic structure of tetracyanoethylene is particularly challenging and, contrary to the other studied molecules can be hardly interpreted in terms of localized CN moieties.

In more-general terms, the B3LYPD3 anharmonic results (Table 1 and blue line in Figure 2) provide systematic errors on the vibrational frequencies of C≡N stretchings ranging between 60 cm^{-1} and 100 cm^{-1}, with respect to the experiment (corresponding to ∼3%) and a mean absolute error (MAE) of ∼70 cm^{-1}. These results confirm that quantitative agreement with experiment cannot be reached by both harmonic and anharmonic computations, even in the absence of strong couplings without using specific scaling factors. The results collected in Table 1 and the yellow line in Figure 2 show that the B2PLYPD3 computed anharmonic frequencies for the C≡

Table 1. Experimental vs Computed Vibrational Frequencies (cm^{-1}) for the Molecules Shown in Figure 1

molecule	mode	ν_{exp}(C≡N)	B3LYPD3/m-aug-cc-pVTZ				B2PLYPD3/m-aug-cc-pVTZ				$\nu_H = \omega_{B2} + \Delta_{B3}$	
			ω_{B3}	ν_{B3}	Δ_{B3}	$\|\nu_{B3} - \nu_{exp}\|$	ω_{B2}	ν_{B2}	Δ_{B2}	$\|\nu_{B2} - \nu_{exp}\|$	ν_H	$\|\nu_H - \nu_{exp}\|$
I	1	2240[a]	2342	2310	32	70	2275	2239	36	1	2243	3
II	2	2228[b]	2335	2306	29	78	2268	2230	38	2	2239	11
III	3	2235[c]	2335	2302	33	67	2269	2229	40	6	2236	1
IV	4	2265[d]	2377	2346	31	81	2305	2272	34	6	2274	9
	5	2265[d]	2369	2337	32	72	2307	2263	44	2	2275	10
V	6	2257[e]	2354	2318	36	61	2291	2255	36	2	2255	2
	7	2257[e]	2355	2326	29	69	2292	2257	35	0	2263	6
VI	8	2239[f]	2342	2309	33	70	2276	2238	38	1	2243	4
	9	2230[f]	2327	2294	37	64	2261	2223	38	7	2228	6
VII	10	2262[f]	2365	2329	36	67	2284	2247	37	15	2248	14
	11	2248[f]	2344	2319	25	71	2265	2233	32	15	2240	8
	12	2237[f]	2340	2315	25	78	2261	2222	39	15	2236	1
	13	2214[f]	2340	2311	29	97	2269	2217	52	3	2240	26
mean absolute error, MAE						72.4				5.8		7.6

[a]In gas phase; data taken from ref 46. [b]In gas phase; data taken from ref 47. [c]In gas phase; data taken from ref 48. [d]In solution (DMSO); data taken from ref 49. [e]In solid phase (neat); data taken from ref 50. [f]In solution (bromoform); data taken from ref 51.
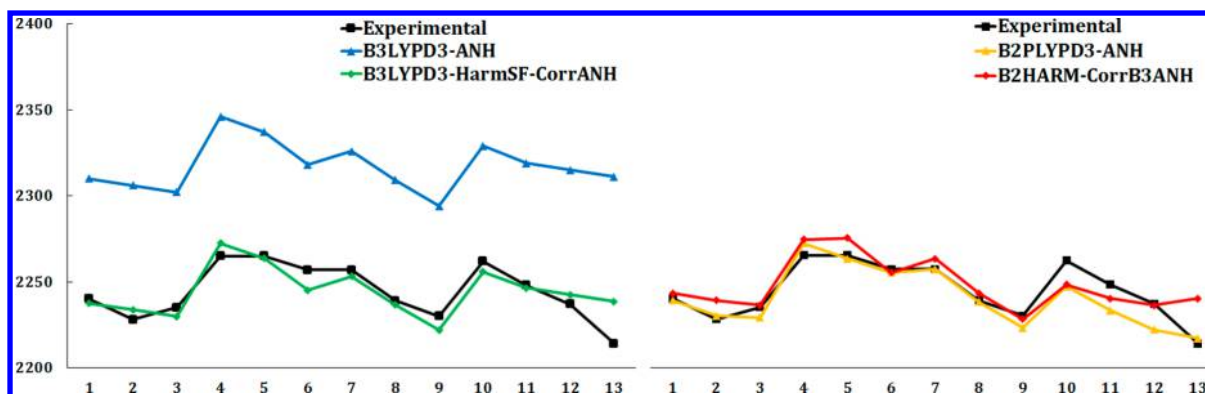

Figure 2. Comparison between experimental frequencies of C≡N stretchings (black) and their counterparts issuing from different computational models: blue = ν_{B3}; green = $K_{B3}\omega_{B3} + \Delta_{B3}$; orange = $\nu B2$; and red = $\omega_{B2} + \Delta_{B3}$. Mode numbering (abscissa) is given in Table 1.

Table 2. B3LYP-D3 Scale Factors

molecule	mode	ν_{exp}	ω_{B3}	ν_{B3}	Δ_{B3}	$\nu_{exp} + \Delta_{B3}$	K_i	ν_{corr}
I	1	2240	2342	2310	32	2272	0.970111	2237
II	2	2228	2335	2306	29	2257	0.966595	2234
III	3	2235	2335	2302	33	2268	0.971306	2230
IV	4	2265	2377	2346	31	2296	0.965923	2272
	5	2265	2369	2337	32	2297	0.969607	2264
V	6	2257	2354	2318	36	2293	0.974087	2245
	7	2257	2355	2326	29	2286	0.970701	2253
VI	8	2239	2342	2309	33	2272	0.970111	2236
	9	2230	2327	2294	33	2263	0.972497	2222
VII	10	2262	2365	2329	36	2298	0.971670	2256
	11	2248	2344	2319	25	2273	0.969710	2246
	12	2237	2340	2315	25	2262	0.966667	2243
	13	2214	2340	2311	29	2243	0.958547	2239

N stretchings are, instead, in remarkable agreement with the experimental data. The discrepancy between theory and experiment ranges between 1 cm^{-1} and 15 cm^{-1} (corresponding to an average error of 0.26%) and the MAE is reduced to a fully satisfactory value (5.8 cm^{-1}). Furthermore, all the experimental trends are correctly reproduced, including the trend for the strongly coupled C≡N moieties of compound

VII. We can thus conclude that the B2PLYPD3 computational model is able to reproduce at the same time intrinsic, environmental, and coupling effects on the CN stretching frequency with remarkable accuracy, whereas this is not the case for the B3LYPD3 computational model, irrespective of inclusion (or exclusion) of anharmonic contributions.

Scaling Factors and Hybrid Approach. In previous works, we showed that the most critical step in the computation of accurate vibrational frequencies and intensities is a good description at the harmonic level, whereas several methods deliver comparable anharmonic corrections.[23,30,31] This finding is fully confirmed for C≡N stretchings, since the average anharmonic corrections for the seven studied compounds are quite similar at both B3LYPD3 and B2PLYPD3 levels (~35 cm^{-1}), whereas the harmonic values are strongly different. For instance, the computed frequencies for the C≡N stretching of compound **I** at the harmonic levels are 2342 and 2275 cm^{-1} for B3LYPD3 and B2PLYPD3, respectively.

We have investigated if the application of a constant scaling factor (K) to the B3LYPD3 harmonic frequencies could lead to improved agreement with experimental frequencies. Equation 1 leads to very similar scale factors for all the CN stretchings of the studied molecules (see Table 2) with an average value (K_{B3} = 0.969) that is very similar to that discussed above for the prototypical HCN molecule (K = 0.966). The use of K_{B3} in eq 1 leads to remarkable agreement with experiment for all the studied compounds (green line in Figure 2) and points out the transferability of the scaling and its "intrinsic" nature, since environmental effects tuning the final frequency value are well-reproduced at the B3LYPD3 level, except for the extreme case of compound **VII**.

A more satisfactory way of reducing the computational effort involved in full anharmonic computations at the B2PLYPD3 level (which become rapidly prohibitive for larger systems) is to couple harmonic B2PLYPD3 vibrational frequencies and intensities with B3LYPD3 anharmonic corrections without introducing any scaling factor. The results (red line in Figure 2) show that, while the overall computational effort becomes reasonable, the final accuracy remains fully satisfactory, with the MAE and maximum error being 7.6 and 26 cm^{-1}, respectively.

Reduced Dimensionality Approach. Another way of obtaining accurate anharmonic frequencies for selected vibrations is the so-called reduced dimensionality approach (RDA) in which displacements are performed only along a selected number of normal modes in the numerical evaluation of third and fourth energy derivatives.[23] For purposes of illustration, we selected compounds **I**, **II**, and **III**, which contain a single C≡N moiety, so that a one-dimensional model (hereafter referenced as 1-RDA) is sufficient to obtain all the leading anharmonic couplings between CN stretching and the other normal modes. Table 3 shows that the results issuing from the 1-RDA approach yield an absolute deviation of <3 cm^{-1}, with respect to the results issuing from a full anharmonic treatment. The strength of the reduced dimensionality

Table 3. Experimental vs Simulated (B3LYPD3, B2PLYPD3/m-aug-cc-pVTZ) Vibrational Frequencies (cm^{-1}) for Compounds Containing a Single C≡N Moiety

molecule	exp	B3LYPD3/m-aug-cc-pVTZ			B2PLYPD3/m-aug-cc-pVTZ		
		Harm	Full Anh	1-RDA	Harm	Full Anh	1-RDA
I	2240[a]	2342	2310	2310	2275	2239	2238
II	2228[b]	2335	2306	2303	2268	2230	2231
III	2235[c]	2335	2302	2300	2269	2229	2227

[a]In gas phase; data taken from ref 46. [b]in gas phase; data taken from ref 47. [c]in gas phase; data taken from ref 48.

approach is, of course, the tremendous saving of computational resources (e.g., by a factor of 20 for compound **III**) coupled to a negligible reduction of the overall accuracy.

IR Spectral Shape. Let us now focus our attention on the reproduction of complete IR spectra. As an example, we show in Figure 3a the IR spectrum of compound **I**, obtained by
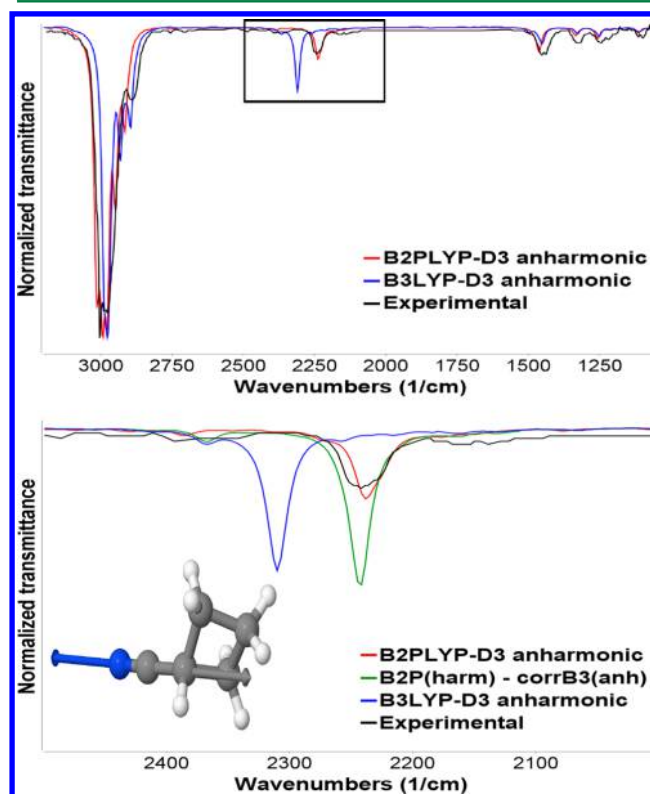

Figure 3. (a) Simulated anharmonic (red = B2PLYPD3, blue = B3LYPD3) and experimental (black) spectra of **I** (1000−3200 cm^{-1} range); (b) enlarged view of the region centered on the CN stretching peak (green = B2PLYPD3 harmonic + correction from anharmonic B3LYPD3). Theoretical spectra have been convoluted with a Lorenzian distribution function with HWHM = 5 cm^{-1}.

B2PLYPD3 (red) and B3LYPD3 (blue) computations, including both mechanical and electrical anharmonicity. Each computed line was convoluted by a Lorentzian function with half-weight at half-maximum (HWHM) of 5 cm^{-1}, chosen on the ground of systematic studies[23] aimed to simulate medium-resolution IR spectra. It is apparent that the overall shape of the spectrum simulated with the B3LYPD3 functional is in good agreement with its experimental counterpart, but the position of the C≡N stretching peak is strongly shifted and its relative height overestimated. In the spectrum simulated using hybrid vibrational frequencies ($\nu_H = \omega_{B2} + \Delta_{B3}$, green line), band positions are nicely reproduced, but the relative intensities remain unsatisfactory. Once again, the B2PLYPD3 functional performs a remarkable job, restoring full agreement with the experiment concerning both the position and the relative intensity of this specific band. Furthermore, a Fermi resonance between the C≡N stretching vibration and the overtone of the 15th normal mode (corresponding to the torsion of the four-membered ring) is now correctly recognized. As a matter of fact, C−H stretchings have similar intensities (51.8 and 47.3 km mol^{-1} at the B3LYPD3 and B2PLYPD3 level, respectively), whereas this is not the case for the C≡N stretching (18.7 and

2.4 km mol^{-1} at the B3LYPD3 and B2PLYPD3 level, respectively). Once again, the problem can be traced back to the harmonic contribution (22.2 and 9.5 km.mol^{-1} at the B3LYPD3 and B2PLYPD3 level, respectively), so that the discrepancy can be strongly reduced by adding B3LYPD3 anharmonic contributions to B2PLYPD3 harmonic intensities. This hybrid intensity (6.0 km mol^{-1}) shows a difference (2.6 km mol^{-1}) from the full B2PLYPD3 value of the same order of magnitude as those observed for "well-behaving" modes, like C−H stretchings. Since this model does not involve any additional computational burden, we strongly suggest using the hybrid approach for both frequencies and intensities possibly in connection with reduced dimensionality models.

CONCLUSION

In the present paper, we have tested the accuracy and robustness of different computational approaches to vibrational frequencies and IR intensities for several compounds including one, two, or four C≡N moieties. Together with conventional harmonic contributions, mechanical and electrical anharmonicities have been taken into account in the framework of generalized second-order vibrational perturbation theory by means of global hybrid B3PLYP or double-hybrid B2PLYP density functionals, together with semiempirical dispersion contribution, and an extended basis set. Anharmonic vibrational calculations including all the normal modes, and selecting only the normal mode corresponding to C≡N stretching were separately performed. As a matter of fact, the C≡N stretching is very sensitive to the functional used, and, especially, to the proper choice of a correlation part. Therefore, it is not surprising that the B2PLYP level of theory (which includes MP2 corrections) delivers more-accurate results than B3LYP, rivaling the performance of the so-called golden standard of computational chemistry (CCSD(T) with complete basis set extrapolation) at a strongly reduced computational cost. Moreover, we further validated an integrated strategy combining B2PLYP harmonic results and B3LYP anharmonic corrections, which dramatically reduced the computational effort without any significant loss of accuracy, except for the extreme case of compound **VII**, involving four strongly coupled CN moieties. It is noteworthy, in this connection, that, besides mechanical effects, electrical effects (here, IR intensities) also are significantly improved including B2PLYP harmonic values. Together the specific interest of the CN moiety, the proposed computational strategy paves the route toward reliable yet effective simulations of IR spectra for large molecular systems involving "problematic" functional groups without the need to introduce any empirical scaling factor. Furthermore, the implementation of the entire computational tool in a well-known commercial code and the availability of a companion graphical user interface allow its use also by nonspecialists to aid experimental spectroscopic studies.

ASSOCIATED CONTENT

Ⓢ Supporting Information

The Supporting Information is available free of charge on the ACS Publications website at DOI: 10.1021/acs.jctc.5b00638.

> Atom displacements for the overtone involved in the Fermi resonance of **I**, simulated and experimental IR spectra of **I**), and electronic energies and Cartesian coordinates for the optimized geometries of all

compounds by both B3LYP and B2PLYP functionals (PDF)

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Notes

The authors declare no competing financial interest.

REFERENCES

(1) Osman, O. I. Experimental and Theoretical Investigation of the Pyrolysis Products of Iminodiacetonitrile, (N≡CCH$_2$)$_2$NH. *J. Phys. Chem. A* **2014**, *118*, 10934−10943.

(2) Morin, M. S. T.; Lu, Y.; Black, D. A.; Arndtsen, B. A. Copper-Catalyzed Petasis-Type Reaction: A General Route to A-Substituted Amides from Imines, Acid Chlorides, and Organoboron Reagents. *J. Org. Chem.* **2012**, *77*, 2013−2017.

(3) Zhang, E.; Tian, H.; Xu, S.; Yu, X.; Xu, Q. Iron-Catalyzed Direct Synthesis of Imines from Amines or Alcohols and Amines via Aerobic Oxidative Reactions under Air. *Org. Lett.* **2013**, *15*, 2704−2707.

(4) Morin, M. S. T.; St-Cyr, D. J.; Arndtsen, B. A.; Krenske, E. H.; Houk, K. N. Modular Mesoionics: Understanding and Controlling Regioselectivity in 1,3-Dipolar Cycloadditions of Münchnone Derivatives. *J. Am. Chem. Soc.* **2013**, *135*, 17349−17358.

(5) Ferris, J. P.; Hagan, W. J., Jr. HCN and Chemical Evolution: The Possible Role of Cyano Compounds in Prebiotic Synthesis. *Tetrahedron* **1984**, *40*, 1093−1120.

(6) Snyder, L. E.; Buhl, D. Observations of Radio Emission from Interstellar Hydrogen Cyanide. *Astrophys. J.* **1971**, *163*, L47.

(7) Balucani, N. Elementary Reactions and Their Role in Gas-Phase Prebiotic Chemistry. *Int. J. Mol. Sci.* **2009**, *10*, 2304−2335.

(8) Balucani, N. Elementary Reactions of N Atoms with Hydrocarbons: First Steps towards the Formation of Prebiotic N-Containing Molecules in Planetary Atmospheres. *Chem. Soc. Rev.* **2012**, *41*, 5473−5483.

(9) Boulanger, E.; Anoop, A.; Nachtigallova, D.; Thiel, W.; Barbatti, M. Photochemical Steps in the Prebiotic Synthesis of Purine Precursors from HCN. *Angew. Chem., Int. Ed.* **2013**, *52*, 8000−8003.

(10) Barone, V.; Biczysko, M.; Puzzarini, C. Quantum Chemistry Meets Spectroscopy for Astrochemistry: Increasing Complexity toward Prebiotic Molecules. *Acc. Chem. Res.* **2015**, *48*, 1413−1422.

(11) Webster, O. W. Cyanocarbons: A classic example of discovery-driven research. *J. Polym. Sci., Part A: Polym. Chem.* **2002**, *40*, 210−221.

(12) Miller, J. S.; Epstein, A. J. Organic and organometallic magnetic materials designer magnets. *Angew. Chem., Int. Ed. Engl.* **1994**, *33*, 385−415.

(13) Her, J.-H.; Stephens, P. W.; Davidson, R. A.; Min, K. S.; Bagnato, J. D.; van Schooten, K.; Boehme, C.; Miller, J. S. Weak Ferromagnetic Ordering of the Li$^+$[TCNE]$^{\bullet-}$ (TCNE = Tetracyanoethylene) Organic Magnet with an Interpenetrating Diamondoid Structure. *J. Am. Chem. Soc.* **2013**, *135*, 18060−18062.

(14) Tucker, M. J.; Getahun, Z.; Nanda, V.; DeGrado, W. F.; Gai, F. A New Method for Determining the Local Environment and Orientation of Individual Side Chains of Membrane-Binding Peptides. *J. Am. Chem. Soc.* **2004**, *126*, 5078−5079.

(15) Lindquist, B. A.; Furse, K. E.; Corcelli, S. A. Nitrile Groups as Vibrational Probes of Biomolecular Structure and Dynamics: An Overview. *Phys. Chem. Chem. Phys.* **2009**, *11*, 8119−8132.

(16) Maienschein-Cline, M. G.; Londergan, C. H. The CN Stretching Band of Aliphatic Thiocyanate Is Sensitive to Solvent Dynamics and Specific Solvation. *J. Phys. Chem. A* **2007**, *111*, 10020−10025.

(17) Barone, V.; Baiardi, A.; Biczysko, M.; Bloino, J.; Cappelli, C.; Lipparini, F. Implementation and Validation of a Multi-Purpose Virtual Spectrometer for Large Systems in Complex Environments. *Phys. Chem. Chem. Phys.* **2012**, *14*, 12404−12422.

(18) Neese, F. Prediction of Molecular Properties and Molecular Spectroscopy with Density Functional Theory: From Fundamental Theory to Exchange-Coupling. *Coord. Chem. Rev.* **2009**, *253*, 526−563.

(19) Puzzarini, C.; Stanton, J. F.; Gauss, J. Quantum-Chemical Calculation of Spectroscopic Parameters for Rotational Spectroscopy. *Int. Rev. Phys. Chem.* **2010**, *29*, 273−367.

(20) Roy, T. K.; Gerber, R. B. Vibrational Self-Consistent Field Calculations for Spectroscopy of Biological Molecules: New Algorithmic Developments and Applications. *Phys. Chem. Chem. Phys.* **2013**, *15*, 9468−9492.

(21) Latouche, C.; Barone, V. Computational Chemistry Meets Experiments for Explaining the Behavior of Bibenzyl: A Thermochemical and Spectroscopic (IR, Raman and NMR) Investigation. *J. Chem. Theory Comput.* **2014**, *10*, 5586−5592.

(22) Stephens, P. J.; Devlin, F. J.; Chabalowski, C. F.; Frisch, M. J. *Ab Initio* Calculation of Vibrational Absorption and Circular Dichroism Spectra Using Density Functional Force Fields. *J. Phys. Chem.* **1994**, *98*, 11623−11627.

(23) Barone, V.; Biczysko, M.; Bloino, J. Fully Anharmonic IR and Raman Spectra of Medium-Size Molecular Systems: Accuracy and Interpretation. *Phys. Chem. Chem. Phys.* **2014**, *16*, 1759−1787.

(24) Lee, C.; Yang, W.; Parr, R. G. Development of the Colle−Salvetti Correlation−Energy Formula into a Functional of the Electron Density. *Phys. Rev. B: Condens. Matter Mater. Phys.* **1988**, *37*, 785−789.

(25) Becke, A. D. Density-Functional Thermochemistry. III. The Role of Exact Exchange. *J. Chem. Phys.* **1993**, *98*, 5648−5652.

(26) Andersson, M. P.; Uvdal, P. New Scale Factors for Harmonic Vibrational Frequencies Using the B3LYP Density Functional Method with the Triple-Z Basis Set 6-311+G(d,p). *J. Phys. Chem. A* **2005**, *109*, 2937−2941.

(27) Merrick, J. P.; Moran, D.; Radom, L. An Evaluation of Harmonic Vibrational Frequency Scale Factors. *J. Phys. Chem. A* **2007**, *111*, 11683−11700.

(28) Bloino, J.; Barone, V. A Second-Order Perturbation Theory Route to Vibrational Averages and Transition Properties of Molecules: General Formulation and Application to Infrared and Vibrational Circular Dichroism Spectroscopies. *J. Chem. Phys.* **2012**, *136*, 124108.

(29) Barone, V. Anharmonic Vibrational Properties by a Fully Automated Second-Order Perturbative Approach. *J. Chem. Phys.* **2005**, *122*, 014108.

(30) Piccardo, M.; Bloino, J.; Barone, V. Generalized Vibrational Perturbation Theory for Rotovibrational Energies of Linear, Symmetric and Asymmetric Tops: Theory, Approximations, and Automated Approaches to Deal with Medium-to-Large Molecular Systems. *Int. J. Quantum Chem.* **2015**, *115*, 948−982.

(31) Bloino, J.; Biczysko, M.; Barone, V. General Perturbative Approach for Spectroscopy, Thermodynamics, and Kinetics: Methodological Background and Benchmark Studies. *J. Chem. Theory Comput.* **2012**, *8*, 1015−1036.

(32) Carnimeo, I.; Puzzarini, C.; Tasinato, N.; Stoppa, P.; Charmet, A. P.; Biczysko, M.; Cappelli, C.; Barone, V. Anharmonic Theoretical Simulations of Infrared Spectra of Halogenated Organic Compounds. *J. Chem. Phys.* **2013**, *139*, 074310.

(33) Latouche, C.; Palazzetti, F.; Skouteris, D.; Barone, V. High Accuracy Vibrational Computations for Transition Metal Complexes Including Anharmonic Corrections: Ferrocene, Ruthenocene and Osmocene as Test Cases. *J. Chem. Theory Comput.* **2014**, *10*, 4565−4573.

(34) Vazart, F.; Calderini, D.; Skouteris, D.; Latouche, C.; Barone, V. Re-Assessment of the Thermodynamic, Kinetic, and Spectroscopic Features of Cyanomethanimine Derivatives: A Full Anharmonic Perturbative Treatment. *J. Chem. Theory Comput.* **2015**, *11*, 1165−1171.

(35) Grimme, S. Semiempirical Hybrid Density Functional with Perturbative Second-Order Correlation. *J. Chem. Phys.* **2006**, *124*, 034108.

(36) Biczysko, M.; Panek, P.; Scalmani, G.; Bloino, J.; Barone, V. Harmonic and Anharmonic Vibrational Frequency Calculations with

the Double-Hybrid B2PLYP Method: Analytic Second Derivatives and Benchmark Studies. *J. Chem. Theory Comput.* **2010**, *6*, 2115−2125.

(37) Frisch, M. J.; Trucks, G. W.; Schlegel, H. B.; Scuseria, G. E.; Robb, M. A.; Cheeseman, J. R.; Scalmani, G.; Barone, V.; Mennucci, B.; Petersson, G. A.; et al. *Gaussian 09 GDVI03*; Gaussian, Inc., Wallingford, CT, 2015.

(38) Papajak, E.; Leverentz, H. R.; Zheng, J.; Truhlar, D. G. Efficient Diffuse Basis Sets: cc-pVxZ+ and maug-cc-pVxZ. *J. Chem. Theory Comput.* **2009**, *5*, 1197−1202.

(39) Dunning, T. H. Gaussian Basis Sets for Use in Correlated Molecular Calculations. I. The Atoms Boron through Neon and Hydrogen. *J. Chem. Phys.* **1989**, *90*, 1007.

(40) Grimme, S.; Antony, J.; Ehrlich, S.; Krieg, H. A Consistent and Accurate *Ab Initio* Parametrization of Density Functional Dispersion Correction (DFT-D) for the 94 Elements H−Pu. *J. Chem. Phys.* **2010**, *132*, 154104.

(41) Grimme, S.; Ehrlich, S.; Goerigk, L. Effect of the Damping Function in Dispersion Corrected Density Functional Theory. *J. Comput. Chem.* **2011**, *32*, 1456−1465.

(42) Barone, V.; Cossi, M.; Tomasi, J. A New Definition of Cavities for the Computation of Solvation Free Energies by the Polarizable Continuum Model. *J. Chem. Phys.* **1997**, *107*, 3210.

(43) Cossi, M.; Scalmani, G.; Rega, N.; Barone, V. New Developments in the Polarizable Continuum Model for Quantum Mechanical and Classical Calculations on Molecules in Solution. *J. Chem. Phys.* **2002**, *117*, 43.

(44) Tomasi, J.; Mennucci, B.; Cammi, R. Quantum Mechanical Continuum Solvation Models. *Chem. Rev.* **2005**, *105*, 2999−3094.

(45) Licari, D.; Baiardi, A.; Biczysko, M.; Egidi, F.; Latouche, C.; Barone, V. Implementation of a Graphical User Interface for the Virtual Multifrequency Spectrometer: The VMS-Draw Tool. *J. Comput. Chem.* **2015**, *36*, 321−334.

(46) *IR—Cyclobutanecarbonitrile*, Webbook.nist.gov, accessed June 22, 2015.

(47) *IR—2-Propenenitrile*, Webbook.nist.gov, accessed June 22, 2015.

(48) *IR—Benzonitrile*, Webbook.nist.gov, accessed June 22, 2015.

(49) Binev, Y. I.; Binev, I. G. Possibilities of Detection and Determination of Propanedinitrile (Malononitrile) as a Carbanion by Means of IR Spectroscopy. *C. R. Acad. Bulg. Sci.* **2000**, *53*, 67.

(50) *IR—Butanedinitrile*, Webbook.nist.gov, accessed June 22, 2015.

(51) Long, D. A.; George, W. O. Spectroscopic Studies of Compounds Containing the −CN Group—I: Vibrational Spectra and Assignments for Fumaronitrile, Maleonitrile, Tetracyanoethylene and the 2-Dicyanomethylene-1,1,3,3-Tetracyanopropanediide Ion. *Spectrochim. Acta* **1963**, *19*, 1717−1729.