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Comment on "Benchmarking Basis Sets for Density Functional Theory Thermochemistry Calculations: Why Unpolarized Basis Sets and the Polarized 6-311G Family Should Be Avoided"

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Recently, McKemmish and co-workers[1] reported benchmark calculations on the performance of density functional theory (DFT) for thermochemistry and barrier heights, using a variety of double- and triple-ζ basis sets. A main conclusion of that study is that such calculations should not be performed without polarization functions. This is very old advice,[2] as is the suggestion that triple-ζ basis sets are needed for DFT thermochemistry.[3] Early benchmark studies suggested that Pople-type basis sets including 6-311+G(2d,p), 6-311+G(3df,2p) and 6-311+G(3df,2pd) were appropriate for thermochemical calculations[3−5] and the largest Pople basis set, 6-311++G(3df,3pd), continues to be used as a benchmark-quality basis.[6−48] As such, the titular prohibition on polarized 6-311G-type basis sets came as a surprise, given that none of the aforementioned examples were considered in ref 1.

Pople-style basis sets have fallen out of favor in modern DFT benchmarking,[49,50] so a fresh and comprehensive look was perhaps warranted. However, ref 1 suggests that basis-set benchmarks and clear recommendations are unavailable in the literature, which is untrue. Unambiguous recommendations are that thermochemical calculations (including barrier heights) should employ basis sets of at least triple-ζ quality,[51−54] although a composite model wherein triple-ζ single-point energies are evaluated at double-ζ geometries is often an acceptable compromise.[5,39,55] Triple-ζ basis sets are also required to obtain converged intermolecular interaction energies,[20,56−59] unless counterpoise correction is employed.[20,58] In all cases, quadruple-ζ basis sets should be used to establish the basis-set limit with certainty,[50,51,60−62] although extrapolation using double- and triple-ζ results also works well.[63] In short, copious basis-set recommendations for DFT calculations are available in the literature, backed up by extensive benchmarking, not least for thermochemistry.[19,52,53] In particular, the 6-311++G(3df,3pd) basis set has been endorsed as an alternative to aug-cc-pVQZ for thermochemical DFT calculations.[19]

To the extent that ref 1 prompts a move away from 6-31G(d) for thermochemical calculations, this would be a useful development, and the suggestion that 6-31G(d) remains too widely used in 21st-century quantum chemistry has been made by others.[64−66] We also concur with the idea that def2-TZVP is a good basis set for routine thermochemical calculations,[1] which is already standard practice.[51−54] However, we reject the blanket admonition to avoid all polarized 6-311G-type basis sets, and we do not believe that the data presented in ref 1 justify such a conclusion.

To examine this in detail, we performed extensive benchmarks using Pople-style basis sets. Calculations in ref 1 employ a small ("diet") subset[67] of the GMTKN55 database,[68] excluding molecules with elements that are not supported by Pople basis sets. We exclude the same data points in order to have equivalent tests for all basis sets, but we otherwise use the full set of GMTKN55 thermochemical and kinetics data. This amounts to 899 data points for each functional and basis set, versus 139 data points in ref 1. We consider the same exchange-correlation functionals as in ref 1, namely, B3LYP,[69,70] M06-2X,[71] and ωB97M-V,[72] except that we augment B3LYP with the D3 dispersion correction.[73] Dispersion effects on thermochemical stabilities can be significant,[74−76] and they are also important for obtaining accurate conformational energies.[77−79] For the calculations reported here, the D3 correction reduces errors by 2−4 kcal/mol relative to uncorrected B3LYP values.

All calculations were performed using Q-Chem v. 6.1.1.[80] For the benchmarks, the integral screening threshold (τ_{ints}) and the shell-pair drop tolerance (τ_{shlpr}) were both set to 10^{-14} a.u. and the self-consistent field (SCF) convergence criterion was set to $\tau_{\text{SCF}} = 10^{-8}\, E_{\text{h}}$. The SG-1 quadrature grid[81] was used for B3LYP, the SG-2 grid[82] for ωB97M-V, and the SG-3 grid[82] for M06-2X. The SG-1 grid is used for the nonlocal VV10 correlation functional[83] in ωB97M-V. These grid choices are the default settings in Q-Chem v. 6.1.1 and were selected in a functional-specific way, following careful testing.[50,82]

Figure 1 combines the error statistics for thermochemistry and barrier heights. (See Figure S1 for a larger collection of basis sets and Figures S2−S4 for a breakdown of reaction

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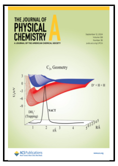

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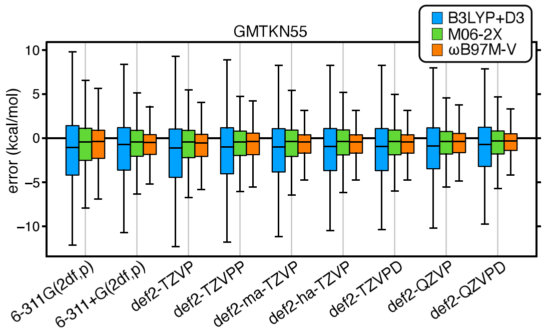

Figure 1. Statistical summary of signed errors for reaction energies and barrier heights in the GMTKN55 data set. Each colored box contains the middle 50% of the data points, and the median error (with respect to the benchmark value) is indicated by a horizontal line. Whiskers represent 1.5× times the interquartile range, representing a 99% confidence interval in the case of a normal distribution.

energies versus barrier heights.) Our assessment includes def2-QZVPD,[84,85] which should lie near the basis-set limit and establishes the inherent accuracy of each functional. We consider a wide range of basis sets in the 6-311G family, including both polarization and diffuse functions, in order to test angular and radial convergence, respectively. Table 1 summarizes the error statistics for selected basis sets; see Table S1 for the full set.

The def2-TZVP basis set is one of those recommended in ref 1, and its performance is within 0.5 kcal/mol of def2-QZVPD. At the same time, error statistics for 6-311G(2df,p) are not much different and actually have smaller standard deviations with respect to the benchmarks. Statistics for 6-311+G(3df,2pd)[86] and G3Large[87] are a bit better still. The latter two basis sets are more expensive than def2-TZVP but less expensive than def2-QZVP, as detailed below. In terms of accuracy, these two Pople basis sets afford comparable or slightly better performance than def2-QZVPD, indicating some error cancellation in the various DFT model chemistries.

The whiskers in Figure 1 provide indicators for the outliers, but we find that standard deviations provide a more useful means to discriminate between basis sets; see Table 1. In particular, 6-311+G(2df,p) reduces the standard deviation of the errors by 2 kcal/mol relative to def2-TZVP, for the meta-generalized gradient approximations (meta-GGAs). This is a significant improvement that is not adequately reflected in the median absolute errors. In view of the full compendium of error statistics, we see little reason to recommend def2-TZVP over 6-311G(2df,p).

These results warrant softening the main conclusion in ref 1, as not every member of the polarized 6-311G family needs to be avoided. Importantly, the sizable body of literature that employs 6-311+G(3df,3pd) as a benchmark-quality basis set for DFT need not be reconsidered. For DFT thermochemistry, 6-311G(2df,p) is a reasonably good basis set, comparable to def2-TZVP, and 6-311+G(3df,2pd) is also a high-quality basis set, comparable to def2-QZVPD. Elsewhere, 6-311+G(2df,2p) has been shown to provide good induction energies in symmetry-adapted perturbation theory,[59] a property that is sensitive to the presence of adequate polarization functions. The G3Large basis set is superior to def2-QZVPD, statistically speaking, especially with regard to reducing the outliers.

The def2-TZVP basis set is convenient, not least because it is defined for the entire periodic table,[84] although G3Large has been extended to 3d transition metals.[88] In any case, for main-group thermochemistry, there are comparable and even superior Pople-style alternatives to def2-TZVP. To choose between these options, computational cost may be part of the consideration. Figure 2 presents timing data for a selection of basis sets using a diazacrown ether naphthalimide molecule ($C_{41}H_{50}O_6N_4$) as a test case.[89] (Timing data for additional

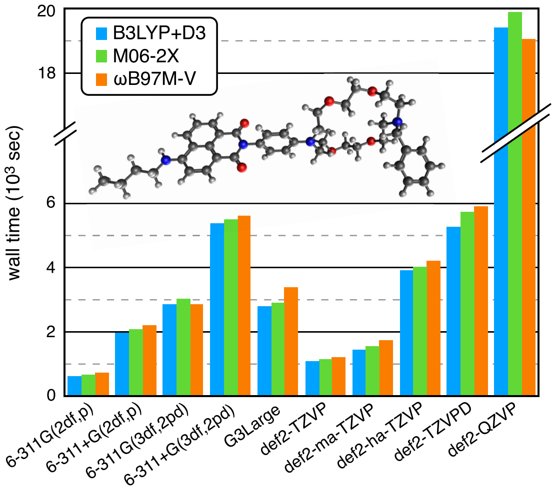

Figure 2. Wall times (on a single 48-core node) for single-point energy calculations on $C_{41}H_{50}O_6N_4$. All calculations use $\tau_{\text{SCF}} = 10^{-8}$ E_h and $\tau_{\text{ints}} = \tau_{\text{shlpr}} = 10^{-12}$ a.u., and each calculation converged in either 14 or 15 SCF iterations.

Table 1. GMTKN55 Error Statistics (Relative to Benchmark Values) for Selected Basis Sets, in kcal/mol

	B3LYP+D3			M06-2X			ωB97M-V		
Basis	median abs.	mean abs.	std. dev.	median abs.	mean abs.	std. dev.	median abs.	mean abs.	std. dev.
6-311G(2df,p)	2.8	5.5	9.4	1.8	4.0	7.3	1.7	3.6	6.6
6-311+G(2df,p)	2.4	4.9	9.5	1.5	3.0	5.6	1.2	2.6	5.4
6-311G(2df,2p)	2.4	5.3	9.0	1.8	3.9	7.2	1.8	3.5	6.4
6-311+G(2df,2p)	2.3	4.8	9.2	1.5	2.9	5.5	1.1	2.4	5.1
6-311+G(3df,2pd)	2.2	4.5	8.7	1.3	3.3	8.2	1.2	2.8	6.6
G3Large	2.2	4.6	8.8	1.3	2.8	5.5	1.1	2.4	4.9
def2-TZVP	2.7	5.3	10.0	1.6	3.4	7.6	1.3	3.4	7.2
def2-TZVPD	2.4	5.0	9.9	1.4	3.2	7.5	1.1	3.0	7.0
def2-QZVPD	2.2	4.9	9.6	1.4	3.2	8.1	1.0	2.8	7.3

basis sets can be found in Figure S5.) For all three functionals considered here, the 6-311G(2df,p) basis set is 1.7× faster than def2-TZVP. This economy is partly the result of the compound *sp* shells that are used in Pople basis sets; see Figure S6 for an indication of the speedups associated with the use of compound shells.

As noted long ago,[90] the use of compound shells in Pople basis sets reduces their variational flexibility. This is discussed at length in ref 1; nevertheless, the accuracy documented herein speaks for itself. Whereas ref 1 suggests that optimization of the contracted *s* functions is the primary problem with Pople basis sets, our results indicate that the absence of sufficient polarization functions is the primary limitation of a basis set such as 6-311G(d,p).

For a molecule as large as $C_{41}H_{50}O_6N_4$, the cost of hybrid DFT is dominated by Hartree−Fock exchange and only minor timing variations are observed among different functionals, despite the higher-quality grids that are necessary for meta-GGAs. For a medium-size molecule such as this, there is hardly any computational advantage to using B3LYP as compared to modern meta-GGAs, although that assessment can be skewed by timing data in low-quality basis sets. For example, a ωB97M-V/6-31G(d) calculation for $C_{41}H_{50}O_6N_4$ is 3.3× more expensive (per SCF iteration) than a B3LYP/6-31G(d) calculation, but ωB97M-V/def2-TZVP is only 1.2× more expensive than B3LYP/def2-TZVP.

As a realistic exemplary application, we computed the reaction energy (ΔE_{rxn}) and forward barrier height ($\Delta E^{\ddagger}$) for a 632-atom active-site model of methyl-group transfer catalyzed by the enzyme catechol O-methyltransferase,[91] whose thermochemistry and kinetics have recently been examined using large-scale quantum chemistry calculations.[91−93] As in previous work,[93] we used the ωB97X-D functional[94] in conjunction with an iterative implementation[95] of the conductor-like dielectric continuum model.[96−98] We obtained ΔE_{rxn} = −18.4 kcal/mol using def2-TZVP versus ΔE_{rxn} = −18.0 kcal/mol with 6-311G(2df,p), and $\Delta E^{\ddagger}$ = 14.6 kcal/mol with def2-TZVP as compared to 13.8 kcal/mol with 6-311G(2df,p). Differences between the two basis sets are well within the intrinsic accuracy of the functional itself,[50] but the def2-TZVP calculations are 1.9× more expensive. This is a significant reduction, given that the ωB97X-D/def2-TZVP calculations required 2,841 h of aggregate computing time on a single 48-processor node.

Finally, let us comment on the proper use of diffuse functions. Ref 1 suggests these should be used only when warranted, leaving open the question of when that might be. The importance of diffuse functions goes well beyond calculations on anions, the only example given in ref 1. Diffuse functions are often needed to converge noncovalent interaction energies,[20,58,59] polarizabilties,[99] and excitation energies computed using time-dependent DFT.[23,100−103] For the latter, the 6-311+G(2df,p) basis set is found to afford converged results.[102] Diffuse functions can also be important for thermochemistry, barrier heights, and isomerization energies.[104,105] For ground-state thermochemistry, we find that the minimally augmented def2-ma-TZVP basis set,[59] which is a proper subset of def2-TZVPD, performs just as well as 6-311+G(2df,p) but is less expensive.

Ref 1 reports convergence problems in the presence of diffuse functions, but these are artifacts of thresholds that are inappropriate for large molecules. The most important threshold is τ_{shlpr}, but for consistency, we always set τ_{ints} = τ_{shlpr}; let us denote this mutual threshold as τ_{thresh}. The setting $\tau_{\mathrm{thresh}} = 10^{-8}$ a.u. that is used in ref 1, reflecting the default for single-point energy calculations in Q-Chem v. 5.4.2, is inappropriate even for medium-size molecules. This value of τ_{thresh} can afford an ostensibly paradoxical situation in which tightening τ_{thresh} actually reduces the calculation time, because a modest increase in the cost of a Fock build (as τ_{thresh} is reduced) is compensated by rapid and robust convergence due to superior handling of numerical linear dependencies. Using a convergence criterion $\tau_{\mathrm{SCF}} = 10^{-8}\ E_{\mathrm{h}}$, we are unable to converge SCF calculations for $C_{41}H_{50}O_6N_4$ within 100 cycles, using any threshold $\tau_{\mathrm{thresh}} > 10^{-11}$ a.u. for 6-311+G(2df,p) and def2-ma-TZVP, or any value $\tau_{\mathrm{thresh}} > 10^{-12}$ a.u. for def2-TZVPD. Loose thresholds are also the reason for convergence problems reported elsewhere for ωB97M-V/def2-SVPD calculations on large van der Waals complexes.[106]

It is suggested in ref 1 that the requisite number of SCF cycles is likely to increase with molecular size. This may be true in principle, given that the energy gradient with respect to orbital rotations ($\mathbf{FP} - \mathbf{PF}$) is size-extensive,[107] but in practice this seems not to be an issue in molecules with up to ∼100 atoms, provided that appropriate thresholds are used. We routinely use $\tau_{\mathrm{thresh}} = 10^{-12}$ a.u. in our own work. For that value, DFT/def2-TZVPD calculations on $C_{41}H_{50}O_6N_4$ converge in 14−15 SCF iterations for $\tau_{\mathrm{SCF}} = 10^{-8}\ E_{\mathrm{h}}$, or 7−8 iterations for $\tau_{\mathrm{SCF}} = 10^{-5}\ E_{\mathrm{h}}$. These are typical values even for small molecules, and similar behavior as a function of τ_{thresh} is observed for the coronene dimer, $(C_{24}H_{12})_2$. For a 157-atom DNA intercalation complex that has become a standard benchmark for noncovalent interactions,[108−112] and which has an overall charge of −2, we find that τ_{thresh} must be tightened to 10^{-12} a.u. for 6-311+G(2df,p) and def2-ma-TZVP, and $\tau_{\mathrm{thresh}} = 10^{-13}$ a.u. is needed for def2-TZVPD. Using these thresholds, convergence is obtained in 16 SCF iterations for $\tau_{\mathrm{SCF}} = 10^{-8}\ E_{\mathrm{h}}$ or 7−9 iterations for $\tau_{\mathrm{SCF}} = 10^{-5}\ E_{\mathrm{h}}$. We recommend $\tau_{\mathrm{thresh}} = 10^{-12}$ a.u. for most applications, switching to $\tau_{\mathrm{thresh}} = 10^{-14}$ a.u. if convergence difficulties arise. For small molecules, these tighter thresholds add little to the overall computational time, and for larger molecules they may actually reduce it.

In summary, we find no support for a universal prohibition on 6-311G-type basis sets for thermochemical DFT calculations, provided that appropriate polarization functions are included. Basis sets such as 6-311G(d,p) certainly exhibit larger errors, as documented in ref 1, but 6-311G(2df,p) affords statistical performance on par with def2-TZVP at roughly half the cost. Basis sets such as 6-311+(3df,2pd) and G3Large afford accuracy rivaling that of def2-QZVPD at 5−10% of the cost. Where diffuse basis functions are involved, we have clarified that numerical thresholds that are satisfactory for small molecules are often inappropriate for larger ones, yet robust SCF convergence is recovered using tight thresholds.

■ ASSOCIATED CONTENT

Supporting Information

The Supporting Information is available free of charge at https://pubs.acs.org/doi/10.1021/acs.jpca.4c00283.

Computational details, data sets, timings, and data for additional basis sets (PDF)

Coordinates for the models used here (TXT)

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Notes

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