

Density Functional Calculations of E2 and S_N2 Reactions: Effects of the Choice of Density Functional, Basis Set, and Self-Consistent Iterations

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Received January 10, 2010

Abstract: We have computed stationary points on the potential energy surface for the *anti*-E2, *syn*-E2, and S_N2 pathways of the reactions of F[−] and Cl[−] with CH₃CH₂F and CH₃CH₂Cl with fully self-consistent fields and Gaussian basis functions. We find large differences from previously reported [Bento, A. P.; Solà, M.; Bickelhaupt, F. M. *J. Chem. Theory Comput.* **2008**, 4, 929] calculations with Slater-type orbitals. We revise the findings of the previous study; in particular, we find average absolute errors in kcal/mol compared to benchmark calculations of 20 stationary point energies (6 saddle points and 14 minima) of 0.9 for M06-2X, 1.2 for M08-SO, 1.4 for M06-HF, 2.0 for M06, 2.3 for B3LYP, 2.5 for OLYP, 2.7 for M06-L, and 3.5 kcal/mol for TPSS. We also compare the predictions of various density functionals for the partial atomic charges at the transition states.

1. Introduction

Density functional theory¹ has become a powerful tool for predicting and understanding trends in chemical reactivity, and considerable time has been expended in validating its predictions.² A recent article³ in this journal presented calculations for bimolecular elimination (E2) and bimolecular nucleophilic substitution (S_N2) reactions with a variety of density functional approximations (DFAs) and compared the results to benchmark calculations. The article found large errors in the predictions of most DFAs in the literature; it found a mean unsigned error for M06-2X of 2.3 kcal/mol, and it found that the M06-L density functional, although being among the best functionals in terms of mean unsigned errors (MUEs) in barrier heights, incorrectly predicted that the S_N2 saddle point for the reaction of F[−] with CH₃CH₂F is lower in energy than that of the *anti*-E2 saddle point. In order to study this, we began to repeat some of their

calculations with a different computer program, and we found surprisingly large differences.

In this article we present our results, compare them to their results, and update the conclusions about the accuracy of various density functionals. We also provide tests of the post-SCF approximation and the density fitting procedure, we test two additional density functionals that were not included in ref 3, and we calculate the charge distributions at the transition states.

2. Methods

We explored several methods where each method is a combination of a DFA and a basis set. The DFAs^{4–13} considered here are summarized in Table 1.

We considered several Gaussian basis sets,^{14–20} which are specified in Table 2, which gives convenient abbreviations for use in the rest of the article. The final row of Table 2 is the Slater-type basis used in the calculations of ref 3, which were all performed with the ADF program.²¹ Our calculations in Tables 3 and 4 were performed with the Gaussian 03²² and MN-GFM programs.²³

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Table 1. Density Functional Approximations^a

name	reference	type	X ^b
OLYP	6, 9	GGA	0
B3LYP	5–9	hybrid GGA	20
TPSS	10	meta-GGA	0
M06-L	4	meta-GGA	0
M06-HF	11	hybrid meta ^c	100
M06	12	hybrid meta	27
M06-2X	12	hybrid meta	54
M08-HX	13	hybrid meta	52.23
M08-SO	13	hybrid meta	56.79

^a We sometimes use the conventional language in which an approximation to the unknown exact exchange–correlation functional is just called a density functional. ^b X denotes the percentage of Hartree–Fock exchange. ^c hybrid meta is short notation for hybrid meta-GGA.

Table 2. Basis Sets

basis	reference	type ^a (quality)	abbreviation
6-311+G(2df,2p)	14, 15	triple- ζ + diffuse	311+
MG3S ^b	16, 17	triple- ζ + diffuse	MG3S
aug-cc-pV(T+d)Z	18	triple- ζ + diffuse	aTZ
aug-cc-pV(Q+d)Z	18, 19	quadruple- ζ + diffuse	aQZ
TZ2P	20	Slater triple- ζ + diffuse	V

^a “triple- ζ quality” is short notation for polarized triple- ζ . ^b MG3S is the same as 6-311+G(2df,2p) for H, C, and F but is improved for Cl. See ref 17.

For all calculations, we used the default fine grid in *Gaussian 03*, which has 75 radial shells and 302 angular points per shell. We have checked the M06-2X/MG3S calculations with the ultrafine grid (99 radial shells and 590 angular points per shell), and we found that the relative energies obtained with the default fine grids agree within 0.05 kcal/mol of those obtained by using ultrafine grids.

The *Gaussian 03* program can carry out Kohn–Sham density functional calculations with or without density fitting,²⁴ and we used both methods, as will be specified in the tables. In principle, density fitting is not an approximation, if the auxiliary basis set used for fitting is converged, but in practice one should check for basis set incompleteness or use well validated large auxiliary basis sets.

3. Results

Tables 3 and 4 show the present results for the F[−] + CH₃CH₂F and Cl[−] + CH₃CH₂Cl reactions, respectively, and Tables 5 and 6 present selected results from Bento et al.,³ arranged the same way for ease of comparison. As in ref 3, we consider the *syn*- and *anti*-E2 reactions and the S_N2 reaction. All calculations in Tables 3–6 are based on the OLYP/TZ2P geometries of Bento et al.³ in order to remove the choice of geometry from the comparison of calculations. In the tables, the symbol “A@B” is used to denote a post-SCF calculation, that is, a calculation in which the final energy is evaluated by method A, but the density is calculated by method B.

All values in the tables are energies relative to the energy of the separated reactants. PC denotes a precursor complex (local minimum of the potential energy occurring at an earlier stage of the reaction coordinate than the saddle point), SP denotes the saddle point, SC denotes a successor complex (local minimum of the potential energy occurring at a later

stage of the reaction coordinate than the saddle point), and P denotes the product.

4. Discussion

4.1. Comparison of Calculations. In addition to density functional calculations, Tables 5 and 6 show benchmark calculations carried out by the coupled cluster method with single and double excitations and a quasiperturbative treatment of connected triple excitations²⁵ (CCSD(T)), extrapolated³ to the complete basis set (CBS) limit. These benchmark calculations are used to compute the mean unsigned error (MUE) for each row of Tables 3–6, and these MUEs are given in the last column of each of these tables. The first observation one makes is that the errors are much bigger in Tables 5 and 6, based on the Slater-type orbitals (STOs),³ than in Tables 3 and 4, based on the Gaussian-type orbital calculations (GTO calculations) presented here.

The striking differences in the results must be attributed to the differences in the calculations: the different basis sets, the use of post-SCF calculations in some of the STO calculations, and the use of frozen core approximation in some of the STO calculations.

The first possible reason for the differences is that we use Gaussian basis sets and ADF uses Slater-type orbitals. However, the first three rows of Tables 3 and 4 show that we get similar results with two different triple- ζ quality and one quadruple- ζ quality basis set, so it does not appear that basis set incompleteness is significant in our GTO calculations. Personal communications from Bickelhaupt and van Gisbergen and their co-workers show that the largest systematic source of discrepancy between the results of ref 3 and the present results is the choice of STO basis set; in particular, a large part of the discrepancy can be removed if one uses larger STO basis sets containing diffuse functions.^{26,27} It is not our goal to trace down every possible contributor to the deviations between the results of ref 3 and the present results but rather to focus on the revised conclusions about the performances of various density functionals, to present results for two density functionals (M08-HX and M08-SO) that were not included in ref 3, and to add a caution about the post-SCF approximation.

ADF can evaluate the energy for the density functionals of interest from a charge density obtained with a simpler density functional; this is called a post-SCF treatment, and it is provided as a convenience to user who wish to get a quick impression of the effect of changing the density functional. In the calculations of Bento et al., all charge densities were obtained with the OLYP functional. Thus all their results except OLYP involve the post-SCF approximation. In contrast, except for a test that we will now report, our calculations were all performed by achieving a full self-consistent field for each function employed. Recently Liao et al.²⁸ indicated that the post-SCF approximation can produce large errors in calculating noncovalent binding energies; in contrast, the authors of ref 3 state that in previous work²⁹ the post-SCF approximation has “been extensively tested and .. shown to introduce an error in the computed energies of only a few tenths of a kcal/mol,” but they did

Table 3. Results with Gaussian Basis Sets for the Reactions of F⁻ with CH₃CH₂F

method	<i>anti</i> -E2				<i>syn</i> -E2				S _N 2		MUE
	PC	SP	SC	P	PC	SP	SC	P	PC	SP	
M06-2X/MG3S	-15.99	-1.15	-5.49	19.16	-12.07	3.85	-35.12	-29.47	-15.99	3.02	1.34
M06-2X/aTZ	-15.10	-0.42	-4.82	18.89	-11.18	4.92	-34.45	-28.95	-15.10	3.65	1.16
M06-2X/aQZ	-15.05	-0.25	-4.74	18.72	-11.20	5.17	-33.99	-28.54	-15.05	4.07	1.20
M06-2X@OLYP/aTZ	-13.60	2.33	-3.63	18.54	-9.89	6.24	-34.24	-28.74	-13.60	6.26	2.07
M06-2X/311+	-15.99	-1.15	-5.49	19.16	-12.07	3.85	-35.12	-29.47	-15.99	3.02	1.34
OLYP/aTZ	-12.51	-0.74	-4.55	12.97	-8.25	4.17	-31.65	-28.15	-12.51	4.16	2.23
OLYP/aQZ	-12.21	-0.39	-4.25	12.94	-7.98	4.52	-31.19	-27.80	-12.21	4.58	2.47
OLYP/311+	-14.63	-2.63	-6.39	13.54	-10.16	1.69	-33.45	-29.37	-14.63	1.35	1.45
B3LYP/311+	-15.98	-2.65	-6.78	16.38	-11.59	2.31	-34.82	-29.98	-15.98	-1.08	1.58
TPSS/311+	-17.54	-1.75	-4.78	20.24	-12.73	0.65	-32.06	-26.98	-17.54	-6.26	3.40
M06/311+	-16.25	-1.76	-5.84	18.49	-12.22	2.86	-31.70	-26.58	-16.25	-1.02	2.14
M06-L/311+	-17.07	-1.95	-5.41	19.32	-12.66	1.69	-31.04	-25.92	-17.07	-4.05	3.05
M06-L/311+ ^a	-17.06	-1.95	-5.41	19.32	-12.65	1.70	-31.04	-25.93	-17.06	-4.03	3.04
M08-HX/311+	-16.56	-1.96	-6.47	18.58	-12.64	3.90	-34.38	-28.67	-16.56	1.26	1.44
M08-SO/311+	-15.87	-2.44	-6.13	18.21	-12.22	4.83	-33.35	-27.77	-15.87	0.89	1.40
M06-HF/311+	-15.80	-0.79	-4.98	19.75	-11.76	4.48	-38.51	-32.77	-15.80	2.92	1.56

^a This calculation was carried out with density fitting; all other calculations in this table were carried out without this additional approximation.

Table 4. Results with Gaussian Basis Sets for the Reactions of Cl⁻ with CH₃CH₂Cl

method	<i>anti</i> -E2				<i>syn</i> -E2				S _N 2		MUE
	PC	SP	SC	P	PC	SP	SC	P	PC	SP	
M06-2X/MG3S	-11.15	17.64	11.56	23.26	-11.15	29.76	-4.54	-1.69	-11.15	5.79	0.54
M06-2X/aTZ	-11.06	17.71	11.56	23.32	-11.06	29.76	-4.47	-1.60	-11.06	5.95	0.53
M06-2X/aQZ	-10.91	18.10	11.83	23.39	-10.91	30.24	-4.08	-1.26	-10.91	6.49	0.61
M06-2X@OLYP/aTZ	-10.38	20.08	12.10	22.94	-10.38	31.80	-4.02	-1.17	-10.38	7.81	1.10
M06-2X/311+	-11.34	17.51	11.71	23.72	-11.34	29.61	-4.83	-1.80	-11.34	5.63	0.69
OLYP/aTZ	-8.03	13.48	9.42	16.65	-8.03	22.62	-8.32	-6.46	-8.03	6.87	3.76
OLYP/aQZ	-7.91	13.79	9.74	16.88	-7.91	22.93	-7.97	-6.11	-7.91	7.24	3.64
OLYP/311+	-8.18	13.12	9.52	17.20	-8.18	22.32	-8.73	-6.84	-8.18	6.45	3.75
B3LYP/311+	-9.89	13.19	8.65	19.08	-9.89	23.64	-7.81	-5.59	-9.89	2.50	3.05
TPSS/311+	-10.42	10.62	10.53	21.95	-10.42	19.61	-7.56	-4.99	-10.42	-1.73	3.56
M06/311+	-11.37	15.97	12.08	24.21	-11.37	25.59	-4.01	-0.87	-11.37	2.25	1.77
M06-L/311+	-11.11	13.33	11.37	23.39	-11.11	22.41	-5.07	-2.01	-11.11	0.05	2.29
M06-L/311+ ^a	-11.11	13.32	11.35	23.37	-11.11	22.40	-5.10	-2.04	-11.11	0.03	2.29
M08-HX/311+	-11.64	18.21	10.77	23.65	-11.64	31.36	-2.89	0.30	-11.64	6.37	0.89
M08-SO/311+	-11.64	17.21	10.36	23.37	-11.64	29.91	-3.33	-0.11	-11.64	4.37	0.98
M06-HF/311+	-11.25	19.31	12.43	24.16	-11.25	34.28	-3.59	-0.39	-11.25	6.40	1.26

^a This calculation was carried out with density fitting; all other calculations in this table were carried out without this additional approximation.

Table 5. Results with Slater-type Basis Sets for the Reactions of F⁻ with CH₃CH₂F

method	<i>anti</i> -E2				<i>syn</i> -E2				S _N 2		MUE
	PC	SP	SC	P	PC	SP	SC	P	PC	SP	
CCSD(T)/CBS	-14.89	-1.27	-6.35	15.77	-11.00	5.68	-37.39	-28.60	-14.89	2.20	
B3LYP@OLYP/V	-19.30	-5.38	-10.66	15.90	-14.50	-2.00	-40.32	-35.34	-19.30	-4.01	4.44
M06@OLYP/V	-18.21	-2.21	-7.47	17.88	-13.96	1.14	-35.19	-30.59	-18.21	-0.35	2.51
M06-2X@OLYP/V	-15.67	1.49	-5.62	18.37	-11.47	4.03	-37.77	-32.90	-15.67	5.82	1.81
TPSS@OLYP/V	-21.38	-5.26	-8.94	19.81	-16.28	-4.16	-37.83	-32.52	-21.38	-10.03	5.53
M06-L@OLYP/V	-20.04	-1.23	-5.44	20.54	-15.33	1.68	-32.57	-27.78	-20.04	-2.95	3.51
OLYP/V	-20.01	-7.95	-12.49	-12.85	-15.20	-4.93	-41.40	-36.41	-20.01	-4.16	8.47

not report tests of these approximations for the reactions under consideration here. We, therefore, tested the post-SCF method for these reactions by carrying out calculations for M06-2X with the OLYP density. These results are given in row four of Tables 3 and 4. The results differ from straight M06-2X calculations with the same basis set by 0.2–2.8 kcal/mol, with an average (over 20 cases) of 1.2 kcal/mol. Clearly the errors are larger than the previous work led the authors of ref 3 to believe, but the deviations of the present results from those of ref 3 are even larger than this, so this

does not contradict the conclusion^{26,27} that the main reason for the inaccuracy of ref 3 is the choice of basis set.

Our OLYP calculations are also important for another reason. Since OLYP is the only method for which the results in ref 3 are full SCF results rather than post-SCF results, this comparison directly tests whether issues other than the post-SCF approximation are indeed important. The results show that they are. Comparing our results with the largest basis set (aQZ) to the results from ref 3 shows absolute deviations of 0.1–10.2 kcal/mol, with an average (over 20

Table 6. Results with Slater-type Basis Sets for the Reactions of Cl[−] with CH₃CH₂Cl

method	<i>anti</i> -E2				<i>syn</i> -E2				S _N 2		MUE
	PC	SP	SC	P	PC	SP	SC	P	PC	SP	
CCSD(T)/CBS	−11.07	18.18	9.77	22.16	−11.07	30.92	−4.85	−1.42	−11.07	5.81	
B3LYP@OLYP/V	−10.60	11.00	7.03	17.83	−10.60	21.22	−10.78	−8.53	−10.60	0.92	4.33
M06@OLYP/V	−12.68	17.33	6.17	22.96	−12.68	23.67	−6.49	−2.92	−12.68	3.36	2.29
M06-2X@OLYP/V	−12.49	10.65	14.98	22.49	−12.49	30.29	−5.85	−4.74	−12.49	10.73	2.72
TPSS@OLYP/V	−10.99	9.34	8.95	20.88	−10.99	17.58	−9.89	−7.01	−10.99	−3.22	4.42
M06-L@OLYP/V	−14.02	12.92	8.99	25.92	−14.02	22.77	−4.73	−2.25	−14.02	2.63	3.09
OLYP/V	−9.66	10.68	7.45	16.33	−9.66	19.58	−11.81	−9.28	−9.66	4.04	4.78

cases) of 5.0 kcal/mol. We note for completeness that the OLYP calculations of ref 3 were carried with a frozen-core approximation, whereas all other calculations in ref 3 were all-electron calculations; our calculations are all of the latter type.

ADF evaluates the matrix elements of the exchange–correlation potential and the Coulomb potential using an auxiliary function representation of the electronic density; this is called density fitting. Gaussian can carry out calculations with or without this additional approximation. When density fitting is employed, it is important to know the adequacy of auxiliary basis sets used for density fitting. Tables 3 and 4 show M06-L calculations with and without this approximation, using the *Gaussian 03* default choice for the auxiliary basis, and the agreement is quite good, with an average deviation of only 0.01 kcal/mol. This is consistent with conclusions we drew in tests of this method on other reactions.^{2f} We did not test the auxiliary basis sets used in ADF, but the sets of auxiliary functions in ADF are rather extensive, and tests of this feature by the developers of ADF show that density fitting errors are quite small (smaller than basis set effects).²¹

4.2. Revised Conclusions about the Accuracy of Density Functional Approximations. The mean unsigned error in the present M06-2X results is 0.9 kcal/mol, as compared to 2.3 kcal/mol in the calculations of ref 3. The average error in the M06-L relative energetics (average over 20 cases) is 2.7 kcal/mol, which is lower than the 3.3 kcal/mol average error found in ref 3. We conclude that the bigger-than-expected errors reported in ref 3 appear to be artifacts of the calculations, especially the basis sets, and not deficiencies of the density functionals applied.

We still find that the M06-L density functional predicts an anomalously low barrier height for the F[−] + CH₃CH₂F S_N2 reaction, and in fact, it also predicts a significantly too low barrier for the Cl[−] + CH₃CH₂Cl S_N2 reaction. Since functionals with no Hartree–Fock exchange sometimes overestimate the amount of charge transfer,³¹ one possible reason for the large error in M06-L in the F[−] case is an overestimate of the amount of charge transfer. To examine this possibility, we computed the partial atomic charges at transition states by Hirshfeld population analysis.^{32,33} The partial atomic charges on the halogen atom are in Table 7, which shows reasonably similar partial atomic charges for various density functionals. Furthermore, the S_N2 reaction has neither the largest nor the smallest partial charges on the halogens. Thus we cannot attribute the poor performance of S_N2 to spurious charge transfer. M06-L is a meta-GGA.

Table 7. Hirshfeld Partial Atomic Charges on F and Cl at the *anti*-E2 and S_N2 Transition States^a

method	<i>anti</i> -E2				S _N 2 ^b	
	leaving F	incoming F	leaving Cl	incoming Cl	F	Cl
M06-L	−0.74	−0.29	−0.73	−0.39	−0.51	−0.58
M06-2X	−0.80	−0.29	−0.77	−0.38	−0.53	−0.59
M06-HF	−0.82	−0.29	−0.78	−0.36	−0.55	−0.59
OLYP	−0.72	−0.28	−0.70	−0.38	−0.49	−0.55
TPSS	−0.73	−0.28	−0.71	−0.38	−0.49	−0.56
HF	−0.84	−0.31	−0.81	−0.39	−0.60	−0.65

^a All calculations in this table employed the 311+ basis set.

^b The incoming and leaving halogen atoms have the same partial charges for the S_N2 reactions.

The only other meta-GGA in this paper is TPSS; TPSS has an even larger error than M06-L for this difficult case.

The average error in the M06-L relative energetics (average over 20 cases) is 2.7 kcal/mol, which is lower than our calculated mean errors for other functionals with no Hartree–Fock exchange: 3.1 and 3.5 kcal/mol for OLYP and TPSS, respectively. Adding Hartree–Fock exchange can reduce the error to 0.9 (M06-2X), 1.2 (M08-HX and M08-SO), 1.4 (M06-HF), or 2.0 kcal/mol (M06), whereas the popular B3LYP functional has a mean unsigned error of 2.3 kcal/mol.

Excluding one saddle point (that for the S_N2 reaction of F[−] with CH₃CH₂F), reduces the mean absolute errors for of M06-2X and M06-L from respectively 0.89 and 2.67 kcal/mol for 20 cases to 0.85 and 2.48 kcal/mol for 19 cases.

5. Concluding Remarks

The density functional results obtained here agree much better than those in ref 3 with benchmark calculations. The final trends in the errors for barrier heights in the present paper are not significantly out of line with what might have been expected on the basis of previous tests,^{2e,2f} although the errors reported in ref 3 are larger than would have been expected for the Minnesota functionals (which was the motivation for our opening the problem for re-examination). The errors in the calculations with the more accurate density functionals could probably be reduced by using consistently optimized geometries rather than OLYP geometries, but that is not the goal of the present article, which is instead designed to reveal differences in the calculated results due to algorithmic choices in ref 3.

Acknowledgment. The authors are very grateful to Stan van Gisbergen, Erik van Lenthe, F. Matthias Bickelhaupt, Marcel Swart, and Miquel Solà for assistance in tracing down the discrepancies between the present calculations and those

of ref 3. The research reported here was supported in part by the Air Force Office of Scientific Research.

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