

Density Functional Calculations of E2 and S_N2 Reactions: Effects of the Choice of Method, Algorithm, and Numerical Accuracy

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Abstract: Herein we provide a detailed account on how the potential energy surfaces of the E2 and S_N2 reactions of X[−] + CH₃CH₂X (X = F, Cl) depend on various methodological and technical choices in density functional calculations. We cover a choice of density functionals (OLYP, various M06-types, and the new SSB-D), basis sets (up to quintuple- and quadruple- ζ for Gaussian- and Slater-type orbitals, respectively, plus polarization and diffuse functions), and other aspects of the computations (among others: nonrelativistic versus zeroth-order regular approximation relativistic; numerical integration accuracy; all-electron versus frozen core; self-consistent field (SCF) versus post-SCF). The program codes ADF and NWChem are used for calculations with Slater- and Gaussian-type basis sets, respectively. The fluoride systems (X = F) appear to not only depend extremely sensitively on the basis set size (especially the presence of diffuse functions) but also on other technical settings, especially in the case of hybrid meta-generalized gradient approximation functionals. This work complements a recent contribution (Y. Zhao, D. G. Truhlar, *J. Chem. Theory Comput.* 2010, 6, 1104) and provides recommendations for density functionals, basis sets, and technical settings.

1. Introduction

Base-induced elimination (E2) and nucleophilic substitution (S_N2) constitute two fundamental types of chemical reactions that play an important role in organic synthesis.^{1,2} E2 elimination is, in principle, always in competition with S_N2 substitution, and the two pathways may occur as unwanted side reactions of each other (see Scheme 1).

Recently,³ some of us reported a benchmark study on the potential energy surfaces (PESs) for the *anti*- and *syn*-E2 and S_N2 pathways of X[−] with CH₃CH₂X (X = F, Cl) in the gas phase. A hierarchical series of ab initio methods was

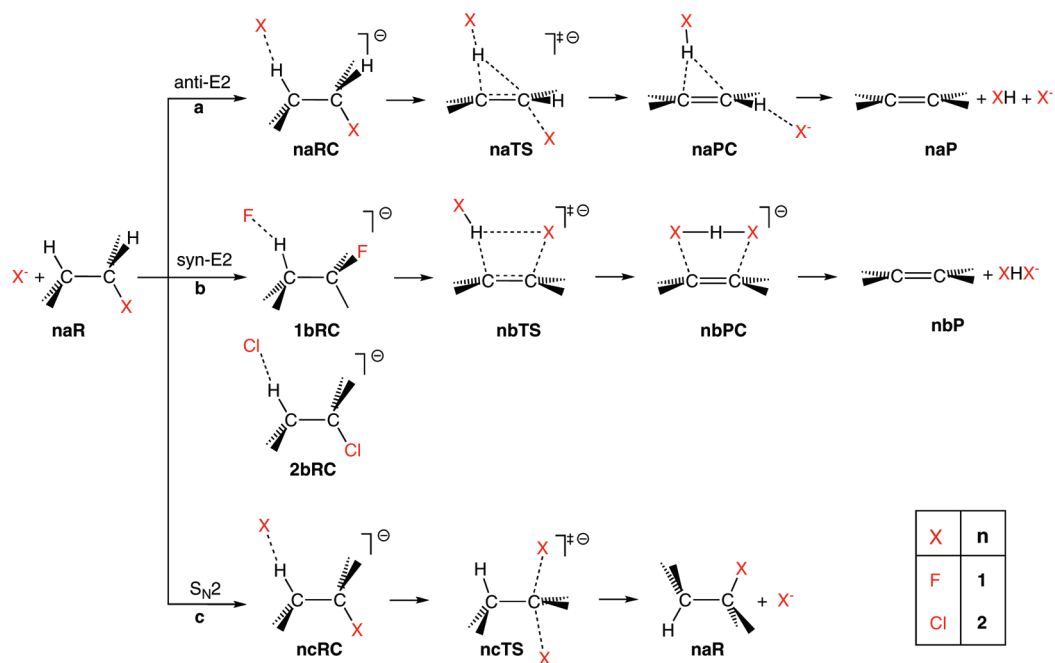
employed (Hartree–Fock (HF), second- and fourth-order Møller–Plesset (MP2 and MP4), coupled-cluster singles and doubles (CCSD), and CCSD(T)) in combination with a hierarchical series of Gaussian-type orbital (GTO) basis sets (up to quadruple- ζ + diffuse functions for reactions involving F, and up to (triple+d)- ζ + diffuse functions for reactions involving Cl). The performance of several popular density functionals were also evaluated using a TZ2P basis set of Slater-type orbitals (STOs).⁴ This TZ2P basis set is in general sufficiently large to be able to draw meaningful conclusions and normally gives results that are close to the basis set limit. In the case of the very demanding systems studied here (see below),⁵ the energies obtained may differ by a few kcal·mol^{−1} from the basis set limit results.⁶ In a recent paper, this is correctly pointed out by Zhao and Truhlar,⁷ who report mean unsigned errors (MUE) for several density functionals

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Scheme 1. E2 and S_N2 Reaction Pathways for X[−] + CH₃CH₂X

that were 1.5–2.0 kcal·mol^{−1} lower than those obtained with the TZ2P basis set. Nevertheless, the relative ordering in performance of the density functionals is much less affected, with the smallest MUE values observed for the Minnesota M06-2X functional,⁸ followed by M06,⁸ SSB-D,⁹ M06-L,¹⁰ OLYP,^{11,12} and TPSS.¹³

In the current contribution, we report a detailed study of the PESs for these competing pathways as obtained with a variety of density functionals and with both GTO and STO basis sets. In particular, we highlight the importance of several aspects of the computational setup that are shown to have a great impact on the results obtained, especially concerning the numerical accuracy. Our contribution not only provides full details referred to in the recent article of Zhao and Truhlar but also augments the latter with the above-mentioned numerical analyses and recommendations for density functionals, basis sets, and technical settings.

2. Computational Details

2.1. Basis Sets and Programs. All calculations using the STOs were obtained with the Amsterdam Density Functional (ADF)^{14,15} program (version 2009.01) using a variety of basis sets ranging in size from double- ζ valence plus polarization (DZP) to an even-tempered quadruple- ζ plus five polarization functions (ET-QZ+5P).¹⁶ The workhorse TZ2P (STO) basis set is of triple- ζ quality, augmented by two sets of polarization functions (2p and 3d on H and 3d and 4f on C, F, and Cl) and contains diffuse functions. In some cases, the zeroth-order regular approximation (ZORA)¹⁷ scalar relativistic Hamiltonian was used, but it was shown to have a small effect on the PES results (see below). All calculations with GTOs were obtained using the NWChem program¹⁸ (version 5.1.1 but locally modified to include SSB-D). The CCSD(T) calculations on the isolated fluoride and chloride anions used a frozen core, similar to those obtained in ref 3. A number of Dunning's^{19,20} correlation-consistent basis sets have been

used, ranging from double- ζ plus polarization (cc-pV(D+d)Z for Cl,²⁰ cc-pVDZ on others, abbreviated as dz) to quintuple- ζ plus diffuse functions (aug-cc-pV(5+d)Z on Cl,²⁰ aug-cc-pV5Z on others, abbreviated as a5z).

2.2. Numerical Integration. Unless noted otherwise, all of these calculations used a precise numerical integration scheme with a fine grid in NWChem (consisting of 70 radial and 590 angular shells for first-row elements and 123 radial and 770 angular shells for second-row elements) and ACCINT = 8.0 within ADF. These grids are used within NWChem only for the matrix elements of the exchange–correlation potential, while within ADF it is also used for other integrals¹⁵ (e.g., Coulomb). This allows for the use of the intrinsically most suitable basis sets (STOs) but is accompanied by a larger dependency on numerical integration. In most cases however, this poses no problem as the grid is generated in such a way that one can smoothly increase the accuracy by using more integration (grid) points. The size of the grid is determined by one parameter, the accuracy level (ACCINT).

2.3. Geometries and Mean Unsigned Errors. All energies of stationary points were obtained using the geometries optimized at OLYP/TZ2P from ref 3. Note, in Scheme 1, that all reactant complexes are trans-coplanar, except for **1bRC** in which [F[−]⋯H]–C^β–C^α–[F] is in a gauche conformation (i.e., **2aRC**, **2bRC**, and **2cRC** are identical species, and **1aRC** and **1cRC** are identical species). Mean unsigned errors (MUEs) in the energies relative to reactants are calculated as the mean absolute deviations with respect to the CCSD(T)/CBS energies for **1aRC**, **1aTS**, **1aPC**, **1aP**, **1bRC**, **1bTS**, **1bPC**, **1bP**, **1cRC**, and **1cTS** (MUE-F, F systems) and **2aRC**, **2aTS**, **2aPC**, **2aP**, **2bRC**, **2bTS**, **2bPC**, **2bP**, **2cRC**, and **2cTS** (MUE-Cl, Cl systems), and MUE is the average of MUE-F and MUE-Cl.

Table 1. Energies Relative to Reactants of Stationary Points Along the *Anti*-E2 Reaction of F⁻ + CH₃CH₂F and MUE for All Six Reactions Compared to CCSD(T)/CBS Data^a

method, basis	<i>E</i>					MUE		
	1aR	1aRC	1aTS	1aPC	1aP	MUE-F ^b	MUE-Cl ^c	MUE ^d
CCSD(T) ^a								
adz	0.0	-15.81	-2.03	-7.16	16.11	0.97	1.16	1.07
atz	0.0	-15.17	-1.31	-6.28	16.51	0.29	0.18	0.24
aqz	0.0	-14.99	-1.33	-6.39	15.95	0.11	n/a	n/a
CBS-limit	0.0	-14.89	-1.27	-6.35	15.77	-	-	-
OLYP								
qz ^e	0.0	-22.58	-10.19	-14.32	14.84	8.02	4.33	6.17
5z ^f	0.0	-17.44	-5.37	-9.55	13.30	3.51	4.17	3.84
aqz ^g	0.0	-12.21	-0.39	-4.25	12.94	2.16	3.64	2.90
a5z ^h	0.0	-11.84	-0.06	-3.88	12.87	2.42	3.67	3.05
TZ2P ⁱ	0.0	-19.90	-7.58	-12.00	13.22	5.94	4.69	5.32
QZ4P ^j	0.0	-17.83	-5.79	-9.83	12.97	3.88	3.72	3.80
df-ATZ2P ^k	0.0	-11.83	-0.22	-4.06	13.07	2.33	3.86	3.10
ET-QZ+5P ^l	0.0	-12.12	-0.45	-4.29	12.79	2.21	3.70	2.95
M06								
qz ^e	0.0	-21.44	-6.64	-11.11	18.79	5.76	2.15	3.96
5z ^f	0.0	-16.86	-2.57	-6.55	18.09	2.03	1.71	1.87
aqz ^g	0.0	-15.14	-0.63	-4.71	18.24	1.56	1.48	1.52
a5z ^h	0.0	-15.41	-1.25	-5.34	17.85	1.44	1.60	1.52
TZ2P ⁱ	0.0	-18.78	-3.00	-8.04	18.81	3.01	2.05	2.53
QZ4P ^j	0.0	-16.74	-2.37	-6.51	17.97	1.85	1.71	1.78
df-ATZ2P ^k	0.0	-14.83	-0.45	-4.63	17.80	1.29	1.51	1.40
ET-QZ+5P ^l	0.0	-14.74	-0.28	-4.24	18.13	1.57	1.74	1.65
M06-2X								
qz ^e	0.0	-20.55	-5.16	-10.31	19.18	5.21	1.12	3.16
5z ^f	0.0	-17.69	-2.62	-7.49	18.69	2.41	0.88	1.65
aqz ^g	0.0	-15.06	-0.26	-4.73	18.71	0.88	0.62	0.75
a5z ^h	0.0	-15.11	-0.41	-4.94	18.56	0.85	0.57	0.71
TZ2P ⁱ	0.0	-18.03	-2.00	-7.49	19.35	2.71	0.84	1.77
QZ4P ^j	0.0	-16.40	-1.79	-6.42	18.34	1.38	0.87	1.13
df-ATZ2P ^k	0.0	-14.81	-0.39	-4.80	18.31	0.85	1.07	0.96
ET-QZ+5P ^l	0.0	-15.11	-0.43	-5.01	18.57	0.86	0.86	0.86
M06-L								
qz ^e	0.0	-21.50	-5.91	-9.27	20.17	5.41	2.58	3.99
5z ^f	0.0	-17.15	-1.70	-4.81	19.62	2.95	2.10	2.52
aqz ^g	0.0	-15.71	0.05	-3.22	19.89	2.72	2.18	2.45
a5z ^h	0.0	-15.81	-0.39	-3.55	19.56	2.63	2.38	2.50
TZ2P ⁱ	0.0	-19.23	-3.11	-7.02	20.45	3.42	2.95	3.18
QZ4P ^j	0.0	-17.55	-1.98	-5.31	19.78	3.02	2.91	2.97
df-ATZ2P ^k	0.0	-15.50	-0.35	-3.72	19.95	2.42	2.66	2.54
ET-QZ+5P ^l	0.0	-15.68	0.00	-3.12	19.94	2.77	3.08	2.93
SSB-D								
qz ^e	0.0	-25.85	-10.61	-13.82	21.55	9.24	3.38	6.31
5z ^f	0.0	-20.32	-5.32	-8.46	20.48	4.56	2.80	3.68
aqz ^g	0.0	-15.92	-0.98	-3.88	20.40	2.83	2.39	2.61
a5z ^h	0.0	-15.74	-0.84	-3.74	20.33	2.78	2.33	2.56
TZ2P ⁱ	0.0	-23.29	-7.62	-11.57	19.40	6.91	3.16	5.04
QZ4P ^j	0.0	-21.55	-6.38	-9.68	20.45	5.33	2.61	3.97
df-ATZ2P ^k	0.0	-15.68	-1.04	-3.97	20.49	2.68	2.45	2.57
ET-QZ+5P ^l	0.0	-15.83	-1.03	-3.95	20.19	2.76	2.45	2.61

^a *E* and MUE are in kcal·mol⁻¹. CCSD(T)/CBS data from ref 3. See Scheme 1 for definition of species. See Computational Details for technical settings. ^b MUE for F-systems (reactions **1a–c**) with respect to CCSD(T)/CBS. ^c MUE for Cl-systems (reactions **2a–c**) with respect to CCSD(T)/CBS. ^d Total MUE for F- and Cl-systems (reactions **1a–c** and **2a–c**). ^e GTO basis: cc-pV(Q+d)Z on Cl and cc-pVQZ on others. ^f GTO basis: cc-pV(5+d)Z on Cl and cc-pV5Z on others. ^g GTO basis: aug-cc-pV(Q+d)Z on Cl and aug-cc-pVQZ on others. ^h GTO basis: aug-cc-pV(5+d)Z on Cl and aug-cc-pV5Z on others. ⁱ STO basis: TZ2P(all-electron). ^j STO basis: QZ4P(all-electron). ^k STO basis: augmented TZ2P:ATZ2P(all-electron) with AddDiffuseFit keyword. ^l STO basis: even-tempered ET-QZ+5P(all-electron).

3. Results and Discussion

3.1. Influence of the Basis Set. Recently,³ some of us reported coupled cluster benchmark results for the *anti*- and *syn*-E2 and S_N2 pathways of X⁻ with CH₃CH₂X (X = F, Cl). Based on an interpolation procedure, estimates for the complete basis set (CBS) limit were obtained³ for the coupled cluster results (see Table 1). Note that in ref 3, the CCSD(T)/CBS value for **1bPC** was inadvertently reported as -37.39 kcal·mol⁻¹ instead of the correct value -34.27 kcal·mol⁻¹.²¹ The CCSD(T) results with the various correlation-

consistent basis sets are also given in Table 1; see Scheme 1 for the definition of the various stationary points. They indicate that even with the quite large aug-cc-pVTZ basis (aug-cc-pV(T+d)Z for Cl) still a deviation of 0.74 kcal·mol⁻¹ can be observed compared to the complete basis set results (see Supporting Information and refs 5 and 22).

The same strong dependence on the size of the basis set is observed for the density functionals. This is shown for both the correlation-consistent GTO and the STO basis sets (see Table 1). However, unlike the case for the CCSD(T)

Table 2. Relative Energies for Fluoride and Chloride Anions with CCSD(T) and Different Density Functionals and Basis Sets^a

	CCSD(T)	OLYP	M06	M06-2X	M06-L	SSB-D
Fluoride Anion						
dz	143.1	90.0	71.5	74.8	66.2	85.1
tz	55.3	41.4	32.5	26.1	29.6	41.9
qz	22.3	23.1	14.7	13.1	12.4	21.2
5z	6.4	9.5	3.3	4.3	2.7	7.5
adz	74.0	21.7	17.7	23.0	19.3	20.9
atz	23.2	6.6	7.5	4.0	6.6	7.6
aqz	6.0	1.7	2.0	1.8	1.4	1.5
a5z	0.0	0.0	0.0	0.0	0.0	0.0
Chloride Anion						
dz	88.4	31.3	23.4	29.8	19.4	27.2
tz	30.0	13.9	10.6	8.8	8.1	13.0
qz	9.1	7.5	3.6	4.5	1.9	5.4
5z	2.7	4.1	1.1	1.7	0.4	2.6
adz	57.1	10.7	6.3	13.4	7.4	9.7
atz	17.7	3.4	4.2	2.4	3.4	3.5
aqz	4.0	1.4	1.2	1.7	0.7	0.8
a5z	0.0	0.0	0.0	0.0	0.0	0.0

^a E is in kcal·mol⁻¹. Relative to results obtained with a5z basis set.

data that seems to systematically lead to a lower MUE value with increasing basis set, there is no such systematical improvement for the density functional theory (DFT) data (see Table 1). For example, with OLYP, the MUE for the F systems decreases from 8.02 (qz) to 3.51 (5z) to 2.16 (aqz) but then increases to 2.42 kcal·mol⁻¹ (a5z). The same is observed for other functionals (see, e.g., MUE-Cl for M06-L with the qz, 5z, aqz, and a5z basis sets) and the STO basis sets (see, e.g., MUE-F of M06 with TZ2P, QZ4P, df-ATZ2P, and ET-QZ+5P). The M06-2X and SSB-D functionals seem to more systematically yield lower MUE values with increasing basis set size, although small jumps of less than 0.05 kcal·mol⁻¹ still occur (see Supporting Information).

The lowering of the MUE with increasing basis set size is in part due to a better description of the anionic nucleophiles (F⁻ and Cl⁻), where in particular, the description of the fluoride anion warrants a more flexible and large basis set. This is shown in Table 2 which, for the five functionals and the eight correlation-consistent GTO basis sets, shows the energies of fluoride and chloride anions, evaluated with the various basis sets, relative to the corresponding energy obtained with the largest basis set. Given that the relative energies in Table 1 are taken with respect to the reactants, which include the anionic halides, it matters greatly how well these anionic reactants are described. For instance for OLYP with the dz basis, the reactant complex energies of the F systems are too low (because the energy of F⁻ is too high), while those of the Cl systems are quite good. The MUEs with respect to the CCSD(T)/CBS data for the reactant complexes at the OLYP/dz level are therefore 21.3 and 1.6 kcal·mol⁻¹ for the F and Cl systems, respectively (see Supporting Information). The same is observed for other functionals, such as M06-2X, which in combination with the dz basis shows a MUE value for the RC complexes of the F systems of 16.9 and 3.2 kcal·mol⁻¹ for the Cl systems. As soon as the basis set allows for a better description of the charge distribution in the anionic halides, the MUE values decrease accordingly (see Table 2). A

similarly delicate dependence on the quality of the basis set was found in the case of the heterolytic dissociation energies of alkalimetal fluorides MF (M = Li, Na, K, Rb, Cs).²³ The extreme sensitivity of bond and reaction energies for systems involving fluorine can be ascribed to the large effective expansion (orbital “breathing effect”), as the very compact fluorine atom takes up excess negative charge.²⁴ This effect is still present for chlorine and heavier halogens but to a much lesser extent.

It should be noted that not just the basis set size but in particular the presence of diffuse functions is very important for these systems. This is not that surprising since the systems studied here are mainly of anionic character, for which diffuse functions are known to be important.⁶ Thus, for these systems, going from the tz to the qz or even the 5z basis yields less of an improvement than simply adding a layer of diffuse functions in the atz basis. For instance, in the case of M06-2X, going from the tz basis to the qz and 5z basis corresponds to a drop in the MUE value from 5.61 to 3.16 (qz) and 1.65 kcal·mol⁻¹ (5z), respectively (see Table 1 and Supporting Information). With the atz basis, a MUE value of just 0.72 kcal·mol⁻¹ is observed (see Supporting Information).

3.2. Evaluation of the Different Functionals. For any basis set, the lowest MUE value is found for the M06-2X functional, which is then followed by M06, M06-L, SSB-D, OLYP, and TPSS. This ordering of the different functionals is in agreement with the trends mentioned in the previous studies by some of us³ and by Zhao and Truhlar⁷ and situates our recently reported SSB-D⁹ as the best GGA functional among the ones applied to the E2 and S_N2 reactions in this study. This holds especially for the central barrier for which, with the ET-QZ+5P basis, an MUE compared to CCSD(T) of 3.1 kcal·mol⁻¹ is observed (see Supporting Information). This value can then be compared to those of the other functionals, i.e., 1.2 (M06-2X), 1.8 (M06), 3.9 (M06-L), 3.8 (OPBE), 4.5 (OLYP), and 6.2 kcal·mol⁻¹ (TPSS). Although the MUE for SSB-D is larger than the M06-2X and M06 results, it is significantly better than M06-L and OPBE which were the best meta-GGA and GGA functionals, respectively, of our previous study.³

The competition between the three pathways (*anti*-E2 vs *syn*-E2 vs S_N2) was shown previously, at CCSD(T)/CBS, to be different for the F and Cl systems.³ For the Cl systems, the S_N2 pathway is found to be the one with the lowest barrier. In contrast, for the F systems the *anti*-E2 pathway has the lowest barrier at the CCSD(T)/CBS level (see Table 3). This is correctly reproduced by most functionals³ but with some exceptions, like LDA, BP86, PBE, VS98, TPSS, M06-L, and BHandH. Again, our SSB-D functional works well for both the F and Cl systems (see Table 3), for which it predicts the lowest barrier to be *anti*-E2 and S_N2, respectively.

The effect of the basis set on the relative ordering of the reaction barriers (i.e., TS energies) is again found to be larger for the F systems than for the Cl systems (see Table 4). Although the energies relative to the reactants show dramatic changes of more than 20 kcal·mol⁻¹, this is mainly due to the description of the isolated halide ions (vide supra, Table 2). More important for the chemistry of these systems is the

Table 3. Energies Relative to Reactants for Transition States of All Six Reactions^a

	1aTS	1bTS	1cTS	2aTS	2bTS	2cTS
Ab Initio/CBS ^b						
CCSD(T)	-1.27	5.68	2.20	18.18	30.92	5.81
DFT/a5z						
OLYP	-0.06	4.90	5.02	13.85	22.98	7.32
M06	-1.25	3.61	0.71	15.57	25.27	2.31
M06-2X	-0.41	4.94	4.02	18.03	30.11	6.31
M06-L	-0.39	3.93	-2.11	13.22	22.32	0.49
SSB-D	-0.84	2.43	0.04	13.88	22.94	5.07
DFT/ET-QZ+5P						
OLYP	-0.45	4.51	4.66	13.62	22.73	7.08
M06	-0.28	4.62	1.42	15.68	27.28	2.67
M06-2X	-0.43	5.00	4.34	18.68	28.77	6.72
M06-L	0.00	4.24	-2.16	10.31	24.18	0.13
SSB-D	-1.03	2.30	-0.13	13.60	22.63	4.68
OPBE	2.90	5.77	7.25	16.38	24.86	10.03
TPSS	-0.14	2.62	-3.64	11.27	20.19	-0.99

^a E is in kcal·mol⁻¹. In bold: pathways with lowest reaction barriers. See Scheme 1 for definition of species. See computational details for technical settings. ^b Based on GTO basis sets, from ref 3.

relative height of the reaction barriers because they determine which one of the three pathways is most competitive (see Scheme 1). It is found that at least the atz (or df-ATZ2P for STO basis sets) basis set is needed for the correct ordering of the pathways for the F systems. This is observed for, e.g., SSB-D (see Table 4) and M06 (Supporting Information). The Cl systems are much less demanding. For example, already with the dz and DZP basis sets does one correctly obtain S_N2 substitution as the most favorable pathway (see Table 4 and Supporting Information).

3.3. Numerical Accuracy. Apart from the effect of the basis set size and the presence of diffuse basis functions, there are a number of other (technical) parameters that influence the results obtained. Some of these are due to the numerical accuracy and integration grid and are therefore more of technical nature, while others are physical. An example of the latter is the use of scalar relativistic corrections. These relativistic corrections are usually relevant mainly for elements starting from the fourth period onward and should have a smaller impact for the systems studied here. This is indeed reconfirmed by our computed ZORA relativistic corrections, which amount to only 0.03 kcal·mol⁻¹ or less (see Table 5).

The size of the integration grid is less stringent for GTO-based programs, like NWChem, in which these grids are only used for the comparatively small exchange-correlation potential and all other terms, especially the large Coulomb potential, are calculated analytically using integrals involving the GTO basis functions. However, the grid should be sufficiently large, which is not always the default option as was recently shown by Wheeler and Houk.²⁵ Within the STO-based ADF program, many more energy terms are calculated numerically. This has clear benefits in terms of, for example, scalability (parallelization). There are also drawbacks because the dependence of the results on the numerical accuracy is larger. Exactly how important the numerical accuracy is depends to a large extent on the combination of the density functional and the basis set. The

Table 4. TS Energies Relative to Reactants of All Six Reactions Computed with 13 Different Basis Sets^a

	1aTS	1bTS	1cTS	2aTS	2bTS	2cTS
CCSD(T) ³						
CBS	-1.27	5.68	2.20	18.18	30.92	5.81
M06-2X						
dz	-12.76	-17.28	-15.98	12.75	23.37	0.46
tz	-8.51	-7.10	-7.28	15.40	27.09	3.09
qz	-5.16	-1.84	-2.51	16.94	28.91	5.01
5z	-2.62	1.85	0.98	17.18	29.17	5.30
adz	-0.82	4.40	2.76	16.69	28.43	5.20
atz	-0.46	4.89	3.62	17.77	29.81	5.95
aqz	-0.26	5.18	4.07	18.16	30.27	6.47
a5z	-0.41	4.94	4.02	18.03	30.11	6.31
DZP	-8.03	-7.98	-6.59	14.17	22.68	0.92
TZ2P	-2.00	2.24	0.90	19.21	28.91	6.06
QZ4P	-1.79	3.35	2.08	18.53	28.72	6.58
df-ATZ2P	-0.39	5.49	4.41	19.87	29.70	7.31
ET-QZ+5P	-0.43	5.00	4.34	18.68	28.77	6.72
M06-L						
dz	-17.36	-20.59	-24.71	7.51	15.47	-5.61
tz	-10.68	-9.91	-14.98	10.86	19.79	-2.41
qz	-5.91	-3.27	-9.36	12.75	21.98	-0.05
5z	-1.70	2.38	-3.93	13.61	22.84	0.65
adz	-2.00	0.93	-5.47	11.92	20.32	-1.12
atz	-0.37	3.70	-2.85	13.42	22.48	0.41
aqz	0.05	4.45	-1.88	13.35	22.59	0.94
a5z	-0.39	3.93	-2.11	13.22	22.32	0.49
DZP	-11.75	-12.06	-15.75	4.29	17.87	-5.35
TZ2P	-3.11	-0.41	-5.56	9.58	23.58	0.09
QZ4P	-1.98	1.79	-4.35	10.58	24.82	0.67
df-ATZ2P	-0.35	3.71	-1.24	10.37	24.50	1.10
ET-QZ+5P	0.00	4.24	-2.16	10.31	24.18	0.13
SSB-D						
dz	-22.08	-26.70	-29.62	6.56	14.77	-2.43
tz	-15.52	-16.48	-17.97	9.87	18.70	0.24
qz	-10.61	-10.20	-12.08	11.56	20.46	2.35
5z	-5.32	-3.23	-5.42	12.47	21.41	3.46
adz	-1.31	1.87	-3.03	12.71	21.64	3.98
atz	-1.14	2.14	-0.42	13.59	22.65	4.49
aqz	-0.98	2.27	-0.22	13.90	22.93	4.98
a5z	-0.84	2.43	0.04	13.88	22.94	5.07
DZP	-15.71	-17.39	-18.28	6.72	15.39	-2.85
TZ2P	-7.62	-6.27	-7.89	12.16	20.75	3.39
QZ4P	-6.38	-4.65	-6.80	13.54	22.59	4.47
df-ATZ2P	-1.04	2.35	0.01	13.13	22.16	4.18
ET-QZ+5P	-1.03	2.30	-0.13	13.60	22.63	4.68

^a E is in kcal·mol⁻¹. In bold: pathways with lowest reaction barriers. See Scheme 1 for definition of species. See computational details for technical settings.

standard TZ2P basis set is robust and can be used for standard production work without any special precaution. One should be more cautious for, e.g., the ATZ2P basis set, which was designed for use in TD-DFT calculations to obtain reasonably accurate excitation energies with a relatively small basis set. Its direct use on ground-state properties, like the energy profiles studied here, should be carried out with care. Importantly, an additional set of diffuse functions (df) is needed in the auxiliary fit set which is employed for fitting the molecular density and to represent the Coulomb and exchange potentials (c.f., “density fitting” or “resolution of identity” scheme).²⁶ This particular combination of basis set (ATZ2P) and diffuse fit set (df) is designated df-ATZ2P.

The ADF program employs the numerical procedure of density fitting also for evaluating the HF exchange potential.²⁷ This implies that results obtained with hybrid func-

Table 5. Influence of Technical and Other Parameters on Energies Relative to Reactants of the *Anti*-E2 Reaction of $F^- + CH_3CH_2F$ and on the MUE of All Six Reactions. Other Parameters (grid size, frozen-core, diffuse functions in fit set, Dependency, ZORA)^a

	<i>E</i>					MUE ^b
	1aR	1aRC	1aTS	1aPC	1aP	
OLYP/aoz						
medium ^c	0.0	-12.20	-0.39	-4.24	12.95	2.90
fine ^d	0.0	-12.21	-0.39	-4.25	12.94	2.90
xfine ^e	0.0	-12.21	-0.39	-4.25	12.94	2.90
gfine ^f	0.0	-12.21	-0.39	-4.25	12.94	2.90
gultra ^g	0.0	-12.21	-0.39	-4.25	12.94	2.90
M06-2X/aoz						
medium ^c	0.0	-14.96	-0.06	-4.59	18.68	0.80
fine ^d	0.0	-15.06	-0.26	-4.73	18.71	0.75
xfine ^e	0.0	-15.06	-0.26	-4.74	18.70	0.75
gfine ^f	0.0	-15.06	-0.27	-4.74	18.70	0.75
gultra ^g	0.0	-15.06	-0.27	-4.74	18.70	0.75
OLYP/TZ2P(Bento et al.) ³						
frozen-core	0.0	-20.01	-7.95	-12.49	12.85	5.50 ^h
OLYP/TZ2P(2009.01)						
frozen-core	0.0	-20.01	-7.94	-12.47	12.87	5.48
all-electron	0.0	-19.90	-7.58	-12.00	13.22	5.32
OLYP/TZ2P						
Accint 6.0, ZORA	0.0	-19.91	-7.60	-12.03	13.19	5.35
Accint 8.0, ZORA	0.0	-19.91	-7.61	-12.03	13.19	5.35
Accint 8.0	0.0	-19.90	-7.58	-12.00	13.22	5.32
Accint 8.0, diff_fit	0.0	-19.89	-7.49	-11.92	13.27	5.26
Accint 8.0, dependency	0.0	-19.90	-7.58	-12.00	13.22	5.32
Accint 10.0	0.0	-19.90	-7.58	-12.00	13.22	5.32
OLYP/ATZ2P						
Accint 8.0	0.0	-11.83	-1.12	-5.33	11.91	3.29
Accint 8.0, diff_fit ⁱ	0.0	-11.83	-0.22	-4.06	13.07	3.10
Accint 8.0, dependency	0.0	-11.75	-0.09	-3.94	12.96	3.13
Accint 10.0, diff_fit ⁱ	0.0	-11.83	-0.23	-4.06	13.07	3.10
M06-2X/TZ2P, Accint 6.0, ZORA						
post-SCF (Bento et al.) ³	0.0	-15.67	1.49	-5.62	18.37	2.42
post-SCF (2009.01)	0.0	-15.67	1.49	-5.62	18.37	2.44
SCF (2009.01)	0.0	-18.28	-1.41	-6.89	19.79	2.73
M06-2X/TZ2P						
Accint 8.0, ZORA	0.0	-18.05	-2.01	-7.50	19.32	1.75
Accint 8.0	0.0	-18.03	-2.00	-7.49	19.35	1.77
Accint 8.0, diff_fit	0.0	-18.09	-2.06	-7.49	19.45	1.81
Accint 8.0, dependency	0.0	-18.03	-2.17	-7.59	19.16	1.71
Accint 10.0	0.0	-18.27	-2.01	-7.45	19.52	1.87
M06-2X/ATZ2P						
Accint 8.0	0.0	-14.82	-0.38	-4.81	18.22	0.95
Accint 8.0, diff_fit ⁱ	0.0	-14.81	-0.39	-4.80	18.31	0.96
Accint 8.0, dependency	0.0	-14.79	-0.15	-4.86	18.55	0.98
Accint 10.0, diff_fit ⁱ	0.0	-15.07	-0.40	-4.77	18.49	0.77

^a *E* and MUE are in kcal/mol. See Scheme 1 for definition of species. ^b Total MUE for F- and Cl-systems (reactions **1a–c** and **2a–c**). ^c Standard medium grid of NWChem (49 radial/434 angular shells for first row and 88/434 for second row elements). ^d Standard fine grid of NWChem (70/590 for first row and 123/770 for second row elements). ^e Standard xfine grid of NWChem (100/1202 for first row and 125/1454 for second row elements). ^f Obtained with NWChem using settings for fine grid in Gaussian09 (75/302 for all elements). ^g Obtained with NWChem using settings for fine grid in Gaussian09 (99/590 for all elements). ^h Total MUE recalculated from data given in ref 3. ⁱ The df-ATZ2P basis set, i.e., combination of AddDiffuseFit keyword with ATZ2P basis set.

tionals have an increased dependence on the size and quality of the auxiliary fit set and the associated numerical procedure. For the calculation of the HF exchange, this sensitivity becomes more important for larger basis sets.

In the case of very large regular or auxiliary basis sets, overcompleteness in certain parts of function space may occur, and the set can thus become (nearly) linearly dependent. In such cases, counter measures can be taken by removing linear combinations of basis functions that correspond to small eigenvalues of the virtual symmetrized fragment orbitals (SFO) overlap matrix; this procedure is

invoked with the ADF input keyword Dependency in combination with some threshold-type technical parameters. We stress at this point that this procedure should be used with great caution, and individual cases must be carefully analyzed. If the threshold parameters are chosen too large, then not only the overcompleteness is tackled but also “useful” portions of the basis-function space are removed which corresponds effectively to a reduction of the basis set quality and therefore the computed energy.

In our present computations, the Dependency procedure (with technical parameters: bas = 1e - 3, fit = 1e - 10,

and $\text{eig} = 1\text{e}8$) has a negligible effect on the results for pure density functionals such as OLYP (see Table 5). But the results obtained with hybrid (meta-GGA) functionals such as M06-2X appear to depend more delicately on this and other numerical procedures. For example, the product energy (**1aP**) of reaction 1a is found in a range between 19.16 and 19.52 kcal·mol⁻¹ for M06-2X/TZ2P, depending on several numerical parameters (see Table 5). Choices that affect the M06-2X/TZ2P energy are, among others, the removal of nearly linear-dependent combinations of basis functions (cf., Dependency keyword), the addition of a set of diffuse fit functions in the fit set, or the integration grid size. For OLYP/TZ2P, this variation is much smaller, i.e., between 13.19 and 13.27 kcal·mol⁻¹. Note that this variation in the obtained energies has a much smaller impact on the MUE values, which for, e.g., M06-2X/TZ2P vary from 1.71 to 1.87 kcal·mol⁻¹. Note also that varying the standard basis sets from a smaller to a larger one causes larger changes in the computed energies. For example, the M06-2X energy of product **1aP** relative to reactants varies some 0.8 kcal·mol⁻¹ between the TZ2P and the ET-QZ+5P basis sets (see Table 1).

3.4. Influence of Self-Consistency. The ADF program contains the option to calculate the energies of density functionals in a post-SCF manner, i.e., to evaluate the density functionals with densities and orbitals as obtained with another density functional. This is a very useful feature because it allows a fast determination of these energies for a large number of density functionals, which we have used very often in the past. Previous studies^{28–34} have shown that for GGA functionals the effect of self-consistency is of the order of 0.1–0.3 kcal·mol⁻¹, depending on the basis set, the numerical accuracy used, etc. For meta-GGA and hybrid (meta-GGA) functionals, the magnitude of this effect was unknown because, until the 2009.01 version, it was not possible to use a meta-GGA or hybrid meta-GGA during the SCF. In a recent study,³⁵ we already observed that for hybrid functionals, like B3LYP or X3LYP, the effect of self-consistency depends on the functional and on the system and may range from 0.3 to 2.2 kcal·mol⁻¹ for B3LYP* and X3LYP, respectively.³⁵ The same trend is observed here, where the effect of self-consistency is larger for hybrid meta-GGA functionals, like M06-2X, as already described by Zhao and Truhlar.⁷ As can be seen in Table 5, for these functionals, the effect can be even larger, i.e., up to 2.8 kcal·mol⁻¹ for any one of the stationary points (R, RC, TS, PC, and P). However, the overall effect of self-consistency is much smaller, as is shown by the MUE value for M06-2X/TZ2P (2.73 kcal·mol⁻¹) and M06-2X@OLYP/TZ2P (2.44 kcal·mol⁻¹), i.e., a difference of only 0.3 kcal·mol⁻¹ (see Table 5). A similar difference is observed (Supporting Information) for the effect of self-consistency for M06-L (0.25 kcal·mol⁻¹), but in that case, the effect for individual stationary points is much smaller (maximum 0.6 kcal·mol⁻¹, see Supporting Information).

4. Conclusions

We have investigated how the potential energy surfaces of the E2 and S_N2 reactions of X⁻ + CH₃CH₂X (X = F, Cl)

depend on various methodological choices in density functional calculations with the ADF and NWChem programs which employ Slater- and Gaussian-type basis sets, respectively. The present work complements the recent contribution by Zhao and Truhlar⁷ by providing full numerical details and recommendations for the usage of the different functionals, basis sets, and technical settings, a selection of which is compiled in this section.

In the case of both programs (and types of basis sets), the fluoride systems (X = F) appear to depend extremely sensitively on basis set size, especially the presence of diffuse functions. For ADF calculations on problems involving fluoride anions, we recommend the QZ4P basis or the even better (but also computationally more expensive) even-tempered ET-QZ+5P basis set. The TZ2P performs excellently for neutral species, but it leads to a significant exaggeration of the fluoride anion's binding capability and reactivity.

Other technical settings are also important, especially for energies computed with hybrid meta-GGA functionals, which depend more strongly, e.g., on the accuracy of the numerical integration than energies computed with GGA functionals. The mean unsigned error (MUE) computed with ADF over all six reaction profiles of this study for M06-2X, for example, decreases from 2.42 to 1.77 to 0.86 kcal/mol as we go from basis set/integration accuracy combinations TZ2P/accint = 6 (similar to ref 3) to TZ2P/accint = 8 to ET-QZ+5P/accint = 8.

Thus, we find M06-2X as the best performing functional in the ADF and NWChem programs. Note that SSB-D is the best GGA functional studied. It improves upon both M06-L and OPBE which were the best meta-GGA and GGA functional, respectively, in our previous study.³ For calculations with the ADF program, we recommend that standard GGA functionals (e.g., OLYP or SSB-D) are evaluated with a numerical integration accuracy parameter accint = 6.0, whereas (hybrid) meta-GGA and hybrid functionals should be evaluated with a higher numerical accuracy, accint = 8.0. Note also that the (hybrid) meta-GGA and hybrid functional implementation in ADF requires all-electron basis sets, i.e., the frozen-core approximation must not be used in these cases.

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Supporting Information Available: Full details of relative energies with Dunning's dz, tz, qz, 5z, adz, atz, aqz, and a5z GTO basis sets and with the DZ, DZP, TZ2P, df-ATZ2P, QZ4P, ET-QZ+5P, and ET-pVQZ STO basis sets; the corresponding mean absolute deviations; full details of the influence of technical parameters on the results obtained.

This information is available free of charge via the Internet at <http://pubs.acs.org/>.

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