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Chemical accuracy for the van der Waals density functional

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Abstract

The non-local van der Waals density functional (vdW-DF) of Dion \textit{et al.} (2004 \textit{Phys. Rev. Lett.} 92 246401) is a very promising scheme for the efficient treatment of dispersion bonded systems. We show here that the accuracy of vdW-DF can be dramatically improved both for dispersion and hydrogen bonded complexes through the judicious selection of its underlying exchange functional. New and published exchange functionals are identified that deliver much better than chemical accuracy from vdW-DF for the S22 benchmark set of weakly interacting dimers and for water clusters. Improved performance for the adsorption of water on salt is also obtained.

(London dispersion interactions are ubiquitous in nature contributing to the binding of biomolecules such as DNA, molecular crystals, and molecules on surfaces. The accurate description of dispersion, which often occurs in conjunction with hydrogen bonds, is a major challenge for many electronic structure theories. Density functional theory (DFT), the most widely used electronic structure theory, often doesn’t meet this challenge. Indeed, it is well established that popular generalized gradient approximation (GGA) or hybrid exchange–correlation functionals are inadequate for the description of dispersion interactions. Many schemes have been developed that allow dispersion to be accounted for within DFT in a more or less approximate manner (see, e.g. [1–7]). One of the most promising and rigorous methods is the non-local van der Waals density functional (vdW-DF) of Langreth and Lundqvist and co-workers [1].

In vdW-DF the non-local correlation is calculated so that the exchange–correlation energy takes the form

\[ E_{xc} = E_{xc}^{\text{GGA}} + E_{xc}^{\text{LDA}} + E_{xc}^{\text{nl}}, \]

where \( E_{xc}^{\text{GGA}} \) is the GGA exchange energy. In the original vdW-DF this is obtained with the revised version of the Perdew, Burke, and Ernzerhof (PBE) [8] functional from Zhang and Yang (revPBE) [9]. \( E_{xc}^{\text{LDA}} \) accounts for the local correlation energy obtained within the local density approximation (LDA), and \( E_{xc}^{\text{nl}} \) is the non-local correlation energy. The formula for \( E_{xc}^{\text{nl}} \) is based on electron densities interacting via a model response function, the particular form of which is still a subject of research [10]. The vdW-DF has been applied to a wide variety of systems where dispersion is important (see [11] for a review) and recent algorithmic developments [12] have made it only marginally more computationally expensive than a regular GGA. However, in many important circumstances the current vdW-DF is simply not accurate enough. For example, for the S22 dataset [13] (a set of 22 weakly interacting dimers mostly of biological importance) it yields a mean absolute deviation (MAD) of \( \sim 60 \) meV [14] compared to coupled cluster reference data. This is outside the so-called ‘chemical accuracy’ of 1 kcal mol\(^{-1}\) or \( \sim 43 \) meV and inferior performance to other DFT-based dispersion correction schemes [3, 5, 7]. Water clusters, important for atmospheric chemistry and liquid water, are another example where vdW-DF substantially underbinds (by \( \sim 20\% \) compared to accurate reference data) and in terms of absolute dissociation energies is worse than a regular GGA such as PBE [15, 16].)
Recognizing that the interaction energies obtained with vdW-DF depend on the exchange functional incorporated within it [1, 14, 17, 18], we aimed to improve vdW-DF by exploring and developing alternative exchange functionals to the original revPBE. Since it is known that vdW-DF correlation is not compatible with Hartree–Fock (HF) exact exchange [17, 18] and the original revPBE exchange functional was just one of many possible choices, we continue in this spirit and search for alternative exchange functionals that yield more reliable interaction energies than revPBE. To this end we first use the S22 dataset since it includes a variety of weakly bonded dimers for which accurate interaction energies and structures have been established [13] and so provides a tough test for molecular simulation methods. Following this we test our methods on two complex systems, for example, liquid water and ice.

Table 1. Mean absolute deviations from the reference data [13] for the S22 set for vdW-DF with various exchange functionals ('Method'). MADs are given for the whole set ('MAD Total'), the hydrogen bonded ('MAD HB'), dispersion bonded ('MAD DB'), and mixed bonding subsets ('MAD MB'). For each functional we also report the difference between the largest and smallest deviations from the reference data ('Range') and the difference in the mean deviations of hydrogen bonded and dispersion bonded subsets ($\Delta^{H-D}$). The new functionals introduced in this study are in the last three rows. All values are in meV.

<table>
<thead>
<tr>
<th>Method</th>
<th>Total</th>
<th>HB</th>
<th>DB</th>
<th>MB</th>
<th>Range</th>
<th>$\Delta^{H-D}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>revPBE-vdW</td>
<td>65</td>
<td>106</td>
<td>52</td>
<td>38</td>
<td>163</td>
<td>57</td>
</tr>
<tr>
<td>B88-vdW</td>
<td>62</td>
<td>76</td>
<td>61</td>
<td>48</td>
<td>124</td>
<td>16</td>
</tr>
<tr>
<td>PBE-vdW</td>
<td>54</td>
<td>33</td>
<td>83</td>
<td>42</td>
<td>117</td>
<td>50</td>
</tr>
<tr>
<td>PW86-vdW</td>
<td>41</td>
<td>14</td>
<td>73</td>
<td>31</td>
<td>130</td>
<td>61</td>
</tr>
<tr>
<td>B86MGC-vdW</td>
<td>28</td>
<td>10</td>
<td>49</td>
<td>20</td>
<td>97</td>
<td>44</td>
</tr>
<tr>
<td>B86-vdW</td>
<td>23</td>
<td>33</td>
<td>25</td>
<td>10</td>
<td>112</td>
<td>58</td>
</tr>
<tr>
<td>PBE = 1-vdW</td>
<td>21</td>
<td>35</td>
<td>19</td>
<td>10</td>
<td>102</td>
<td>54</td>
</tr>
<tr>
<td>optPBE-vdW</td>
<td>15</td>
<td>21</td>
<td>16</td>
<td>8</td>
<td>77</td>
<td>37</td>
</tr>
<tr>
<td>optB88-vdW</td>
<td>10</td>
<td>13</td>
<td>10</td>
<td>7</td>
<td>44</td>
<td>6</td>
</tr>
</tbody>
</table>

Let us first examine the results for the standard form of the vdW-DF where revPBE exchange is used. Throughout, we denote a combination of an exchange functional X with vdW correlation as X-vdW, hence we refer to vdW-DF as revPBE-vdW. The differences in the revPBE-vdW and reference interaction energies for each of the dimers in the S22 dataset are shown in figure 1. One can see from figure 1 that with revPBE-vdW most of the dimers are substantially underbound. The MAD is 65 meV (table 1), which is in good agreement with the MAD of 60 meV in Gulans et al [14]. The errors for the individual hydrogen bonded (HB), dispersion bonded (DB), and mixed dispersion and hydrogen bonded (MB) subsets are all quite large at 106, 52, and 38 meV, respectively. Further, this functional yields a very large ‘Range’ of errors (i.e., the difference between the largest and smallest errors) of 163 meV and does not provide a good balance between H bonding and PBE (correlation) calculations was used for all functionals except PBE and revPBE, where density from the respective exchange–correlation functional was used. Care was taken with the VASP calculations to ensure that converged energies were obtained, which involved the use of hard projector-augmented wave (PAW) [22, 23] potentials, an 800–1000 eV cut-off, dipole corrections, and 20–25 Å unit cells. Since the efficient self-consistent calculation of vdW-DF energies has only very recently become possible [12], we checked at the latter stages of this study how the non-self-consistent and self-consistent interaction energies differ with the grid-based GPAW code [24]. For the S22 dataset the non-self-consistent and self-consistent interaction energies are within 1.5 meV, except for the large dispersion bonded dimers (dimers 11–15) where the differences are $\leq$4 meV. For the water hexamers the non-self-consistent and self-consistent interaction energies are within $\sim$2 meV. Since we are interested in establishing precisely how each functional tested performs compared to the accurate reference data, interaction energies were computed on the reference structures and geometry optimizations were not performed.

Figure 1. Differences in interaction energies for vdW-DF ($E_{\text{int}}$[DFT]) with various exchange functionals from the CCSD(T) reference data ($E_{\text{int}}$[CCSD(T)]) [13]. We show data for revPBE, B88, PBE, B86 and three new exchange functionals ‘PBEκ = 1’, ‘optPBE’, and ‘optB88’.

\[ E_{\text{int}}[\Delta\text{CCSD(T)}] \] with various exchange functionals from the CCSD(T) reference data ($E_{\text{int}}[\Delta\text{CCSD(T)}]$) [13]. We show data for revPBE, B88, PBE, B86 and three new exchange functionals ‘PBEκ = 1’, ‘optPBE’, and ‘optB88’.
dispersion. This is shown by $\Delta^{\text{H-P}}$ which gives the difference between the mean deviations (MD) of the HB and DB subsets (i.e., $\Delta^{\text{H-D}} = \text{MD(HB)} - \text{MD(DB)}$). The smaller this quantity, the better the balance between the different types of bonding. The rather large value of $\Delta^{\text{H-D}}$ for revPBE-vdW of 57 meV reveals that on average the HB dimers are underbound compared to the DB dimers, an effect that comes from too steep a repulsive potential at short separations. Therefore, the original vdW-DF does not deliver chemical accuracy for either systems held by dispersion or H bonds, it yields a large range of errors, and on average underbinds the H bonded compared to the dispersion bonded systems.

We now consider alternatives to revPBE for $E^G_{\text{rev}}$ in (1), discussing the results from just a few of the most interesting functionals, namely PBE, Becke86 (B86) [25], Becke86 with modified gradient correction (B86MGC) [26], Perdew–Wang86 (PW86) [27], and Becke88 (B88) [28]. As can be seen from table 1 all functionals yield smaller MADs than revPBE-vdW and overall the performance is qualitatively different. For example, in contrast to revPBE-vdW, PBE-vdW systematically overbinds the dimers. Although the MAD of B88-vdW is only marginally smaller (62 meV) than that of revPBE-vdW of 57 meV reveals that on average the HB dimers are underbound compared to the DB dimers, an effect that comes from too steep a repulsive potential at short separations. Therefore, the original vdW-DF does not deliver chemical accuracy for either systems held by dispersion or H bonds, it yields a large range of errors, and on average underbinds the H bonded compared to the dispersion bonded systems.

Can the errors on the S22 set be further reduced? The contrasting performance of PBE-vdW and revPBE-vdW, which was also observed by Gulans et al [14], provides the necessary physical insight to identify improved exchange functionals. As we know, the GGA exchange energy density is given by $e_{\text{LDA}}(n,s) = e^{\text{LDA}}(n)F_\kappa(s)$, where $e^{\text{LDA}}(n)$ is the LDA exchange density and $F_\kappa(s)$ is the enhancement factor that depends on the reduced density gradient $s = |\nabla n|/2(3\pi^2)^{1/3}n^{4/3}$. The enhancement factors of PBE and revPBE have the same form:

$$F_\kappa^{\text{PBE}}(s) = 1 + \kappa - s^2/(1 + \mu^2 s^2/\kappa).$$  \hspace{0.5cm} (2)

The parameter $\mu$ is also the same and so the functionals differ only in the value of the parameter $\kappa$. revPBE has a larger value of $\kappa$ than PBE ($\kappa^{\text{revPBE}} = 1.245$, $\kappa^{\text{PBE}} = 0.804$), which causes $F_\kappa$ to rise more rapidly with revPBE than PBE (see figure 2 to see the enhancement factors). As a consequence, regions with large reduced density gradients are stabilized more with revPBE than PBE, which in turn leads to weaker interactions with revPBE (see [31] for a more detailed discussion on this issue). Therefore, in principle, a simple strategy for obtaining improved interaction energies is to identify an exchange functional intermediate between PBE and revPBE. To this end we varied $\kappa$ from the PBE to revPBE values (in 0.05 increments) and calculated interaction energies within vdW-DF for the complete S22 dataset. A value of $\kappa = 1.00$ resulted in the smallest MAD of only 21 meV. We dub this new exchange functional ‘PBE$\kappa = 1’$ 5. Pushing the PBE-style (i.e., PBE and its various revised forms) functionals yet further we varied $\mu$ and $\kappa$, and also considered other forms of the enhancement factor. After optimization we obtained an exchange functional ‘optPBE’ that yielded a MAD of only 15 meV. This functional turned out to be a $\kappa = 94.5268\%$ PBE and (100 $- \chi$)% RPBE [31] combination with $\mu = 0.175519$ and $\kappa = 1.04804$. Although this functional has been obtained by fitting to the S22 dataset it can be seen from figure 2 that it varies smoothly over the entire $s$ range shown. It has one new parameter, simply the mixing ratio of PBE and RPBE.

The two PBE-style functionals introduced above offer substantial improvements over revPBE. However, they still exhibit large errors in $\Delta^{\text{H-D}}$ and overbind the methane dimer (dimer 8, by 25 meV or 108% with PBE$\kappa = 1$ and 19 meV or 85% with optPBE). Since B88 is free from these deficiencies we explored optimized versions of it. The B88 exchange enhancement factor can be written as

$$F_\kappa^{\text{B88}}(s) = 1 + \mu s^2/(1 + \beta s \text{arcsinh}(cs)).$$  \hspace{0.5cm} (3)

where $c = 2^{4/3}(3\pi^2)^{1/3}$, $\mu \cong 0.2743$, and $\beta = 9\mu(6\pi)^{1/3}/(2c)$. As B88 underbinds the dimers, we modified the ratio $\mu/\beta$ to lead to increased binding, resulting in an optimal $\mu/\beta$ of 1.2 and a $\mu$ of 0.22. The new exchange functional, which we dub ‘optB88’, yields a MAD of only 10 meV, an accurate binding energy for the methane dimer, and similar mean deviations for all three subsets. Thus the small changes made to the original B88 parameters lead to a new functional that is the most accurate for the S22 dataset of all the functionals considered.

We now consider whether the improved performance of vdW-DF carries over to other systems and start with gas phase

5 A similar functional that produces results between RPBE and PBE is PBE$\alpha$ (Phys. Rev. B 75 195108 (2007)) with $\alpha = 2$. The MAD from this functional is 25 meV.
Table 2. Dissociation energies (meV/H$_2$O) for four low energy isomers of the water hexamer calculated using $\Delta$CCSD(T), PBE (with no vdW correction), and the vdW-DF with various exchange functionals. Unless indicated otherwise MP2 geometries from [16] were used. The $\Delta$CCSD(T) data in this table was computed as part of this study in the standard way, i.e., the MP2-CCSD(T) difference at the triple zeta level (aug-cc-pvtz basis set) was added to the MP2 complete basis set dissociation energies.

<table>
<thead>
<tr>
<th>Isomer</th>
<th>Prism $\Delta$E</th>
<th>Cage $\Delta$E</th>
<th>Book $\Delta$E</th>
<th>Cyclic $\Delta$E</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\Delta$CCSD(T)</td>
<td>$-334$</td>
<td>$-332$</td>
<td>$-329$</td>
<td>$-321$</td>
</tr>
<tr>
<td>PBE</td>
<td>$-333$</td>
<td>$-335$</td>
<td>$-341$</td>
<td>$-339$</td>
</tr>
<tr>
<td>revPBE-vdW</td>
<td>$-280$</td>
<td>$-279$</td>
<td>$-277$</td>
<td>$-269$</td>
</tr>
<tr>
<td>B86-vdW</td>
<td>$-284$</td>
<td>$-286$</td>
<td>$-286$</td>
<td>$-281$</td>
</tr>
<tr>
<td>PBE-vdW</td>
<td>$-379$</td>
<td>$-377$</td>
<td>$-370$</td>
<td>$-357$</td>
</tr>
<tr>
<td>B86-vdW</td>
<td>$-327$</td>
<td>$-326$</td>
<td>$-322$</td>
<td>$-313$</td>
</tr>
<tr>
<td>PBEex = 1-vdW</td>
<td>$-324$</td>
<td>$-323$</td>
<td>$-321$</td>
<td>$-312$</td>
</tr>
<tr>
<td>optPBE-vdW</td>
<td>$-335$</td>
<td>$-334$</td>
<td>$-332$</td>
<td>$-323$</td>
</tr>
<tr>
<td>optB88-vdW</td>
<td>$-347$</td>
<td>$-347$</td>
<td>$-344$</td>
<td>$-334$</td>
</tr>
<tr>
<td>optB88-vdW$^b$</td>
<td>$-352$</td>
<td>$-354$</td>
<td>$-349$</td>
<td>$-339$</td>
</tr>
</tbody>
</table>

$^a$ From [15].

$^b$ Optimized self-consistently with GPAW.

Water hexamers. Hexamers are interesting for many reasons (e.g. they are key constituents of the condensed phases of water) and not least because they provide a tough test for DFT [16]. In particular many functionals (including those widely used to study water such as PBE and BLYP) incorrectly predict that a ‘cyclic’ or ‘book’ cluster has the lowest energy, in contrast to coupled cluster which favours a ‘prism’ structure. The energy differences between the various isomers are very small (≤10 meV) and only when dispersion is taken into account is the correct energy ordering recovered [16]. We have tested the various functionals discussed above on the water hexamers and the results are reported in Table 2. Compared to pure PBE the vdW-DF improves the relative energies of the hexamers and B86-vdW and the three new functionals yield considerably improved absolute dissociation energies over revPBE-vdW [15]. In particular the dissociation energies for optPBE-vdW are essentially identical to those obtained with $\Delta$CCSD(T). The fact that there is now a functional which predicts both accurate absolute and relative energies for water hexamers is very encouraging and makes optPBE-vdW an interesting prospect for condensed phase simulations of water. Finally we note that for one of the new exchange functionals (optB88-vdW) we have performed self-consistent geometry optimizations which resulted in only slightly different dissociation energies (net differences of ∼7 meV; Table 2) and, moreover, very similar geometries.

We have also applied the new functionals to another important class of problem, namely adsorption on surfaces. The accurate determination of adsorption energies is an issue of central importance to many disciplines. However, in general, there is a paucity of accurate reference data. Water on NaCl(001) is an exception where an adsorption energy of −487 ± 60 meV at the $\Delta$CCSD(T) level was recently obtained using an embedded cluster approach [32]. Using the geometry from [32] and a slab model of the surface we computed adsorption energies for vdW-DF with revPBE exchange, B86 exchange and the three new functionals. In contrast to revPBE-vdW, which yields an adsorption energy of −334 meV, the alternative choices of exchange predict adsorption energies of −413 (PBEex = 1-vdW) to −424 meV (optB88-vdW). Although the values presented are below the lower end of the error bar on the reference adsorption energy, they are closer to it than revPBE-vdW and a regular GGA such as PBE (−328 meV). This is an encouraging development with scope for improvement.

In summary, we have shown that the accuracy obtained from vdW-DF for a range of systems can be greatly improved by making alternative choices for the GGA exchange component. Based on a combination of physical insight and optimization three new exchange functionals have been proposed (PBEex = 1, optPBE, and optB88). PBEex = 1 is the simplest alternative, optPBE is an optimized PBE-style functional that in addition to a low MAD on the S22 set yields precise results for the water hexamers, and optB88 yields the overall best performance on the S22 dataset. All three functionals represent minor changes to existing functionals and introduce at most one new parameter. We hope that this study lays the foundations for further improvements of vdW-DF and will enable more accurate treatments of a wide variety of dispersion and H bonded systems, such as liquid water. Along with the recent efficiency improvements [12] we suggest that vdW-DF is now a serious medium-term contender for high precision simulations before more rigorous approaches such as the random phase approximation or quantum Monte Carlo become routine.

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References


$^6$ The MAD in the O–O distances is only 0.01 Å and in the H bond angles it is 0.69° when the optB88-vdW optimized and reference geometries are compared.