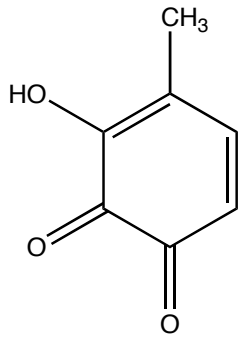
Chemistry 4021/8021 **Computational Chemistry** 3/4 Credits

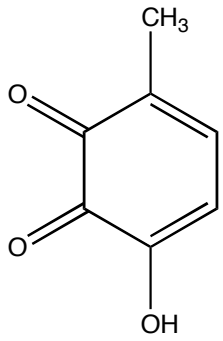
Spring Semester 2010

(Due 5 / 2 / 10)

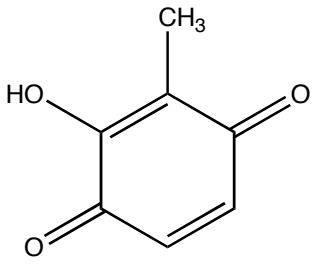
1. Consider the below 3 molecules, which might result from the oxidation of methylphenol.



1



2



3

You've got a reaction that makes one of these possible products stereoselectively (congratulations!) But, which one is it? In the NMR, there are aromatic protons in an AB quartet having chemical shifts of 7.0 and 7.4 ppm. Use computational models to decide which one you've made. Describe what you do and how you arrive at your conclusions. You *may* very well find useful a trip to ~cm8021pr/templates on Calhoun to take a look at some files I have there called tms.com, tms.out, tmsnmr.com, and tmsnmr.out.

I chose to optimize my geometries at the M06-2X density functional level (a good one for organic molecules, typically) using the 6-31G(d) basis set (reasonable balance of efficiency and quality—this step is just for geometries) including chloroform solvation effects via the SMD solvation model. All these choices are evident from looking at the tms.com file alluded to above. By looking at tmsnmr.com, it is apparent that I chose the same level to compute NMR chemical shifts (if I were feeling more rigorous, I probably would have gone to a bigger basis set, or I might have chosen a DFT model specifically designed for chemical shift prediction, but I was in a quick and dirty mode...)

At the level indicated, the absolute isotropic shieldings of the TMS protons are computed to be 32.2175 ppm.

Subsequent optimizations/NMR calculations for molecules **1**–**3** at precisely the same levels leads to predicted isotropic shieldings for the aromatic protons of **1**: 25.9, 24.8; **2**: 26.2, 25.1; **3**: 25.2, 24.8. Deshieldings (chemical shifts on the δ scale) are computed as

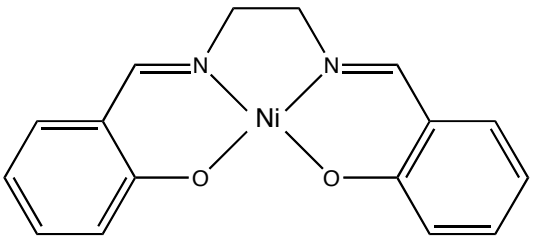
TMS shielding minus solute shielding which provides **1**: 7.4, 6.3; **2**: 7.1, 6.1; **3**: 7.4, 7.0. Clearly compound **3** has computed values in much better agreement with experiment than either of the other two.

> Would UV/Vis spectroscopy (in combination with theory) also have been useful to identify the isomer that you made? Here, too, describe what computational protocol you choose to answer this question and summarize your results.

I chose to compute TD-DFT UV/Vis excitations at the same level that I did NMR, i.e., M06-2X/6-31G(d) with chloroform solvent. At that level, the longest wavelength absorptions predicted for **1**, **2**, and **3** *having non-zero oscillator strength* are 472, 489, and 378 nm, respectively. It is evident that **3** again stands out with a very different spectrum than the other two (consistent with **3** being a *meta* quinone where the other two are *para* quinones).

2. The below molecule is a salen complex of nickel. What is the predicted standard reduction potential, relative to the $Ag/AgNO_3$ electrode, for reduction of Ni^{II}(salen) to Ni^{I}(salen) in acetonitrile? The experimental value is –2.1 V (see Miranda et al. *J. Org. Chem.* **2005**, *70*, 8017).

In order to compare to an absolute potential, which is what derives from a computation, it is critical to assess what the experimental value of –2.1 V is *relative* to, i.e., what is the reference electrode. Looking at the cited paper, we find that it is an $Ag/AgNO_3$ reference, which has a standard potential relative to the normal hydrogen electrode (NHE) of 0.594 V (the paper actually reports the $Ag/AgNO_3$ potential relative to the saturated standard calomel electrode (SSCE), and it is easy to find the SSCE potential relative to NHE, which then permits assignment of $Ag/AgNO_3$ relative to NHE).



To answer this question, compute molecular free energies for the neutral, singlet, Ni^{II} complex and the anionic, doublet, Ni^{I} complex at the SMD(acetonitrile)/M06-L/6-311+G(2df,p)//SMD(acetonitrile)/M06-L/6-31G(d) level. Note that this notation implies that each geometry is optimized at the SMD(acetonitrile)/M06-L/6-31G(d) level, so the thermal contributions to free energy will be taken from a frequency calculation at this

level and *not* from a frequency calculation with the larger basis set (*don't try to do the larger frequency*). To save time, use a density-fitting basis set with the M06-L functional. The keyword for this is `auto` in *Gaussian09*. Thus, for each geometry optimization and frequency, you will have as keywords `M06L/6-31G(d)/auto`, and for each large basis single-point energy you will have `M06L/6-311+G(2df,p)/auto` in the keywords line. To use SMD solvation in acetonitrile, use the keywords `scrf=(smd,solvent=acetonitrile)`.

Note that the Ni^{II} complex belongs to the C_2 point group, but the Ni^{I} complex, unfortunately, has no symmetry. The frequency calculation on the C_1 open-shell Ni^{I} complex takes almost a full hour on Calhoun, so expect to do this frequency calculation as a separate job.

The computations outlined should give the data in the below table:

Table 1. Components (a.u.) of composite energy used to compute Ni reduction potential.

Quantity, Level of Theory	Ni^{II}salen	Ni^{I}salen$^{\bullet-}$
ΔG_{298}, SMD(MeCN)/M06-L/6-31G(d)[a]	0.229 31	0.222 23
E, SMD(MeCN)/M06-L/6-311+G(2df,p)// SMD(MeCN)/M06-L/6-31G(d)[a]	−2386.587 20	−2386.671 32
$E + \Delta G_{298}$, composite	−2386.357 89	−2386.449 09
Relative G_{298}	0.000 00	−0.091 19

[a] Auto-generated density fitting basis set employed.

Thus, the "best" G for each species is that derived from adding the thermal contributions to G computed with the smaller basis set to the electronic energy including solvation computed with the larger basis set.

You may find it useful to know that the absolute potential of the normal hydrogen electrode is 4.28 V (the course textbook says 4.36 V, but that is an error).

The relative G value listed above in the table, –0.091 19 a.u. corresponds, for a 1-electron process, to an absolute potential of 2.48 V. The potential relative to NHE would be 2.48 – 4.28 = –1.80 V. As experiment was reported relative to $Ag/AgNO_3$ that, as noted above, has a standard potential relative to NHE of 0.594, we must now take –1.80 – 0.594 to arrive at a final potential, relative to $Ag/AgNO_3$ of –2.39 V. Compared to the reported experimental potential of –2.1 V, that is an error of 290 mV, or about 7 kcal/mol.

If the computed value is not in perfect agreement with experiment, what may be contributing to the error (put differently, how might one do a "better" calculation)?

There are many possible sources of error. As a general rule, it is more difficult to get a good energy for a more negatively charged species than for a less negatively charged one (because the one with more electrons has a larger amount of correlation energy *and* a greater demand on the basis set to deal with negative charge). So, we would expect our computed reduction potential to be insufficiently positive (or too negative, if it's sign is negative, as it is here), and that is precisely what we see. Thus, a single-point energy with a still larger basis set might improve agreement. But, there are also the questions of (i) is M06-L accurate?, (ii) is the solvation model sufficiently accurate for the anion (which will have the largest solvation free energy, being charged)?, (iii) is the harmonic oscillator approximation accurate for all of the vibrations being used to compute thermal contributions to *G*? To test these points, we could survey the sensitivity to choice of functional (one hopes for low sensitivity), choice of solvation model (same hope), and one could replace frequencies below 100 cm^{-1} or so with values of 100 cm^{-1}.

Another point to consider is whether the molecular model is adequate. What if an MeCN solvent molecule acts as a ligand to Ni in either or both the oxidized or reduced state? The continuum model might fail to represent such an interaction accurately.

So, in the absence of knowing the experimental result ahead of time, one would likely wish to survey *all* of the above issues prior to feeling comfortable with any particular prediction.

3. Here continues a problem that will carry over to the final exam. We add to the data at:

`pollux.chem.umn.edu/8021/PES/`

As previously, full credit for sensible data uploaded.