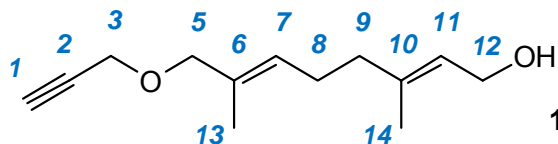


Problem Set 1 Solutions
Basic 1D NMR Interpretation

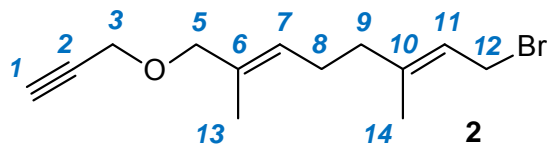
1. a.



proton	intensity	chemical shift (δ , ppm)	multiplet	coupling constants
H ₁	<1H	2.413	t	$J_{1,3} = 2.5$ Hz
H ₃	2H	4.065	d	$J_{1,3} = 2.5$ Hz
H ₅	2H	3.920	s	<i>none</i>
H ₇ and H ₁₁	1H and 1H	5.413 and 5.391	t and t	$J_{7,8} = 5.9$ Hz and $J_{11,12} = 6.5$ Hz
H ₉ and H ₈	2H and 2H	2.159 and 2.061	?	<i>broad, so tough to interpret</i>
H ₁₂	2H	4.127	d	$J_{11,12} = 6.5$ Hz
H ₁₃ and H ₁₄	3H and 3H	1.662 and 1.638	s and s	
OH		1.7 ?		

Here I've chosen not to specify which resonance goes with which proton for the H₇/H₁₁ and H₈/H₉ pairs of protons, because the NMR evidence isn't conclusive, but I do think you can make guesses. Of H₇ and H₁₁, H₇ is closer to an electron-withdrawing, deshielding oxygen atom, so I would guess that H₇ would be downfield of H₁₁, and the same argument places H₉ downfield of H₈.

It's not clear where the alcohol proton is. It might be the broad hump at 1.7 ppm, which is difficult to integrate because of overlap with other protons and junk; or it could be that the hydrogen-bonded peak is so broad that it disappears.

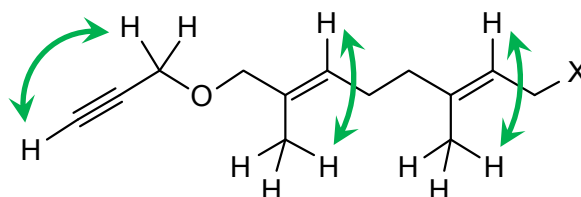


proton	intensity	chemical shift (δ , ppm)	multiplet	coupling constants
H ₁	<1H	2.418	t	$J_{1,3} = 2.4$ Hz
H ₃	2H	4.084	d	$J_{1,3} = 2.4$ Hz
H ₅	2H	3.940	s	<i>none</i>
H ₇	1H	5.413	tq	$J_{7,8} = 7.0$ Hz and $J_{7,13} = 1.1$ Hz
H ₉ and H ₈	2H and 2H	2.177 and 2.138	?	<i>broad, so tough to interpret</i>
H ₁₁	1H	5.543	tq	$J_{11,12} = 8.4$ Hz and $J_{11,14} = 1.5$ Hz
H ₁₂	2H	4.022	d	$J_{11,12} = 8.4$ Hz
H ₁₃	3H	1.658	d (barely)	$J_{7,13} = 1.1$ Hz
H ₁₄	3H	1.738	d	$J_{11,14} = 1.5$ Hz

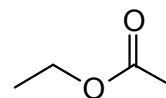
Here, you can make absolute assignments that you couldn't for molecule **1**, because of additional measurable coupling constants. I took a few liberties in the J assignments for H₁₃ and H₁₄--I think the left-hand peak label for H₁₄ is a bit off, and the doublet for H₁₃ isn't labeled, but the coupling constants are clear from H₇ and H₁₁.

Probably the most distinguishing feature of the charts for **1** and **2** is how similar they are for protons 1-8, and how the reaction changes things for protons 9-12.

- b. There is no geminal coupling, because there are no geminal inequivalent protons. But there is long range (4J) coupling:

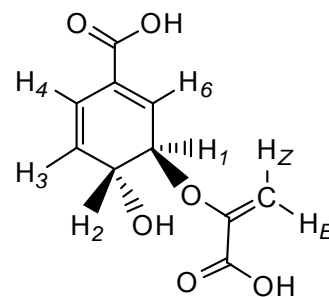


- c. In class, we talked about how integrated intensity is dependent on how far the bulk magnetization \mathbf{M} for a proton manages to relax back to \mathbf{M}_0 between RF pulses. If there is incomplete relaxation (because $\tau < 5T_1$), the total magnitude of the measured FID will appear low (because there is still intensity yet to be recorded). The most efficient route of relaxation for nuclei is through-bond spin exchange with nearby protons. H_1 , unfortunately, is pretty far away from other protons, and this causes its T_1 to be anomalously high. This is very typical for terminal alkyne protons.
- d. It's difficult to compare the chemical shifts of **1** and **2** in CDCl_3 with the chemical shift of **3** in D_2O --solvent can have an effect on chemical shift. One very big change, though, is that the doublet that used to correspond to H_{12} is now shifted way downfield, and has become a triplet. The added splitting is caused by coupling between H_{12} and the closer of the two phosphorus atoms. (This splitting doesn't show up in the ^{31}P spectrum, because that spectrum is ^1H -decoupled, but it does show up in the ^1H spectrum.) So I think the reaction worked, and produced **3**.
- e. Nope, there isn't enough splitting for these peaks to correspond to the *n*-butyl group in tetrabutylammonium ion. They could, on the other hand, represent an ethyl group (triplet + quartet) bound to an electron-withdrawing atom, and an uncoupled methyl group (singlet) next to a double bond. These criteria are satisfied by ethyl acetate, a common solvent.
- f. There are two inequivalent phosphorus atoms in **3**, and they couple to one another with $J_{\text{POP}} = 22 \text{ Hz}$. The four peaks correspond to two doublets.



2. a.

proton	chemical shift (δ , ppm)	multiplet	coupling constants
H ₁	4.76	dd?	$J_{1,2}$: can't measure $J_{1,6}$: can't measure
H ₂	4.916	dd	$J_{2,3} = 2.4$ Hz $J_{1,2} = 11.7$ Hz
H ₃	5.970	dd	$J_{2,3} = 2.4$ Hz $J_{3,4} = 10.0$ Hz
H ₄	6.328	dt	$J_{3,4} = 10.0$ Hz $J_{4,6} = 1.7$ Hz $J_{2,4} = 1.7$ Hz
H ₆	6.558	<i>broad</i>	$J_{1,6}$: can't measure $J_{4,6}$: can't measure
H _Z	4.580	d	$J_{E,Z} = 2.9$ Hz
H _E	5.211	d	$J_{E,Z} = 2.9$ Hz

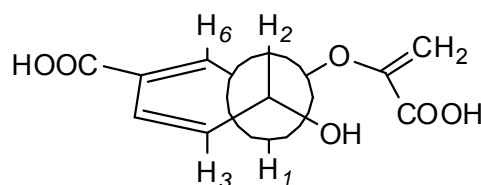


A couple of notes on this listing. The resonance for H₁ overlaps with that of HOD, so it's difficult to tell its multiplicity, but coupling constants from other resonances allow us to say something about it. The resonance for H₆ is a broad singlet; I think there are multiple small coupling constants in that singlet, but they can't be measured directly, so I've inferred them from the coupling partners.

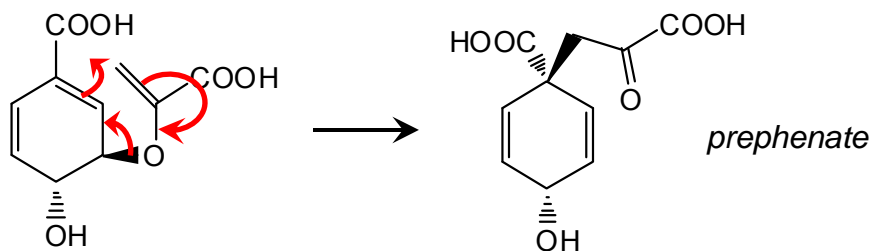
The carboxylic acid and alcohol protons are not observed. In the case of ¹H NMR spectra collected in CDCl₃, these types of protons are sometimes not observed because hydrogen bonding results in broadening. In this case, however, the spectrum was taken in D₂O, where -OH and -COOH protons are *never* observed because of exchange between the protons and the deuterons from solvent. There are a lot more D's than H's in an NMR sample, so this exchange pretty much eliminates the population of alcohol or carboxylate H's.

- b. One interesting thing about this molecule is that $J_{2,3}$ is small, and there is no $J_{1,6}$, even though those protons are vicinal. One possible explanation for this is that the dihedral angle between these protons is near 90°, which the Karplus equation says would produce a small or nonexistent J . By contrast, $J_{1,2}$ is extremely large, indicating that the dihedral angle between those protons is either very large or very small.

Both of these facts support a predominantly diequatorial conformation for chorismate, where the dihedral angle $\phi_{2,3} \approx 90^\circ$, $\phi_{1,6} \approx 90^\circ$, and $\phi_{1,2} \approx 180^\circ$.

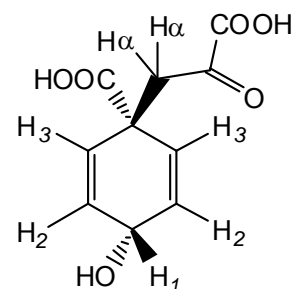


c. Chorismate forms prephenate via a pericyclic reaction:



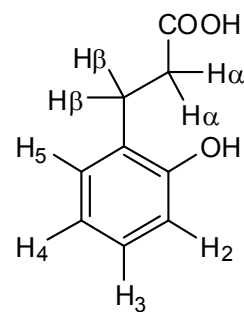
Prephenate is symmetric, so there should be fewer inequivalent types of protons in it than chorismate.

proton	chemical shift (δ , ppm)	multiplet	coupling constants
H ₁	4.510	<i>broad</i>	$J_{1,2}$: can't measure $J_{1,3}$: can't measure
H ₂	5.921	dd	$J_{2,3} = 10.3$ Hz $J_{1,2} = 3.2$ Hz
H ₃	6.024	dd	$J_{1,3} = 1.4$ Hz $J_{2,3} = 10.3$ Hz
H _{α}	3.129	s	

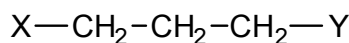


3. The aromatic region has four different inequivalent protons, so the molecule can't be the symmetric, *para*-substituted phenol. The aromatic region has two large- J doublets and two large- J triplets; if large J s correspond to vicinal coupling constants, that must mean a contiguous set of four protons, which can only happen in the *ortho*-substituted phenol.

proton	chemical shift (δ , ppm)	multiplet	coupling constants
H ₂	6.900	dd	$J_{2,3} = 8.0$ Hz $J_{2,4} = 1.2$ Hz
H ₃	7.161	td	$J_{2,3} = 8.0$ Hz $J_{3,4} = 7.8$ Hz $J_{3,5} = 1.6$ Hz
H ₄	6.940	td	$J_{2,4} = 1.2$ Hz $J_{3,4} = 7.8$ Hz $J_{4,5} = 7.5$ Hz
H ₅	7.213	dd	$J_{3,5} = 1.6$ Hz $J_{4,5} = 7.5$ Hz
H _{α}	2.485	t	$J_{\alpha,\beta} = 7.5$ Hz
H _{β}	2.843	t	$J_{\alpha,\beta} = 7.5$ Hz

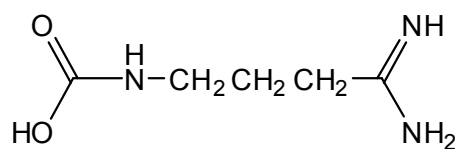
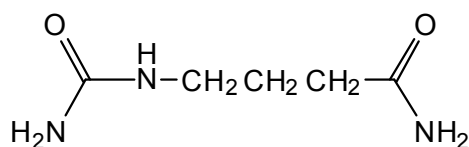
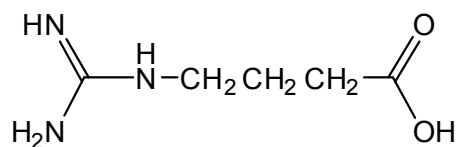


4. The NMR spectrum shows two triplets and a quintet, which means two sets of H's with two neighbors and one set with four. The integrals on the full spectrum are 1:1:1, but it seems likely that they actually would be 2:2:2 (or 3:3:3, but I think 2:2:2 makes more sense). The simplest explanation is a three-carbon, saturated chain:



That explains three out of five carbons, and 6 out of 11 protons. But where are the rest?

Chemical shift says that one of the two ends of the chain is attached to a pretty electronegative atom--O or N--and that the other end is not. We might guess that the end that is more upfield is next to a carbonyl, maybe a carboxylic acid. This is very consistent with the ^{13}C peak at $\delta = 185$ ppm. The downfield end must be attached to a nitrogen or oxygen atom, probably nitrogen because oxygen would put $\delta > 3.5$ ppm for the α - CH_2 . This in turn would have to be attached to another carbonyl or imine carbon. As long as you drew something in which all the other protons were exchangeable (no aldehydes or methyl ketones), you were right. So, you might have drawn



or something similar.