

# NMR Determination of Keto-Enol Equilibrium Constants

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May 9, 2016

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## Introduction/Objective

This experiment uses proton NMR to determine the keto-enol equilibrium constants for two compounds, acetylacetone and ethyl acetoacetate. The NMR spectra are analyzed to determine which peaks correspond to which of the tautomers and the ratios of the integrated intensities of corresponding protons in either form are used to determine the ratio of enol to ketone contained in solution. In addition, the enol-ketone equilibrium for acetylacetone is compared in two solvents, carbon tetrachloride ( $\text{CCl}_4$ ) and methanol ( $\text{CH}_3\text{OH}$ ).

## Experimental Procedure

Five NMR samples were created. The first contained a 0.20 mole fraction of acetyl acetone in  $\text{CCl}_4$ . The second contained a 0.20 mole fraction of acetyl acetone in  $\text{CH}_3\text{OH}$ . The third contained a 0.20 mole fraction of ethyl acetoacetate in  $\text{CCl}_4$ . The fourth contained pure  $\text{CCl}_4$  and the fifth contained pure  $\text{CH}_3\text{OH}$ . A few drops of TMS were added to each sample to act as the reference compound to which each proton frequency would be standardized to.

## Results

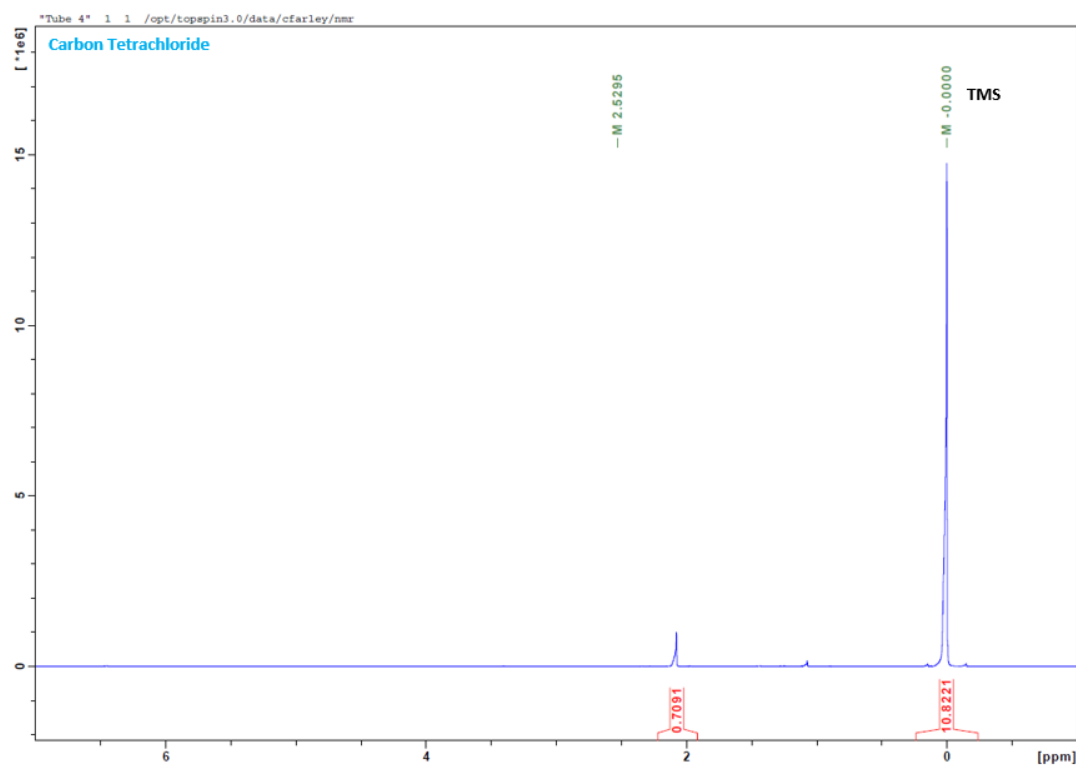


Figure 1: NMR spectrum of pure carbon tetrachloride.

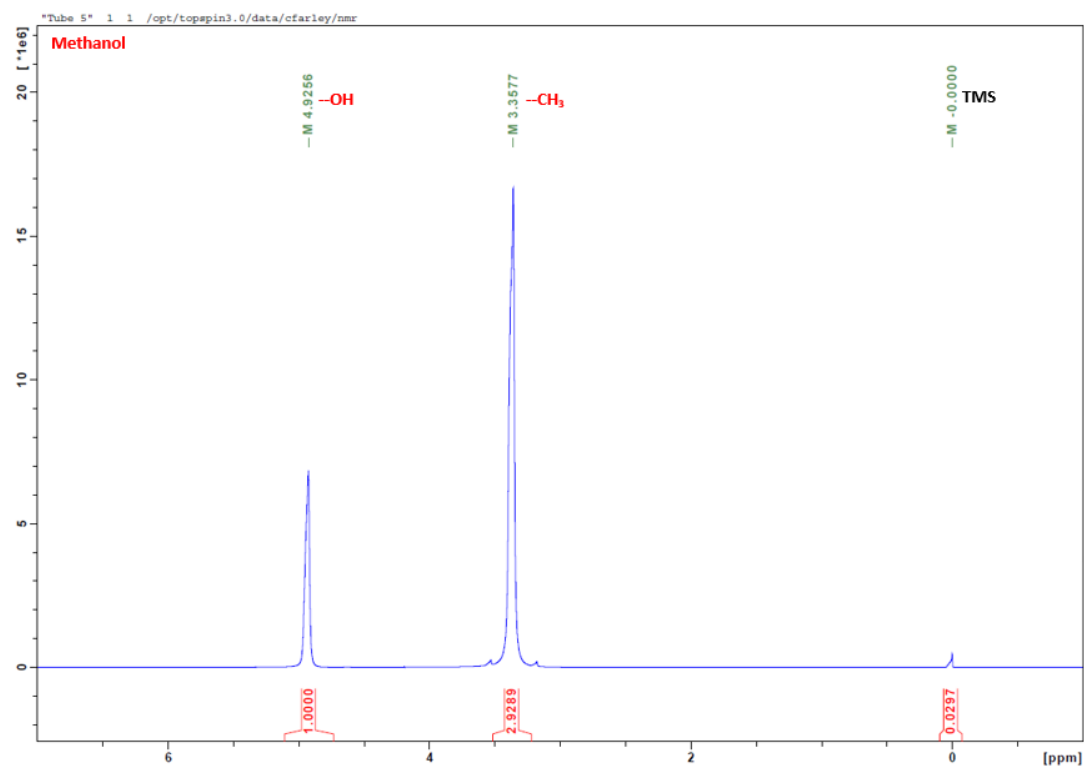


Figure 2: NMR spectrum of pure methanol with relevant proton peaks labeled.

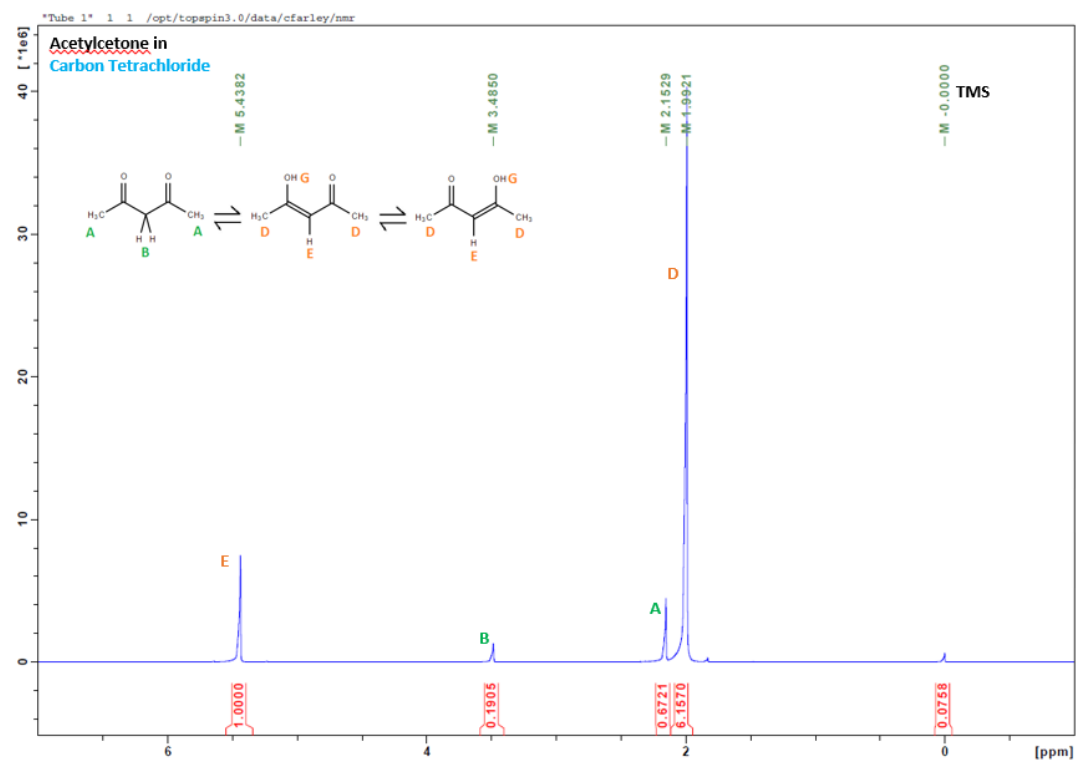


Figure 3: NMR spectrum of acetylacetone in CCl<sub>4</sub>. Peaks corresponding to protons in the ketone (green) and enol (orange) forms are labeled.

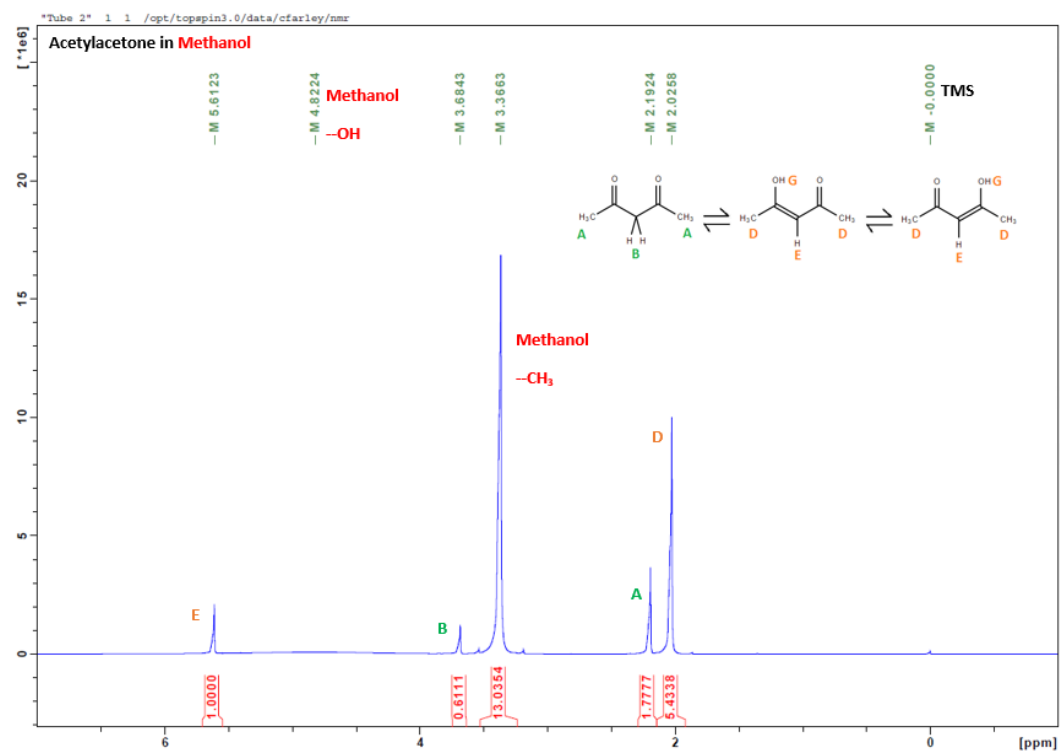


Figure 4: NMR spectrum of acetylacetone in  $\text{CH}_3\text{OH}$ . Peaks corresponding to protons in the ketone (green) and enol (orange) forms are labeled.

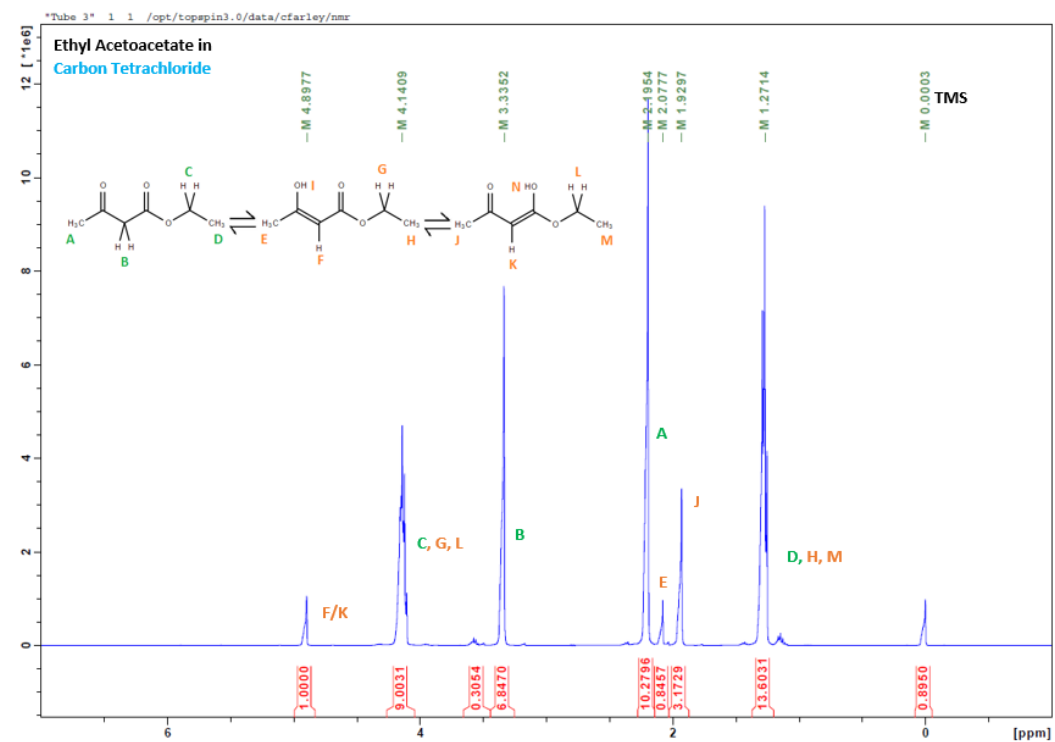


Figure 5: NMR spectrum of ethyl acetoacetate in  $\text{CCl}_4$ . Peaks corresponding to protons in the ketone (green) and enol (orange) forms are labeled.

From the NMR spectra for “Tube 4” and “Tube 5,” which were filled with pure CCl<sub>4</sub> and methanol respectively, it was possible to identify the peaks, if any, that corresponded to the solvent protons in the NMR spectra for the different solutions.

Tube 1 -- ACETYLACETONE in CCl4					
	KETONE	ENOL		K	$\Delta G^\circ$ (kJ/mol)
chem shift	2.1529	1.9921		9.16	-5.488
integration	0.6721	6.157			
Tube 2 -- ACETYLACETONE in MeOH					
	KETONE	ENOL		K	$\Delta G^\circ$ (kJ/mol)
chem shift	2.1924	2.0258		3.06	-2.768
integration	1.7777	5.4338			
Tube 3 -- ETHYL ACETOACETATE in CCl4					
	KETONE	ENOL		K	$\Delta G^\circ$ (kJ/mol)
chem shift	2.1954	2.0777	1.9297	0.309	2.912
integration	10.2796	0.8457	3.1729		

## Discussion

Tautomerization is a type of interconversion between isomers known as tautomers. In this experiment, the ketone-enol tautomerization is of interest. This ketone to enol conversion is possible when a ketone carbonyl group is in an α position relative to a saturated carbon atom. This configuration allows for one of the hydrogen atoms on the α-carbon to be abstracted by the carbonyl oxygen.

Typically, when keto-enol tautomerism is possible, the ketone form is favored, but due to the β-diketone nature of the substrates in this experiment, the enol forms of the tautomers are stabilized by intramolecular hydrogen bonding, significantly shifting the equilibrium in favor of the enol tautomer. The proton peak for the –OH protons are shifted so far downfield, that they are not represented in the NMR spectra collected in this experiment, but other peaks in the spectra can be compared to determine the enol to ketone ratio in solution.

The finding that the enol form of acetylacetone was favored in both the nonpolar and polar solvents was unexpected, especially that the equilibrium was shifted more toward the enol in CCl<sub>4</sub>. However, it is worth noting that in the enol form of acetylacetone, the electrons are distributed over a wide area, making the overall molecule strictly less polar, and thus stable even in nonpolar solvents like CCl<sub>4</sub>. Building upon this, the presence of an intramolecular hydrogen bond in the enol form, deceptively makes it seem that this form will be more soluble in a solvent that can participate in hydrogen bonding like methanol. The ketone form, which does not have the intramolecular hydrogen bond, actually has four hydrogen bond acceptor sites, whereas the enol form only has two, because two sites are involved in the intramolecular hydrogen bond. The enol form maybe be more stable in CCl<sub>4</sub> rather than in methanol as originally expected because the intermolecular hydrogen bonding between the enol and methanol may decrease the efficiency of the **intramolecular** hydrogen bond in the enol, without which the enol form would probably not be present in any significant amount otherwise. This analysis can explain why the enol form is favored more in CCl<sub>4</sub> than in CH<sub>3</sub>OH. In addition, steric repulsions that arise due to the free rotations of the methyl groups in the ketone form are decreased in the enol form due to

the rigid, planar geometry created by the double bond between the carbon atoms which prevents free rotation. This can be a reason why the enol form of acetylacetone is favored in both  $\text{CCl}_4$  and  $\text{CH}_3\text{OH}$ . This steric repulsion effect is less significant in the ethyl acetoacetate because inherent to the  $\beta$ -ketoester structure is the increase in distance between the “bulky” rotating groups, which supports the finding that the ketone form is favored for this molecule. According to the lab manual (pg. 451), “ $\alpha$  substitution of electron-withdrawing groups ... favor the enol form.” Then, it can be hypothesized that electron-donating groups would shift the equilibrium in favor of the ketone form. The ester oxygen acts as an electron donating group, which would again support the finding that the ketone form of ethyl acetoacetate is the favored structure.

## References

- Acetylacetone NMR in  $\text{CDCl}_3$   
[http://www.hanhonggroup.com/nmr/nmr\\_en/B11121.html](http://www.hanhonggroup.com/nmr/nmr_en/B11121.html)
- Ethyl acetoacetate NMR in  $\text{CDCl}_3$   
[http://www.hanhonggroup.com/nmr/nmr\\_en/B15628.html](http://www.hanhonggroup.com/nmr/nmr_en/B15628.html)