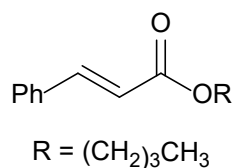


Esterification and Infrared Spectroscopy

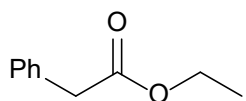
What are Esters?

Many of the compounds that contribute to the flavors and aromas in fruits and flowers are esters. Natural flavors and aromas result from complex mixtures of many compounds, esters being a large component. For example, the natural orange aroma consists of 30 different esters, 10 carboxylic acids, 34 alcohols, 34 aldehydes and ketones, and 36 hydrocarbons. The food industry attempts to mimic natural flavors by formulating artificial mixtures that approximate the real thing. Even artificial flavors are composed of mixtures, albeit not as complex as their natural counterparts. One example is an artificial pineapple mixture: 7 esters, 3 carboxylic acids, and 7 essential oils (other natural extracts).

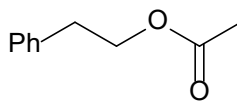
In some cases, just one individual ester smells similar to a natural aroma. Some examples include:



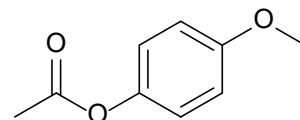
n-butyl cinnamate
(chocolate)



ethyl 2-phenylacetate
(honey)



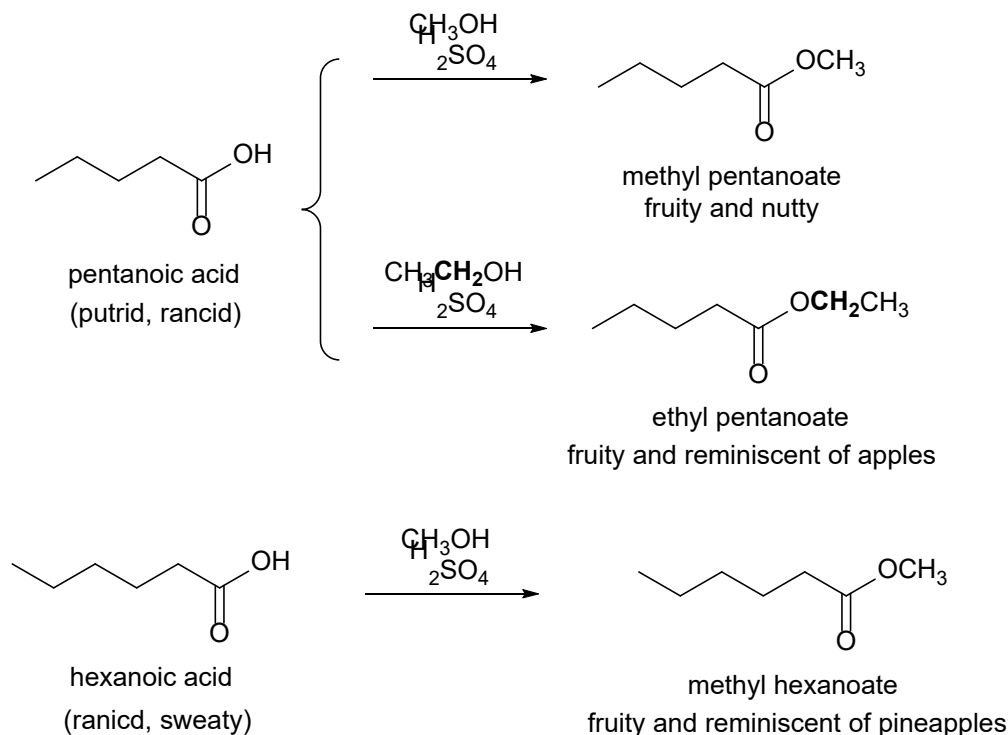
phenethyl acetate
(caramel)



4-methoxyphenyl acetate
(vanilla)

Note, however, that although one can often recognize a natural aroma in a single pure ester, the odor usually resembles a cheap imitation.

Also note that although the lower MW esters are generally sweet smelling, the carboxylic acids from which they are synthesized often have a disagreeable odor. The common name for pentanoic acid is caproic acid, from the Latin, *capra*, meaning goat. The following descriptions of odor are taken from a catalog of Flavors and Fragrances.

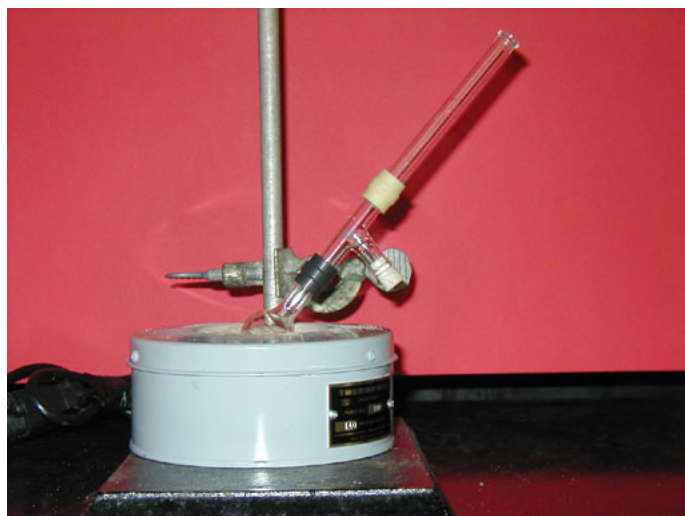


Mixing an alcohol with a carboxylic acid will produce no ester. A strong-acid catalyst such as sulfuric acid (denoted below as H_3O^+) is required. Even then the reaction is in equilibrium and so does not go to completion. Note that it is the oxygen of the alcohol that is incorporated into the ester.



For esters in which the alcohol and carboxylic acid are sterically unhindered, a 1:1 mixture of alcohol and carboxylic acid will yield an equilibrium mixture that is about 70% ester. This means that if ester were isolated from this mixture, at best a 70% yield would be obtained. A 70% yield is not usually considered to be acceptable for a synthesis reaction. Recall Le Chatelier's principle. If a ratio of 3:1 or 1:3 of alcohol:carboxylic acid were used, the equilibrium would be driven towards ester product and for unhindered systems would result in a 90% yield. In practice often a 10:1 or 1:10 ratio is used, which results in even higher yields of ester. The drawback in this method is that most of the excess reactant is left unreacted, requiring extra steps to remove it. It is also wasteful. A second method to drive the equilibrium towards product is to remove one of the products as it is formed. This is also an application of Le Chatelier's principle. Note that one product of the esterification reaction is water. A simple experimental set-up can be used to remove the water from the reaction mixture as the water, and ester, form. As water is removed the equilibrium is upset and corrects itself by moving towards the products. Eventually, when the final amount of water is removed and all the starting materials have reacted, the reaction has gone to completion and a 100% yield can be attained. This is the method used in your esterification reaction. Think of this as pulling the equilibrium towards product, whereas using an excess of one of the reactants is more like pushing the reaction towards product.

The set-up used to remove water is shown below. Reactants and sulfuric acid catalyst are placed into the round-bottomed flask, which is heated on the hot plate. Ester and water begin to form and distill up into the air-cooled condenser along with reactants. The vapors, upon contacting the cool tube, condense back to liquid and flow back down towards the reaction flask. The side-arm between the condenser and flask collects the descending liquid. Because water is immiscible with the organic phase and also denser than the organic phase, it will collect as a separate lower phase in the side-arm. Once the side-arm is full of liquid, the organic phase overflows back into the reaction flask, leaving the lower water phase trapped at the bottom of the side-arm. Thus the water that is produced in the reaction is being removed from the reaction mixture, allowing the reaction equilibrium to be driven towards products. Eventually when all of the reactants are converted to ester and water the reaction can be stopped. An extraction process removes sulfuric acid and any unreacted carboxylic acid. The identity and purity of the product is determined by IR spectroscopy.



air-cooled
condenser

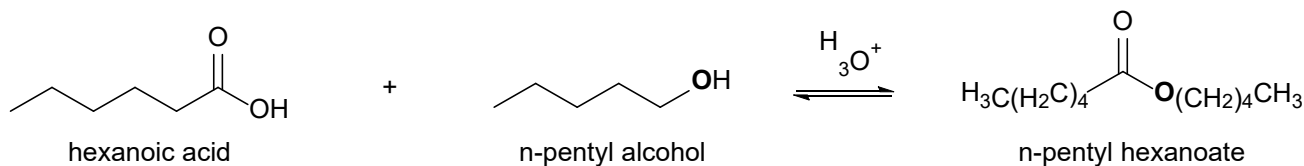
side arm

ESSENTIAL: Prelab Work. You will be assigned to prepare one of the following esters:

3-methylbutyl propionate, 3-methylbutyl acetate, or n-propyl propionate (3-methylbutyl = isoamyl = isopentyl, propionate = propanoate).

Which ester you are assigned to prepare is done by your locker number and is posted on the Chem 269 website (ester experiment page). **BEFORE YOU COME TO LAB**, you must plan a synthesis and write out a procedure to produce 11 mmol of your assigned ester. Quantities (mmol, g, mL) and BPs of reagents and products must be determined before you come to lab. Because each student will be assigned to synthesize one of several possible compounds, quantities of reactants will differ from student to student. If you have trouble with the calculations, see someone BEFORE your lab period. If you come to lab unprepared you will lose points. The OWL assignment walks you clearly through the calculations.

From the name of your assigned ester you must first determine what alcohol and what carboxylic acid will be needed to prepare that ester. To do this you must know how esters are named. Read the references to your lecture text. Example: assume that your ester is n-pentyl hexanoate (this is just an example and is not one of the possibilities). The first part of the name, n-pentyl (the "n" stands for "normal"), refers to the alcohol needed to make the ester, in this case n-pentyl alcohol (1-pentanol). The second part of the name, hexanoate, refers to the carboxylic acid needed, in this case, hexanoic acid (drop -ate and add -ic acid). Next, use structural formulas to write out the balanced equation for the preparation of the ester. In this example,



To synthesize 11.0 mmol of ester, you will use 11.0 mmol of alcohol and 13.0 mmol of carboxylic acid (Why the slight excess of carboxylic acid? Although the balanced reaction shows a 1:1 mole ratio of starting materials, because it is easier to remove excess carboxylic acid than excess alcohol, and because it is difficult to measure small volumes accurately, using a slight excess of carboxylic acid helps to ensure that little or no alcohol will be left at the end of the reaction. Note that because it's only a slight excess, it will not significantly impact the yield. The ratio is still roughly 1:1. Our method of improving yield is by removing water.)

Find or determine the molecular weights (MWs) of the starting materials and products. From their MWs determine the number of grams of starting materials needed (remember to use the excess of carboxylic acid). Also determine the number of grams of products that will be produced. Using densities, convert the weights to volumes. Physical properties of these compounds can be found on the Sigma-Aldrich website. For your synthesis, set up a table of reagents as you have done with the previous synthesis (formal report) experiments.

Before beginning any work, your quantities must be checked by your TA. Photos of the techniques used in this experiment are shown on the website and will be helpful in carrying out the experiment. As with any distillation, be sure to check the plastic connectors to be sure they are not frayed too badly.

Prelab: You may either print out your prelab and bring it with you to lab, or bring your computer. Your TA will grade it on the spot before you begin the experiment. For the in lab observations, you may use scratch paper and record later in your ELN, or bring your computer and record directly in your ELN.

Postlab Report: Make sure to use the Formal postlab report template on the course website!

Reaction Procedure

1. Into a 5 mL round-bottomed (rb) flask, carefully measure in the volumes of alcohol and carboxylic acid (via the calibrated pipets on the common bench) that you calculated in the prelab.
2. Add 4 drops of concentrated sulfuric acid (caution!) and mix the contents by drawing them into a clean, new pipet and expelling back into the flask. Failure to mix the liquids well will result in the conc. sulfuric acid reacting to form unwanted darkly colored by-products, in which case you will need to start over, however, some discoloration is expected.
3. Add a few boiling chips then set up the apparatus as shown above and on the demo bench (to secure the flask to the ring stand use the red connector support rod that attaches to the black plastic connector, NOT the small three-pronged clamp.
 - a. If the support rod diameter is too narrow for the clamp, to secure the rod tightly, place a 1" piece of 1/4" rubber tubing onto the support rod and then clamp it tightly into place.
 - b. Note that the distillation head can be connected to the flask in two different orientations, with the side arm at a slightly greater angle up or down. The orientation that should be used is that in which the side arm points slightly downward when the rb flask with distillation head attached is held in an upright position. (Hold the apparatus vertically; the side arm should point slightly downward, not upward if the apparatus is correctly assembled.) This makes trapping the water more effective.
 - c. The apparatus should then be set up at about a 45° angle.
4. Carefully heat the flask to a boil on the hot plate. Adjust the heating so that vapors condense about 1/3 of the way up the reflux condenser, well above the side arm. It may take several minutes for the vapors to reach this point.
 - a. Note that during the heating period, insufficient heating will not allow the vapors to reflux above the side arm. This will prevent water from being removed from the reaction mixture and will result in an incomplete reaction. On the other hand, overheating will allow product and reactants to escape into the atmosphere.
5. As the reaction proceeds, two phases of liquid will collect in the side arm: an upper organic phase and a lower water phase. However, on this small scale, there is not much water being formed and it tends to stick to the glass surface. *This is okay*. The point is to remove the water and if it distills up and sticks to the glassware, it is still being removed.
6. To help ensure that the reaction goes to completion, do the following: after the reaction has refluxed for ~15 minutes, raise the apparatus from the heat and carefully tip it back so that most of the upper phase in the side arm drips back into the reaction flask. If you cannot make out a distinct water layer, tip back approximately 1/2 - 3/4 of the side-arm contents. Be certain that none of the lower water phase goes back into the reaction flask.
7. Lower the apparatus back into the hole in the aluminum block and resume reflux for another 15 minutes. After 15 min, again lift the apparatus from the heat and carefully tip it back so that the upper phase returns to the flask.
8. Allow the reaction mixture to reflux for another 15 minutes (45 minutes total). At the end of the third reflux period, allow the apparatus to cool completely (10-15 minutes).
9. *After the mixture is cooled sufficiently*, water is not a problem, so empty the entire contents of the side-arm into the flask.

Reaction Work-up

1. Use a pipet to transfer the *cooled* contents of the flask into a centrifuge tube containing about 1 mL of water. Mix the layers thoroughly by drawing the lower layer into a pipet and squirting it back through the mixture. Do this somewhat forcefully to allow for layer contact (again, think mixing Italian dressing). Remove the aqueous layer and place it into a beaker marked for waste.
2. Add ~1 mL of saturated aqueous sodium bicarbonate (caution: evolution of CO₂ may occur and cause foaming). Mix the layers thoroughly as you did above. Remove the aqueous layer and add it to the waste beaker. Repeat this process one more time.
3. Add ~1 mL of saturated aqueous sodium chloride to the ester, mix thoroughly, remove lower aqueous layer, and add to waste beaker.
4. Pipet the organic layer into a vial, making sure that all water droplets are left behind, add about 5 spheres of anhydrous CaCl₂ to the liquid, and swirl the mixture. If all the spheres of drying agent clump together, add a few more spheres, swirl, and let the mixture stand for about five minutes, swirling it occasionally. If all the drying agent clumps together, it means that not all of the water has been removed, so more drying agent is needed.
 - a. If all the visible droplets of water were not left behind, instead of clumping together, the first few spheres of drying agent will break apart and form a cloudy looking mass (layer) at the bottom of the vial. In this case carefully pipet the contents to another clean dry vial, leaving behind the cloudy layer. Add drying agent in small amounts as before until a few of the spheres no longer clump together.)
5. Using a pipet carefully transfer the liquid (leaving behind the CaCl₂) to a DRY tared capped vial
6. Describe the odor of your ester (exploratory wafting) and check the odors of different esters made by your classmates. Carefully note the odors of the starting materials.
7. Determine the % yield of product and determine and interpret the infrared (IR) spectrum (read references). For comparison, check the IR spectra of a carboxylic acid, an alcohol, and an ester. These are posted near the spectrometers and are shown in the OWL assignment.

WASTE DISPOSAL: Place all liquid wastes into the Organic Liquid Waste container. Used drying agent should be placed into the dish labeled as such in the waste hood. When you are finished with the product and your TA has examined it, place it into the Organic Liquid Waste container.

BEFORE YOU LEAVE THE LAB: turn off the hot plate, put away your equipment, clean up your work areas, close the fume hood sash completely and ask your TA for their signature. If you see caps off of bottles, replace the caps. If you see spilled chemicals, clean them up or at least report it to your TA.

Postlab Questions

- 1.) Write out the detailed step-wise mechanism for YOUR esterification.
- 2.) This is an equilibrium reaction. For the esters in this experiment, equimolar amounts of carboxylic acid and alcohol in the presence of acid catalyst will produce only about 70% ester. In this experiment how is the equilibrium driven towards product to produce a higher yield of ester?
- 3.) What is the purpose of the sulfuric acid?

4.) During which step or steps is most of the excess carboxylic acid removed?

5.) What is the product of the reaction below?

