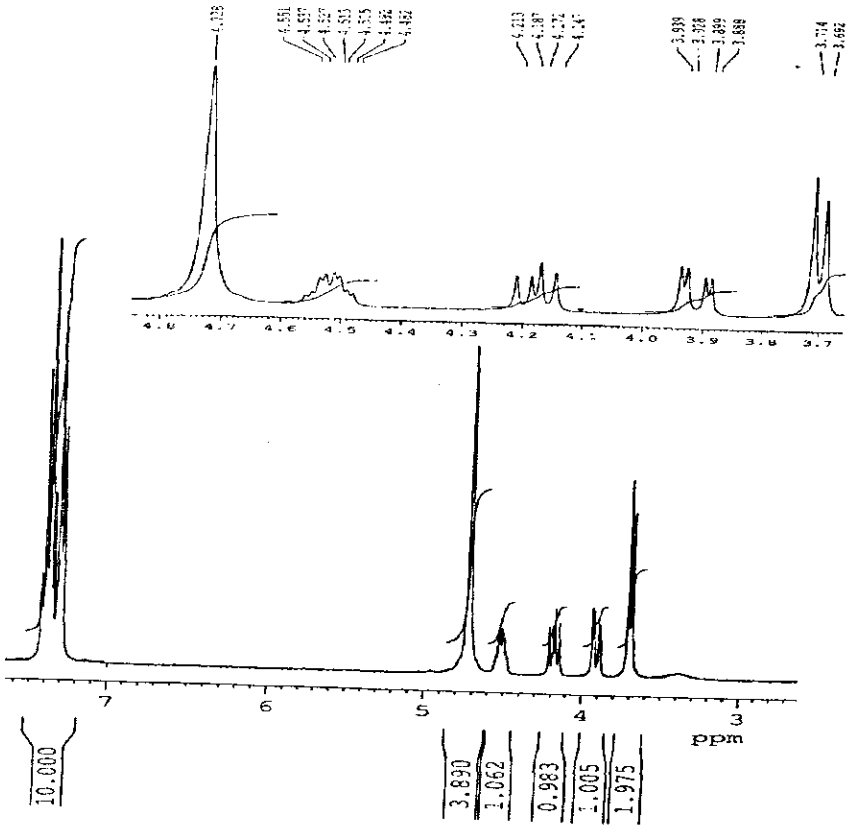


Fig. 6/2002. The ^{1}H NMR spectrum of the product. The NMR spectrometer frequency is 300 MHz. The values of chemical shifts are given in parts per million (ppm). The large-scale fragment of the spectrum from 3.6 to 4.8 ppm is given on the upper insert. The peak positions are also given in ppm on the insert, and can be recalculated in Hz by multiplying by factor 300. Relative intensities of the peaks are shown under the scale of chemical shifts on the lower spectrum. The determination accuracy is of ±3%.

The 37th Mendeleev Olympiad (2003)

Synthesis of benzimidazole

(authors – Beklemishev M.K., Druzhinin S.V., Nenajdenko V.G.)

The task consists of two parts. First, you will have to determine titrimetrically the formic acid, followed by the benzimidazole synthesis.

Reagents, labware and equipment

Item	*Quantity*	*Label*
For each participant		
10 mL graduated pipette	1 pc.	
Pipette filler	1 pc.	
Laboratory stand with burette clamp	1 pc.	
25 mL burette	1 pc.	
50 mL beaker, to be used under the burette	1 pc.	
150 mL conical flask for titration	4 pcs.	
Flask without the mark, for the analyzed solution **1**	1 pc.	Solution 1
100 mL volumetric flask with the stopper, for the diluted solution **2**	1 pc.	Solution 2
Funnel for filling the burette	1 pc.	
Formic acid, 30-45 % solution (the precise concentration to be determined)	20 mL	HCOOH
NaOH, 0.1 M standard solution	100 mL	NaOH
Phenolphthalein, ~0.1 % solution	2 mL	Phenolphthalein
Na_2CO_3, ~1 M solution (the oxidation medium)	100 mL	Na_2CO_3
H_2SO_4, solution ~1:4 (the Fe^{2+} titration medium)	100 mL	H_2SO_4
$KMnO_4$, ~0.1 M solution (for formate oxidation)	25 mL	$KMnO_4$ ~0.1 M
$KMnO_4$, 0.01 M standard solution (the titrant)	100 mL	$KMnO_4$, 0.01 M
Mohr's salt, 0.2 M standard solution (the reducer)	100 mL	Mohr's salt
Waste container	1 pc.	
100 mL round-bottom flask	1 pc.	
Reflux condenser with hoses to water supply and drain	1 pc.	
Hotplate	1 pc.	

20 mL vial with tetrahydrofuran	1 pc.	THF
20 mL vials with eluents (A, B, and C)	3 pcs.	A, B, and C
Boiling chips	A few pcs.	
100 mL beaker	1 pc.	
pH-indicator strips	5 pcs.	
250 mL glass beaker for TLC, covered with a Petri dish	3 pcs.	
Distilled water in wash bottle	0.5 L	H_2O
TLC capillary	5 pcs.	
TLC plate	4 pcs.	
Glass rod	1 pc.	
Spatula	1 pc.	
Tweezers	1 pc.	
Ruler	1 pc.	
Pencil	1 pc.	
o-Phenylenediamine	To be determined	Sample
Formic acid, 42 % solution	100 mL	HCOOH, 42 %
Fritted glass filter	1 pc.	
Bunsen flask	1 pc.	
Water-jet pump with a hose	1 pc.	
Weighing bottle for the product	1 pc.	Product
Capillary for melting point determination	3 pcs.	
For each 4 participants		
0.5 L bottle for the alkali	1 pc.	NaOH
0.5 L bottle for the Mohr's salt	1 pc.	Mohr's salt
0.5 L bottle for soda	1 pc.	Na_2CO_3
0.5 L bottle for the permanganate solution for oxidation	1 pc.	$KMnO_4$ ~0.1 M
0.5 L bottle for the permanganate solution for titration	1 pc.	$KMnO_4$, 0.01M
0.5 L bottle for sulfuric acid	1 pc.	H_2SO_4
10 mL measuring cylinder	2 pcs.	
Vial with dropper for adding the indicator	1 pc.	
At the table of common use		
Analytical balance	1 pc.	
Iodine chamber	1 pc.	
Apparatus for melting point determination	1 pc.	
Glass tube for filling the capillaries	1 pc.	
Latex gloves (M, S, L)	3 packs	

Part 1.

Titrimetric determination of the formic acid concentration in solution

In this task you have to determine the formic acid concentration in its solution by titrimetry. The analytical part includes two determinations. First you have to carry out an acid-base titration of a sample of the formic acid solution with the standard alkali solution using phenolphthalein as the indicator. This is followed by the redox permanganatometric titration of the formate ion. Oxidation of formate is a non-stoichiometric reaction, thus you need to carry out the oxidation with the permanganate excess in an alkaline medium.

Permanganate can be reduced to both manganese dioxide and manganese as a result of formate oxidation in an aqueous soda solution. Besides, an incomplete formate oxidation leading to the oxalate ion is also possible:

$$2MnO_4^- + 6HCOO^- \rightarrow 3C_2O_4^{2-} + 2MnO_2 + 2H_2O + 2OH^-.$$

The formate oxidation affords the anion-radical $CO_2^{\bullet-}$ as an intermediate. The latter can either lose another electron giving CO_2 or form a dimer of the oxalate ion. Too high pH values favor the oxalate formation, thus oxidation is carried out in mildly alkaline medium (soda rather than alkali solution). The oxidation proceeds slowly, so the mixture is incubated for 20–60 min at room temperature, and then the excess of the oxidant is determined by ferrometry. However, it is impossible to titrate permanganate with Mohr's salt directly because of the uncertainty of the endpoint fixation (the suspension of MnO_2 reacts very slowly with Fe^{2+}, if the latter is present in low concentration). Therefore, the medium is adjusted to acidic, and Mohr's salt is added in an excess. Finally, the excess is titrated with permanganate.

The described above method is referred to as *double back titration*.

Procedure

You are given the formic acid solution of an unknown concentration (lying in the range of 30-45 % by mass) in the mark-free flask labeled Solution **1**.

a) Perform the acid-base titration (fig. 1/2003). Fill the burette with the standard alkali solution ($c_{NaOH} \approx 0.1$ M). Introduce a 5.0 mL aliquot of the starting formic acid solution (Solution **1**) into the 100 mL volumetric flask and bring up to the mark, thus obtaining a ~0.3-0.5 M solution (Solution **2**). Using the pipette, transfer a 10.00 mL aliquot ($V_{HCOOH,1}$) of Solution **2** into a titration flask. Add 2–3 drops of phenolphthalein and titrate until the pink color is stable for at least 30 s. Add the titrant slowly and uniformly, which will permit to reduce the dispensing error.

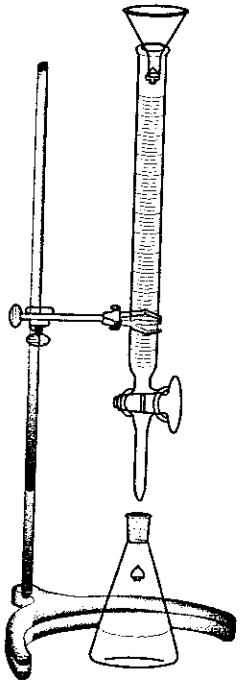


Fig. 1/2003. A typical titration setup.

b) Repeat the titration as necessary. Write down the titration results and the accepted titrant volume, mL.

Note. It is recommended to perform a draft titration adding the titrant in ~1 mL portions prior to the precise titrations.

Questions and assignments

1. Write down equation of formic acid reaction with alkali.

2. Derive the formula for calculation of the formic acid concentration in mol/L. Calculate (with 3-digit precision) the concentration of formic acid in the analyzed solution. Use the precise concentrations of the standard solutions given on the bottle labels.

c) Perform the redox titration. Place 2.0 mL ($V_{HCOOH,2}$) of the undiluted solution of formic acid (Solution **1**) using the pipette, 10 mL of 1 M soda solution using the measuring cylinder, and 5.0 mL ($V_{Mn,1}$) of the standard permanganate solution for the formate oxidation ($c_{Mn,1}$ ~ 0.1 M) into a titration flask. Mix the flask contents well and incubate the mixture for not less than 20 and not longer than 60 min.

Then using the measuring cylinder introduce 10 mL of H_2SO_4 (1:4) and 12.00 mL of the standard Mohr's salt solution (c_{Fe} ~ 0.2 M) into the flask.

Attention! Add the sulphuric acid solution carefully to avoid foaming.

Note. It is recommended to prepare the mixture as described in item c) in several flasks simultaneously, if you feel like doing more than one titration.

d) Fill the burette with the permanganate solution for titration ($c_{Mn,2}$~0.01 M) and titrate the excess of iron(II).

e) Repeat the titration as necessary. Write down the titration results and the accepted titrant volume, mL.

Note. It is recommended to perform a draft titration adding the titrant in ~1 mL portions prior to the precise titrations.

Questions and assignments

3. Write down equations of the main reactions which may occur upon formate oxidation by permanganate in the soda solution.

4. Write down equations of the reactions occurring upon interaction of Mohr's salt with the acidified solution obtained as a result of formate oxidation by permanganate.

5. Write down equation of the reaction occurring upon titration of the Mohr's salt excess with potassium permanganate.

6. Derive the final formula for calculation of the formic acid concentration in mol/L. Calculate (with 3-digit precision) the concentration of formic acid in the analyzed solution. Use the precise concentrations of the standard solutions given on the bottle labels.

7. Can the following side processes affect the accuracy of the formic acid determination based on its oxidation with permanganate in alkaline solution?

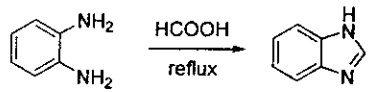
1) $2MnO_4^- + H_2O \rightarrow 2MnO_2 + 2OH^- + 1.5O_2$;
2) $2MnO_4^- + 6HCOO^- \rightarrow 3C_2O_4^{2-} + 2MnO_2 + 2H_2O + 2OH^-$;
3) $HCOO^- + 0.5O_2 + H_2O \rightarrow CO_2 + H_2O + OH^-$;
4) $HCOO^- + O_2 + H_2O \rightarrow CO_2 + H_2O_2 + OH^-$;
5) $HCOO^- + MnO_2 + H_2O \rightarrow Mn(OH)_2 + CO_2 + OH^-$.

Part 2.

Synthesis of benzimidazole

You have to synthesize a heterocyclic compound benzimidazole and determine the retention coefficient (R_f) of the starting compound, intermediates and product by thin-layer chromatography (TLC), as well as to study some other characteristics of

the synthesized compound. To prepare benzimidazole, you have to carry out the reaction of *o*-phenylenediamine with the formic acid solution with the concentration determined in Part 1.



Thin-layer chromatography (TLC) is widely used in organic chemistry for identification of compounds and their purity check. Each individual compound in a mixture is characterized by its retention factor (R_f), which is defined as the ratio of the distance the spot moved above the origin to that the eluent front moved above the origin (fig. 2/203):

$$R_f = \frac{x}{y}$$

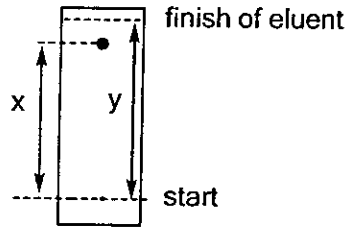


Fig. 2/2003. A TLC plate.

Procedure

a) Assemble the setup consisting of the round-bottom flask equipped with the reflux condenser connected to the water supply and drain.

b) Weigh the *o*-phenylenediamine sample on the analytical balance and transfer the substance into the flask.

c) Calculate the volume of the 42 % aqueous solution of formic acid required to complete the reaction (note that a ten-fold excess of the formic acid solution is needed to attain the complete reaction). Place the calculated volume of formic acid into the flask and add the boiling chips. Attach the reflux condenser to the flask and place the setup over the hotplate. Boil the mixture under reflux for about 1 h fig. 3/2003).

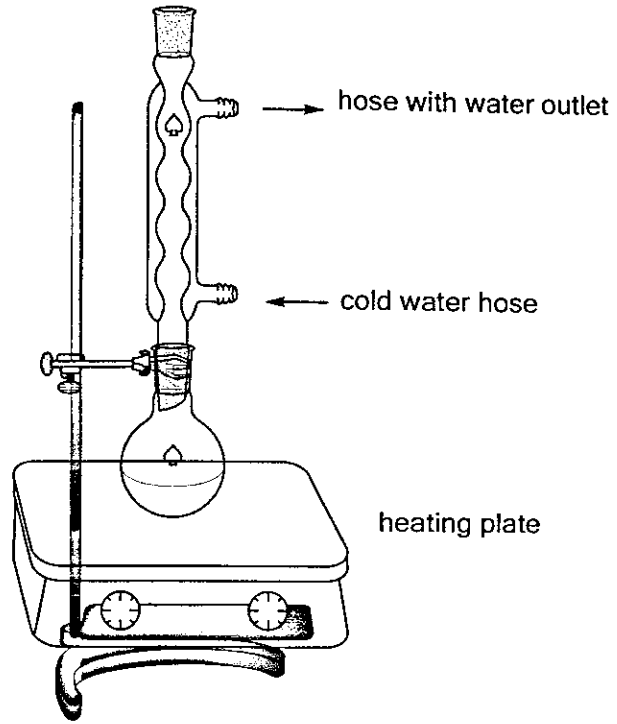


Fig. 3/2003. A setup for benzimidazole synthesis.

d) Use TLC to estimate the reaction completeness. To do so, use a capillary to take a sample of the reaction mixture in about 30 min since it started boiling and apply it to each of the three TLC plates (A, B, and C) at the dot labeled "1". Use a clean capillary to apply the reference *o*-phenylenediamine solution to each of the three TLC plates at the dot labeled "2". Place Plate A into the chamber with eluent A (hexane), Plate B into the chamber with eluent B (hexane – ethyl acetate, 1/1), and Plate C into the chamber with eluent C (ethyl acetate) (fig. 4/2003).

Retrieve the plates once the eluent front nearly reaches the top side of each plate. Dry the plates in air for 3 to 5 min, then develop in the iodine chamber.

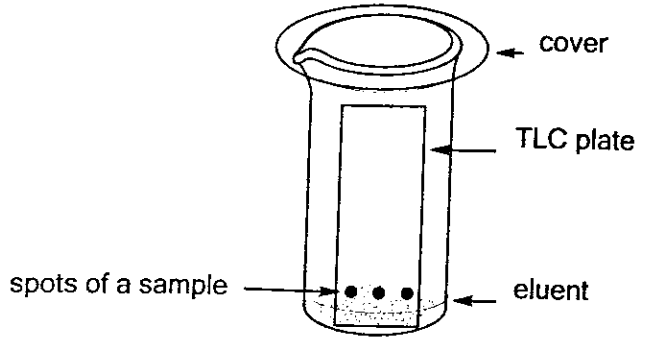


Fig. 4/2003. A TLC chamber.

Questions and assignments

8. Take a sketch of the TLC plates A, B, and C.

9. Determine the R_f value of benzimidazole when the reaction is not complete and that of *o*-phenylenediamine.

10. Which of the chromatography systems (A, B, or C) is more suitable for the reaction mixture analysis? Give proofs.

e) Use TLC to estimate the reaction completeness in about 1 h since the reaction mixture started boiling. Stop boiling, let it cool down slightly, and then continue cooling down to room temperature in a beaker with cold water. Use a capillary to take a sample of the reaction mixture and apply it to Plate E at the dot labeled "1". Use a clean capillary to apply the reference *o*-phenylenediamine solution at the dot labeled "2". Place the plate into the chamber with the eluent you decided optimal for the reaction mixture (of those studied in item d). Retrieve the plate once the eluent front nearly reaches the top side of the plate. Dry the plate at air for 3 to 5 min, then develop in the iodine chamber.

f) Transfer the flask contents in a dry clean beaker. Add dropwise the aqueous sodium hydroxide solution to the reaction mixture with an intense mixing with the glass rod till the pH 9.5–10 (check with the pH-indicator strips). Observe how precipitation starts. Scratch the beaker walls with the glass rod and put it aside for 5 min till the precipitation is complete.

) Assemble a setup for vacuum filtration using the water-jet pump. Use the spatula to stir the precipitate in the beaker and transfer it to the fritted glass filter. Switch on the water-jet pump, connect the flask to the hose leading to vacuum line and filter the precipitate under vacuum. Once you can see no more drops of the mother waters coming, disconnect the vacuum hose. Pour a few milliliters of tetrahydrofuran to the precipitate on the filter and carefully stir with the spatula (note that the product is significantly soluble in tetrahydrofuran!). Attach the

vacuum hose and filtrate the precipitate again. To dry the substance, leave it on the filter for 10 min with the water-jet pump switched on (fig. 5/2003).

Attention! *The water-jet pump valve can be closed only when the vacuum hose is disconnected from the setup.*

h) Weigh the obtained product in the weighing bottle.

i) Determine the melting point of the obtained compound.

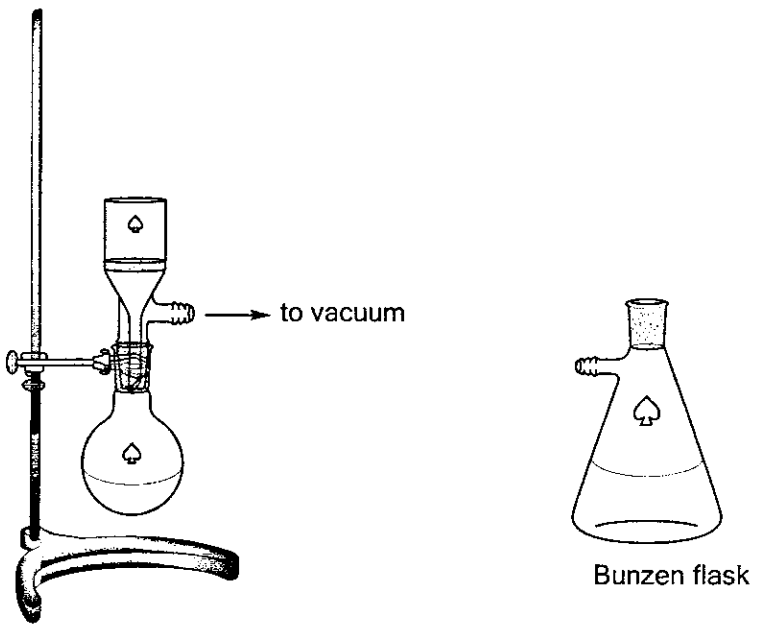


Fig. 5/2003. A setup for vacuum filtration. Alternatively, one can use a Bunsen flask.

The melting point is determined by using a special apparatus and a capillary packed with a substance to be analyzed. Fill the open end of the capillary with the substance and bring it to the bottom throwing the capillary several times through a glass tube placed on a solid surface. Repeat as needed to pack the capillary tightly. Place the ready capillary into the apparatus for melting point determination (fig. 6/2003).

Questions and assignments

11. Take a sketch of TLC plate E.

12. Estimate the reaction completeness by TLC.

13. Write down the product mass and calculate the yield. Describe the product appearance (the structure and color of the crystals).

14. Write down the recorded melting point.

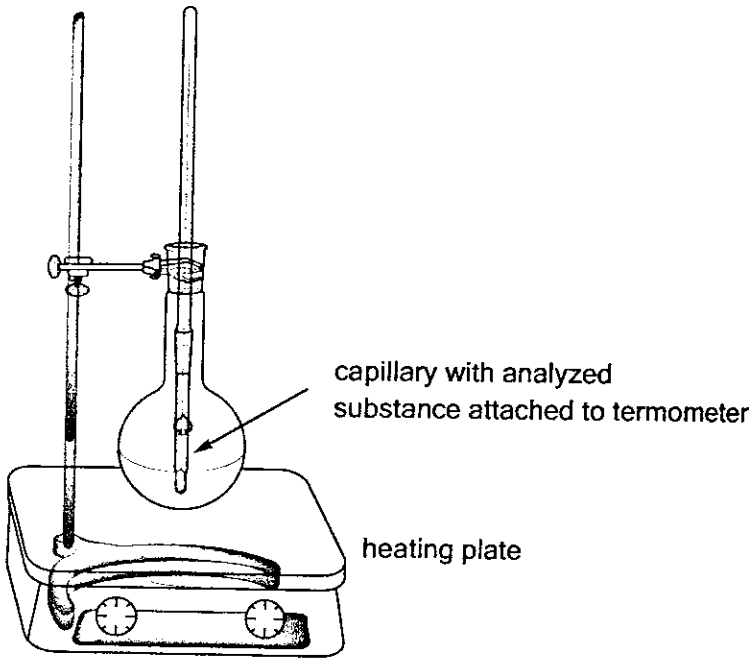


Fig 6/2003. A setup for melting point determination.

The 38th Mendeleev Olympiad (2004)

Determination of acidity of a wine sample and its sugar concentration. Identification of an unknown methyl ketone

(authors – Beklemishev M.K., Nenajdenko V.G.)

In this task, you will have to analyze a sample of wine. You will determine its acidity (in particular, check whether the normal acidity is exceeded because of excessive souring) and the content of reducing sugars, which will allow the wine classification as dry, semidry, semisweet, or sweet.

General information on chemical composition of grape wines

The content of ethanol appearing as a result of natural fermentation in grape wines never exceeds 20 % by volume. Ethanol is produced from sugars via alcoholic fermentation in an acidic medium. Vinegar bacteria oxidize ethanol to acetic acid, which is behind souring of wines.

Only yeast, lactic acid and vinegar bacteria as well as certain moulds occur in grape juice and wine, which is due to the presence of relatively strong organic acids, such as tartaric, citric, succinic, malic, and acetic. The acids are responsible for low pH values (2.5-4.2) preventing other microorganisms from growth under such conditions.

Tartaric acid is typically present in the highest concentration, thus the total acid content is usually reported on the assumption that the total acidity is due to the tartaric acid only. The content of volatile acids in wines (recalculated to acetic acid) does not exceed 1.8 g/L, and that of free amino acids is lower than 1 g/L. A wine acidity calculated as tartaric acid content should not exceed 5-7 g/L, the normal level depending on the wine type.

A detectable amount of hydrosulphite is often found in wines. The norm of its content calculated as SO_2 should not exceed 200 mg/L. SO_2 is an antiseptic. It prevents the wort from excessive fermentation if present in concentrations higher than 100 mg/L calculated as free SO_2.

Glucose, fructose and tiny amounts of disaccharides are found in wines. The sugar content in wines is as follows: in dry wines less than 0.3%, in semidry wine in the