ACS USNCO
U.S. National Chemistry Olympiad

2024 U.S. NATIONAL CHEMISTRY OLYMPIAD

NATIONAL EXAM PART II

Prepared by the American Chemical Society Chemistry Olympiad Examinations Task Force

OLYMPIAD EXAMINATIONS TASK FORCE

Seth N. Brown, **Chair**, *University of Notre Dame,* Notre Dame, IN

Monica Marie Arroyo, *Pontifical Catholic University of Puerto Rico*, Ponce, PR
James Ayers, *Colorado Mesa University*, Grand Junction, CO
Jerry Bell, *Simmons University*, Boston, MA (retired)
Jesse Bernstein, *Miami Country Day School*, Miami, FL (retired)
Alan D. Crosby, *Newton South HS*, Newton, MA (retired)
Mark DeCamp, *University of Michigan*, Dearborn, MI (retired)
James Dohm, *University of Pennsylvania*, Philadelphia, PA
Kimberly Gardner, *United States Air Force Academy,* CO
Paul Groves, *South Pasadena HS*, South Pasadena, CA (retired)
Nicolas Hamel, *Clackamas Community College*, Oregon City, OR (retired)
John Kotz, *State University of New York*, Oneonta, NY (retired)
Mariusz Kozik, *Canisius College*, Buffalo, NY
Sarah Leite, *Hopkins School*, New Haven, CT
Michael A. Morgan, *Francisco Bravo Medical Magnet HS*, Los Angeles, CA
Jane Nagurney, *Scranton Preparatory School*, Scranton, PA (retired)
Anne O'Connor, *Cleveland State University*, Cleveland, OH

DIRECTIONS TO THE EXAMINER

Part II of this test requires that student answers be written in this test booklet in the spaces provided underneath the questions. Part II test booklet and scratch paper should be made available to the student only during the examination period. All testing materials including scratch paper should be collected from students after the examination. Only test booklets should be shipped to the USNCO office immediately after the national exam and no later than **April 22, 2024**.

When the student has completed **Part II**, or after one hour and forty-five minutes have elapsed, the student must turn in **Part II** of the testing materials and all scratch paper. Be sure that the student has supplied the same identification number used for **Part I** has been used again for **Part II**.

There are three parts to the National Olympiad Examination. You have the option of administering the three parts in any order, and you are free to schedule rest breaks between parts.

Part I	**60 questions**	**single-answer multiple-choice**	**1 hour, 30 minutes**
Part II	**8 questions**	**problem-solving, explanations**	**1 hour, 45 minutes**
Part III	**2 lab questions**	**laboratory practical**	**1 hour, 30 minutes**

A periodic table and other useful information are provided on page two for student reference.

Students should be permitted to use only non-programmable calculators. The use of a programmable calculator, cell phone, or any other device that can access the internet or make copies or photographs during the exam is grounds for disqualification.

DIRECTIONS TO THE EXAMINEE - DO NOT TURN THE PAGE UNTIL DIRECTED TO DO SO.

Part II requires complete responses to questions involving problem-solving and explanations. **One hour and forty-five minutes** are allowed to complete this part. Be sure to use the same identification number you used for **Part I and write it on top of each page in the indicated fields**. Use separate sheets for scratch paper and do **not** attach your scratch paper to this examination. When you complete **Part II** (or at the end of one hour and forty-five minutes) you must turn in all testing materials and scratch paper.

STUDENT USNCO ID:

ABBREVIATIONS AND SYMBOLS					
amount of substance	n	Faraday constant	F	molar mass	M
ampere	A	free energy	G	mole	mol
atmosphere	atm	frequency	ν	Planck's constant	h
atomic mass unit	u	gas constant	R	pressure	P
Avogadro constant	N_A	gram	g	rate constant	k
Celsius temperature	°C	hour	h	reaction quotient	Q
centi– prefix	c	joule	J	second	s
coulomb	C	kelvin	K	speed of light	c
density	d	kilo– prefix	k	temperature, K	T
electromotive force	E	liter	L	time	t
energy of activation	E_a	measure of pressure	mm Hg	vapor pressure	VP
enthalpy	H	milli– prefix	m	volt	V
entropy	S	molal	m	volume	V
equilibrium constant	K	molar	M	year	y

CONSTANTS
$R = 8.314$ J mol^{-1} K^{-1}
$R = 0.08314$ L bar mol^{-1} K^{-1}
$F = 96{,}500$ C mol^{-1}
$F = 96{,}500$ J V^{-1} mol^{-1}
$N_A = 6.022 \times 10^{23}$ mol^{-1}
$h = 6.626 \times 10^{-34}$ J s
$c = 2.998 \times 10^{8}$ m s^{-1}
0 °C = 273.15 K
1 atm = 1.013 bar = 760 mm Hg
Specific heat capacity of H_2O = 4.184 J g^{-1} K^{-1}

EQUATIONS

$$E = E^{o} - \frac{RT}{nF}\ln Q \qquad \ln K = \left(\frac{-\Delta H^{o}}{R}\right)\left(\frac{1}{T}\right) + \text{constant} \qquad \ln\left(\frac{k_2}{k_1}\right) = \frac{E_a}{R}\left(\frac{1}{T_1} - \frac{1}{T_2}\right)$$

PERIODIC TABLE OF THE ELEMENTS

1 1A												13 3A	14 4A	15 5A	16 6A	17 7A	18 8A
1 **H** 1.008	2 2A																2 **He** 4.003
3 **Li** 6.941	4 **Be** 9.012											5 **B** 10.81	6 **C** 12.01	7 **N** 14.01	8 **O** 16.00	9 **F** 19.00	10 **Ne** 20.18
11 **Na** 22.99	12 **Mg** 24.31	3 3B	4 4B	5 5B	6 6B	7 7B	8 8B	9 8B	10 8B	11 1B	12 2B	13 **Al** 26.98	14 **Si** 28.09	15 **P** 30.97	16 **S** 32.07	17 **Cl** 35.45	18 **Ar** 39.95
19 **K** 39.10	20 **Ca** 40.08	21 **Sc** 44.96	22 **Ti** 47.88	23 **V** 50.94	24 **Cr** 52.00	25 **Mn** 54.94	26 **Fe** 55.85	27 **Co** 58.93	28 **Ni** 58.69	29 **Cu** 63.55	30 **Zn** 65.39	31 **Ga** 69.72	32 **Ge** 72.61	33 **As** 74.92	34 **Se** 78.97	35 **Br** 79.90	36 **Kr** 83.80
37 **Rb** 85.47	38 **Sr** 87.62	39 **Y** 88.91	40 **Zr** 91.22	41 **Nb** 92.91	42 **Mo** 95.95	43 **Tc** (98)	44 **Ru** 101.1	45 **Rh** 102.9	46 **Pd** 106.4	47 **Ag** 107.9	48 **Cd** 112.4	49 **In** 114.8	50 **Sn** 118.7	51 **Sb** 121.8	52 **Te** 127.6	53 **I** 126.9	54 **Xe** 131.3
55 **Cs** 132.9	56 **Ba** 137.3	57 **La** 138.9	72 **Hf** 178.5	73 **Ta** 180.9	74 **W** 183.8	75 **Re** 186.2	76 **Os** 190.2	77 **Ir** 192.2	78 **Pt** 195.1	79 **Au** 197.0	80 **Hg** 200.6	81 **Tl** 204.4	82 **Pb** 207.2	83 **Bi** 209.0	84 **Po** (209)	85 **At** (210)	86 **Rn** (222)
87 **Fr** (223)	88 **Ra** (226)	89 **Ac** (227)	104 **Rf** (261)	105 **Db** (262)	106 **Sg** (263)	107 **Bh** (262)	108 **Hs** (265)	109 **Mt** (266)	110 **Ds** (281)	111 **Rg** (272)	112 **Cn** (285)	113 **Nh** (286)	114 **Fl** (289)	115 **Mc** (289)	116 **Lv** (293)	117 **Ts** (294)	118 **Og** (294)

58 **Ce** 140.1	59 **Pr** 140.9	60 **Nd** 144.2	61 **Pm** (145)	62 **Sm** 150.4	63 **Eu** 152.0	64 **Gd** 157.3	65 **Tb** 158.9	66 **Dy** 162.5	67 **Ho** 164.9	68 **Er** 167.3	69 **Tm** 168.9	70 **Yb** 173.0	71 **Lu** 175.0
90 **Th** 232.0	91 **Pa** 231.0	92 **U** 238.0	93 **Np** (237)	94 **Pu** (244)	95 **Am** (243)	96 **Cm** (247)	97 **Bk** (247)	98 **Cf** (251)	99 **Es** (252)	100 **Fm** (257)	101 **Md** (258)	102 **No** (259)	103 **Lr** **(262)**

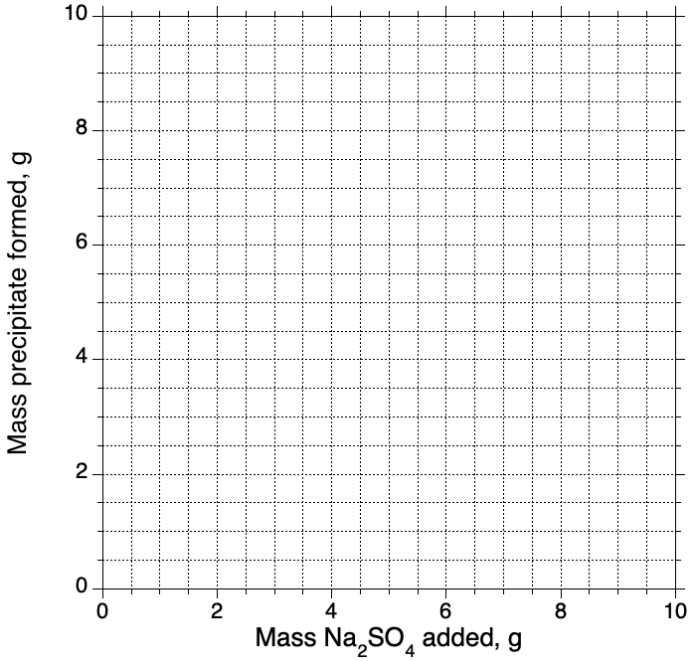
1. [10%] An unknown salt MX_2 is a group 2 metal halide.

   a. 10.00 g MX_2 dissolves in 50.0 g water to give a homogeneous solution. The freezing point of this solution is –4.50 °C. What is the molar mass of MX_2? For water, $K_f = 1.86$ °C/*m*.

   b. 10.00 g Na_2CO_3 and 10.00 g MX_2 are mixed in 200.0 mL of water. A precipitate of MCO_3 forms. What is the pH of the supernatant? The K_a of H_2CO_3 is 4.3×10^{-7} and the K_a of HCO_3^- is 4.7×10^{-11}

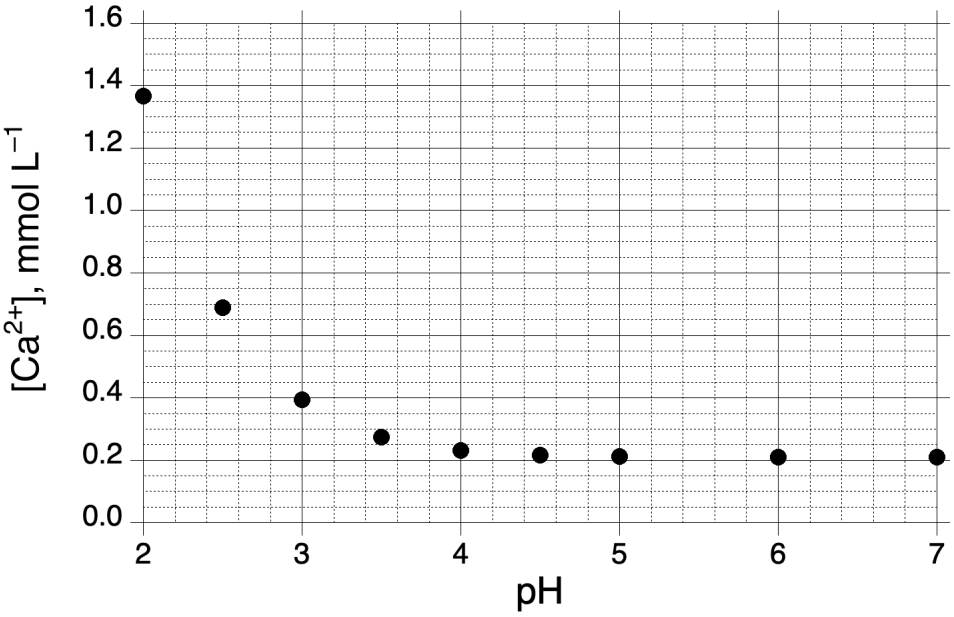
   c. A solution of 10.00 g MX_2 in water is treated with excess silver nitrate. The precipitate is dried; the mass of the dried compound is 15.2 g. What is the identity of MX_2?

d. A sample of 10.00 g MX_2 dissolved in 50 mL water is treated with increasing amounts of Na_2SO_4 up to 10 g in total. How will the mass of precipitate formed vary with the mass of added Na_2SO_4? Graph your answer on the grid provided.



e. What color flame test does MX_2 give?

2. [13%] A sample of solid calcium fluoride is suspended in water in an unreactive container and stirred until it achieves equilibrium. The pH of the solution is lowered by careful addition of nitric acid, and the pH and concentration of $Ca^{2+}(aq)$ are noted at several points as shown on the graph below. Note that the units on the *y* axis are millimoles per liter.



a. Determine the K_{sp} of CaF_2 from the data provided.

b. Qualitatively, what is the cause for the increase in solubility of CaF_2 at low pH?

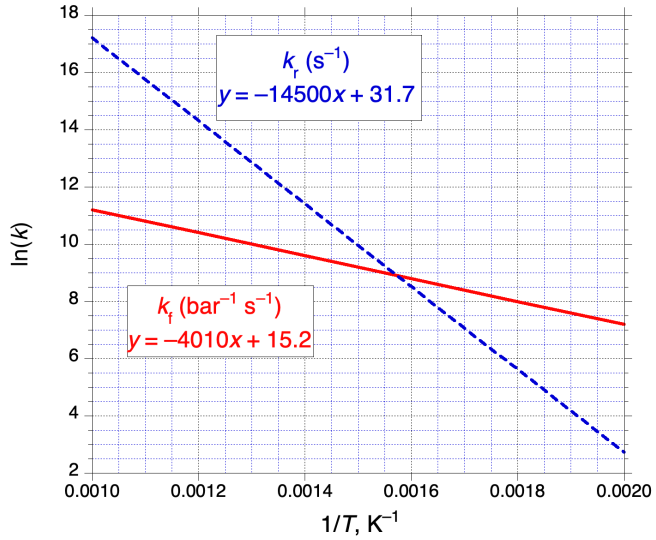
c. From the data provided, determine the K_a of HF.

d. How many moles of HNO_3 must be added to the CaF_2/water mixture to achieve a pH = 3.00 in this experiment? The volume of solution is 1.00 L.

e. Carbon dioxide dissolves in water at 25 °C and 1 atm pressure to the extent of 0.0345 mol L^{-1}. An aliquot of the solution taken from the above experiment at pH = 5 is stirred under 1 atm CO_2 and the pH slowly raised by addition of solid NaOH until $CaCO_3$ just begins to precipitate. What is the pH of the solution at this point? The K_{sp} of $CaCO_3$ is 8.7×10^{-9}, the K_a of aqueous CO_2 ("H_2CO_3") is 4.3×10^{-7}, and the K_a of HCO_3^- is 4.7×10^{-11}.

3. [13%] Ethene, C_2H_4, can react in the gas phase in the presence of radicals R to form polyethylene as shown in the equation below. Here n is the degree of polymerization. The forward reaction is second-order while the reverse reaction is first-order. The values of these rate constants are independent of the degree of polymerization n and the identity of R.

$$C_2H_4(g) + \bullet CH_2(CH_2)_{2n}CH_2R \underset{k_r}{\overset{k_f}{\rightleftharpoons}} \bullet CH_2(CH_2)_{(2n+2)}CH_2R$$



a. A sample of polyethylene has an average degree of polymerization $n = 1200$. How many polymer chains are present in 1.0 g of this material?

b. Calculate $\Delta H°$ and $\Delta S°$ for the polymerization reaction.

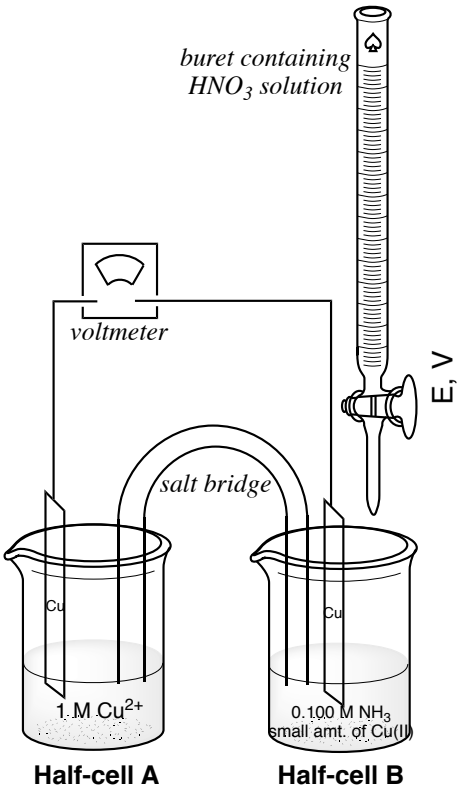
c. The bond dissociation enthalpy (BDE) for a typical carbon-carbon single bond is 345 kJ mol^{-1}. From the data given, what is the BDE of the carbon-carbon double bond in ethene?

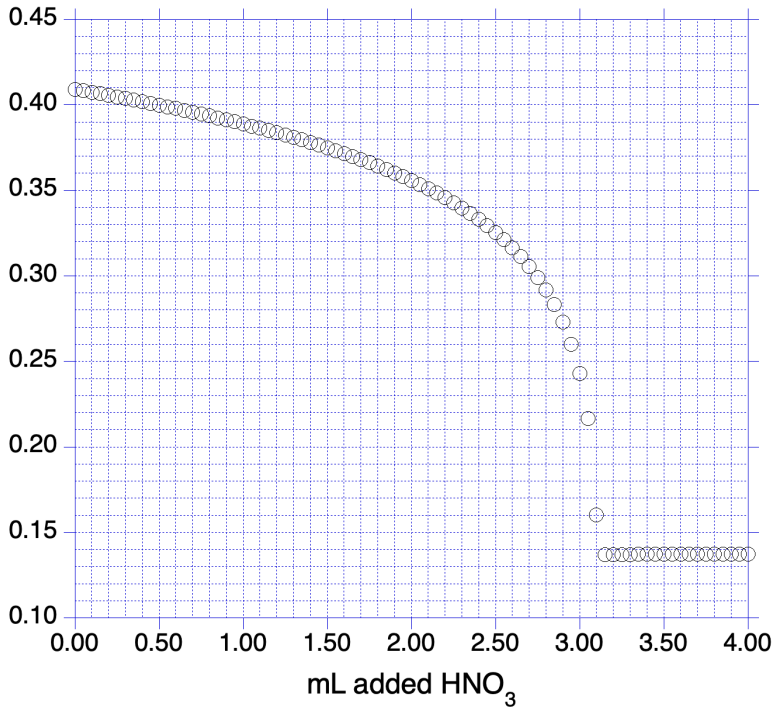
d. Ethene is charged to a fixed vessel at 25 bar and 720 K. Traces of radical are then added to initiate polymerization. What is the percent conversion of ethene into polymer at equilibrium under these conditions?

e. In the presence of a catalyst for the polymerization reaction, the forward rate constant as a function of temperature is $\ln(k_f) = -3050(1/T) + 21.0$. By what factor does the catalyst accelerate the rate of the forward reaction at 500 K?

f. By what factor does the catalyst change the rate of the reverse reaction at 500 K?

4. [13%] Copper(II) forms a complex ion with ammonia, $Cu(NH_3)_4^{2+}$, with $K_f = 1.7 \times 10^{13}$. An electrochemical cell is set up as shown below at 298 K. Half-cell **A** contains 100 mL of 1.00 M $Cu(NO_3)_2$, while half-cell **B** contains 100 mL of a solution that contains a small amount of copper(II) and is 0.100 M in NH_3. A solution of nitric acid is slowly added to half-cell **B** and the potential measured by the voltmeter is recorded as a function of the added volume of HNO_3.





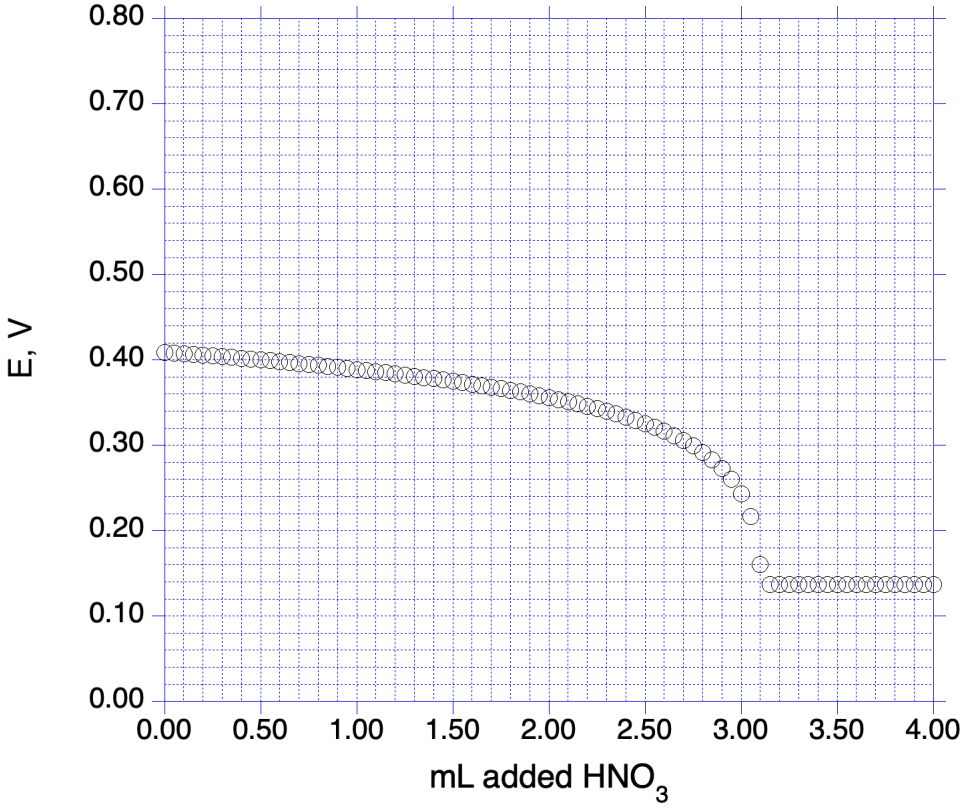
a. Which half-cell is the cathode and which is the anode? Justify your answer.

b. Qualitatively explain the shape of the graph.

c. What is the total concentration of copper(II) in the solution in half-cell **B**?

d. What is the concentration of nitric acid in the buret?

e. Suppose that the experiment is set up again with silver metal in place of copper metal and silver(I) ion in place of copper(II) ion, but with all concentrations and all other reagents identical. What would the graph of E vs. mL added HNO_3 look like in this experiment? Sketch your result on the grid below (the graph shown above is redrawn for your convenience), and explain your answer. Silver(I) forms a complex ion with ammonia, $Ag(NH_3)_2^+$, with $K_f = 1.7 \times 10^7$.



5. [12%] Write net equations for each of the reactions below. Use appropriate ionic and molecular formulas and omit formulas for all ions or molecules that do not take part in a reaction. Write structural formulas for all organic substances, and clearly show stereochemistry where relevant. You need not balance the equations or show the phase of the species.

a. Aqueous ammonia and acetic acid are mixed.

b. Sodium iodate is added to an excess of hydriodic acid.

c. Manganese(IV) oxide is added to concentrated aqueous hydrochloric acid.

d. Propyl benzoate is heated with aqueous sodium hydroxide.

e. Calcium oxide and graphite are heated to 2200 °C.

f. Iodine-124 undergoes radioactive decay by electron capture.

6. [14%] Consider the properties of the group 1 elements, whose valence shell electron configuration is ns^1, in the table below.

Element *M*	*n*	First ionization energy, kJ mol^{-1}	Energy required to excite the valence electron to the $(n+1)s$ orbital, kJ mol^{-1}	Molar density of solid *M*Cl, mol cm^{-3}
H	1	1312	984	0.0403
Li	2	520	325	0.0507
Na	3	496	308	0.0371
K	4	420	252	0.0266
Rb	5	403	241	0.0232
Cs	6	376	222	0.0237

a. Rationalize the observed trend in first ionization energies with increasing *n*.

b. Suppose a hydrogen atom were excited to its $2s^1$ state. If that excited state atom were to transfer its electron to Cs^+ to form a ground-state Cs atom, how much energy would that reaction absorb or release?

c. All but one of the atoms listed in the table have an excited state that is significantly lower in energy than the $(n+1)s^1$ state described in the table. Explain this observation, noting which atom is the exception and why.

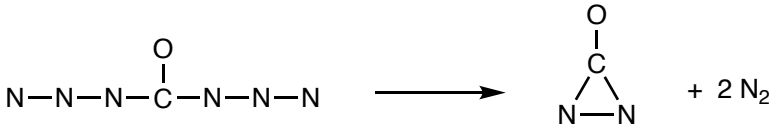
d. All but one of the atoms listed in the table have an excited state that is modestly higher in energy (38 – 55 kJ mol^{-1}) than the $(n+1)s^1$ state described in the table. Explain this observation, noting which atom is the exception and why.

e. The compounds MCl(*s*) show a smooth decrease in their molar densities, except that HCl(*s*) is less dense than expected from the trend and CsCl(*s*) is more dense than expected. Explain this periodic trend, and give reasons for the two exceptions to the trend.

f. ^{137}Cs (136.9070895 amu) undergoes radioactive decay to give a stable product whose atomic mass is 136.9058274 amu. What type of radioactive decay is this, and what is the identity of the decay product?

g. Calculate the energy, in kJ mol^{-1}, released by the radioactive decay of ^{137}Cs.

7. [13%] Flash vacuum pyrolysis of carbonyl azide (CON_6) at 420 °C gives low yields of a cyclic compound, diazirinone, as shown in the equation below. Note that the illustrations of carbonyl azide and diazirinone correctly show the connectivity of the atoms but are NOT correct Lewis structures. The bond dissociation enthalpies (BDE, in kJ mol^{-1}) of various bonds among carbon, oxygen, and nitrogen are given in the table.



carbonyl azide *diazirinone*

Bond	BDE, kJ mol^{-1}	Bond	BDE, kJ mol^{-1}	Bond	BDE, kJ mol^{-1}	Bond	BDE, kJ mol^{-1}
C–O	350	C–N	290	N–N	160	N–O	200
C=O	741	C=N	615	N=N	418	N=O	480
C≡O	1080	C≡N	891	N≡N	949		

a. Draw complete Lewis structures for carbonyl azide and for diazirinone, including all lone pairs and nonzero formal charges. You need only draw one Lewis structure for each molecule, even if there are multiple possible resonance structures.

b. Diazirinone decomposes in the gas phase over the course of several days at room temperature to give carbon monoxide and nitrogen gas. Based on the given BDEs, calculate $\Delta H°$ for this decomposition reaction.

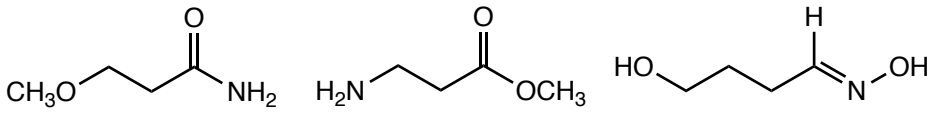
c. The actual $\Delta H°$ for the decomposition of diazirinone is –347 kJ mol^{-1}. Comment on any discrepancy you find between this value and the value you determined in part b. Be sure your comment addresses the direction of deviation of the two values.

d. Will $\Delta G°$ for decomposition at 298 K be algebraically greater than, less than, or equal to $\Delta H°$ for decomposition? Briefly justify your answer.

e. There is an isomer of diazirinone that has a chain structure with the connectivity NCNO. Draw a Lewis structure for this molecule and clearly describe or sketch its geometry.

f. Would you expect acyclic NCNO to be more or less stable than diazirinone? Clearly justify your prediction.

8. [12%] Consider the three isomers of $C_4H_9NO_2$ shown below:



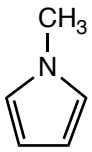
I **II** **III**

a. Which compound is the most basic? Justify your answer.

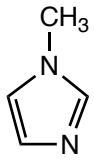
b. Draw the structures of the conjugate acids of the three compounds.

c. Draw the structure of a chiral isomer of $C_4H_9NO_2$.

Consider the two nitrogen heterocycles shown below:



IV



V

d. Which compound is more basic? Draw the structure of its conjugate acid.

e. Which compound is more reactive towards Br_2? Explain why it is more reactive and draw the structure of a major product of its reaction with Br_2.

This page is intentionally left blank

This page is intentionally left blank

2024 USNCO Part 2 Solutions

1. a. $(-4.50\ °C)/(-1.86\ °C/m) = 2.42\ m$
Since MX_2 gives 3 moles of ions per mole of compound, the solution is $(2.42\ m/3) = 0.807\ m$.

$$(0.807\ \text{mol } MX_2/\text{kg water}) \times (0.0500\ \text{kg water}) = 0.0404\ \text{mol } MX_2$$
$$10.00\ \text{g } MX_2/0.0404\ \text{mol} = 248\ \text{g mol}^{-1}$$

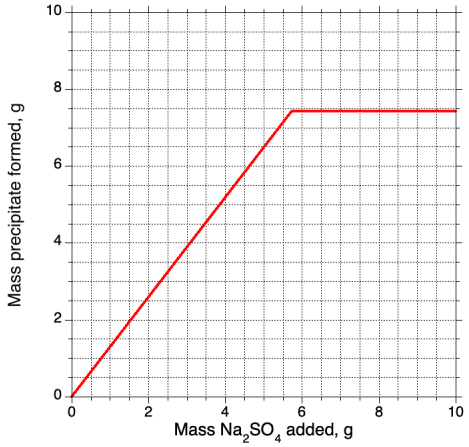
b. $10.00\ \text{g } Na_2CO_3/(105.99\ \text{g mol}^{-1}) = 0.09435\ \text{mol } Na_2CO_3$.
After reaction with 0.0404 mol MX_2, approximately 0.0404 mol MCO_3 will precipitate, leaving behind 0.0540 mol CO_3^{2-} in solution. In 200 mL, this gives a 0.270 M solution of CO_3^{2-}. The carbonate ion reacts with water as follows:

$$CO_3^{2-}(aq) + H_2O(l) \rightleftharpoons HCO_3^-(aq) + OH^-(aq) \qquad K_{eq} = K_w/(K_a \text{ of } HCO_3^-)$$

$$\frac{[HCO_3^-][OH^-]}{[CO_3^{2-}]} = 2.1 \times 10^{-4}$$
$$\frac{[OH^-]^2}{[0.270]} = 2.1 \times 10^{-4}$$
$$[OH^-] = 7.6 \times 10^{-3}\ \text{M}$$
$$\text{pH} = 14 + \log_{10}[OH^-] = 11.88$$

c. $15.2\ \text{g AgX}/(0.0404 \bullet 2\ \text{mol X}) = 188\ \text{g mol}^{-1}$ of AgX
Since the atomic mass of Ag is 107.9, the molar mass of X is 80 => X is Br.
Subtracting the mass of 2 Br from 248 g mol^{-1} molar mass of MX_2 gives an atomic mass of M = 88. Thus M = Sr.

d. $0.0404\ \text{mol } SrSO_4 \times 183.69\ \text{g mol}^{-1} = 7.42\ \text{g } SrSO_4$ is the maximum amount of precipitate that can form. The amount actually formed will increase linearly until 0.0404 mol Na_2SO_4 (= 5.74 g) are added, then will not increase further as Sr^{2+} becomes the limiting reagent.



e. Sr gives a red flame test.

2. a. From the graph, the molar solubility of CaF_2 at high pH is about 0.21 mmol/L, so $[Ca^{2+}] = 2.1\times10^{-4}$ M and $[F^-] = 2[Ca^{2+}]$.

$$K_{sp} = [Ca^{2+}][F^-]^2 = (2.1 \times 10^{-4})(4.2 \times 10^{-4})^2 = 3.7 \times 10^{-11}$$

b. F^- reacts with H^+ to form HF, lowering the concentration of F^- and shifting the solubility equilibrium to cause more solid CaF_2 to dissolve.

c. Choosing any low-pH point should work, but it is better to choose a point with pH < 3 so that the error from reading the plot is minimized. As an example, we can use pH = 2 (1.36×10^{-3} M = $[Ca^{2+}]$). At this point, $[H_3O^+] = 10^{-pH} = 0.010$ M. One can determine the concentration of F^- from the K_{sp}:

$$K_{sp} = [Ca^{2+}][F^-]^2$$
$$3.7 \times 10^{-11} = [1.36 \times 10^{-3}][F^-]^2$$
$$[F^-] = 1.65 \times 10^{-4} \text{ M}$$

Since each Ca^{2+} in solution must be accompanied by two fluorines (in whatever form),

$$[F^-] + [HF] = 2[Ca^{2+}]$$
$$[1.65 \times 10^{-4}] + [HF] = 2[1.36 \times 10^{-3}]$$
$$[HF] = 2.56 \times 10^{-3} \text{ M}$$

One can then solve for K_a:

$$K_a = \frac{[H_3O^+][F^-]}{[HF]} = \frac{[0.01][1.65\times10^{-4}]}{[2.56\times10^{-3}]} = 6.4 \times 10^{-4}$$

d. At pH = 3, from the graph, $[Ca^{2+}] = 3.9 \times 10^{-4}$ M, so $[F^-] + [HF] = 7.8 \times 10^{-4}$ M. At this pH, $[H_3O^+] = 1.0 \times 10^{-3}$ M, so

$$6.4 \times 10^{-4} = \frac{[0.001][F^-]}{[HF]}$$
$$[F^-]/[HF] = 0.64$$
$$(7.8 \times 10^{-4} - [HF]) = 0.64[HF]$$
$$[HF] = 4.8 \times 10^{-4} \text{ M}$$

The added nitric acid either protonates fluoride ion or produces H_3O^+. So

$$\text{mol added } HNO_3 = \text{mol HF} + \text{mol } H_3O^+$$
$$\text{mol added } HNO_3 = 4.8 \times 10^{-4} + 1.0 \times 10^{-3}$$
$$\text{Total of } 1.5 \times 10^{-3} \text{ mol added } HNO_3$$

e. $[Ca^{2+}] = 2.1 \times 10^{-4}$ M. From the K_{sp},

$$[Ca^{2+}][CO_3^{2-}] = 8.7 \times 10^{-9}$$
$$[CO_3^{2-}] = 4.1 \times 10^{-5} \text{ M}$$

One can relate the concentration of CO_3^{2-} to the concentration of H_2CO_3 by combining the two acid-base dissociations:

$$H_2CO_3 + 2\ H_2O \rightleftharpoons CO_3^{2-} + 2\ H_3O^+$$
$$K_{eq} = (K_a \text{ of } H_2CO_3)(K_a \text{ of } HCO_3^-) = 2.0 \times 10^{-17}$$
$$\frac{[CO_3^{2-}][H_3O^+]^2}{[H_2CO_3]} = 2.0 \times 10^{-17}$$
$$\frac{[4.1 \times 10^{-5}][H_3O^+]^2}{[0.0345]} = 2.0 \times 10^{-17}$$
$$[H_3O^+] = 1.3 \times 10^{-7} \text{ M}$$
$$\text{pH} = 6.88$$

3. a. $M = 1200(28.05\text{ g mol}^{-1}) = 3370\text{ g mol}^{-1}$
Thus 1.0 g polymer = 3.0×10^{-5} mol = 1.8×10^{19} molecules

b. $K_{eq} = k_f/k_r$, so $\ln(K_{eq}) = \ln(k_f) - \ln(k_r) = 10500(1/T) - 16.5$
Since $\Delta G° = -RT\ln(K_{eq}) = \Delta H° - T\Delta S°$, $\ln(K_{eq}) = -(\Delta H°/R)(1/T) + (\Delta S°/R)$

$$\Delta H° = -10500R = -87.3\text{ kJ mol}^{-1}$$

$$\Delta S° = -16.5R = -137\text{ J mol}^{-1}\text{ K}^{-1}$$

c. $$\Delta H°_{rxn} = \{\text{BDE of C=C}\} - 2\times\{\text{BDE of C–C}\} = -87.3\text{ kJ mol}^{-1}$$

$$\{\text{BDE of C=C}\} - 2\times(345\text{ kJ mol}^{-1}) = -87.3\text{ kJ mol}^{-1}$$

$$\{\text{BDE of C=C}\} = 603\text{ kJ mol}^{-1}$$

d. Since the properties of the shorter and longer polymer radicals are the same, their concentrations are effectively equal, so $K_p = 1/P_{C2H4}$.

$$K_p = k_f/k_r = 0.147\text{ at 720 K}$$

So at equilibrium $P_{C2H4} = 6.8$ bar. Thus 6.8/25 × 100% = 27% unreacted ethene, 73% incorporation into polymer.

e. From the equations:

$$k_f\text{ (uncatalyzed, 500 K)} = 1310\text{ bar}^{-1}\text{ s}^{-1}$$

$$k_f\text{ (catalyzed, 500 K)} = 2.96 \times 10^6\text{ bar}^{-1}\text{ s}^{-1}$$

$$k_{cat}/k_{uncat} = 2300$$

The catalyzed reaction is 2300 times faster than the uncatalyzed one.

f. Since addition of a catalyst cannot change K_{eq}, the reverse reaction must also be accelerated by a factor of 2300 by the catalyst.

4. a. Half-cell B has a much lower concentration of $Cu^{2+}(aq)$. Not only is it stated that there is only a small amount of Cu(II), at $[NH_3] = 0.1$ M, almost all copper will be in the form of $Cu(NH_3)_4^{2+}$. Since current will flow spontaneously in a concentration cell in a direction that tends to equalize the concentrations in the two half-cells, reduction of Cu(II) will happen preferentially in half-cell A, which is thus the cathode. Half-cell B is the anode.

b. As HNO_3 is added, it protonates NH_3 and decreases its concentration. Less NH_3 means a higher concentration of uncomplexed Cu^{2+} and hence a smaller voltage. When all the NH_3 is protonated, then all the Cu(II) is in the form of $Cu^{2+}(aq)$, which does not change further, so the voltage is stable after the endpoint.

c. The easiest way to solve this is to use the potential past the endpoint, where the copper is in the form of $Cu^{2+}(aq)$. From the graph, $E = 0.14$ V:

$$E = E° - (RT/nF)\ln([Cu^{2+}]_B/[Cu^{2+}]_A)$$

With $n = 2$, $[Cu^{2+}]_A = 1.00$:

$$0.14 = 0 - (0.0128)\ln([Cu^{2+}]_B)$$

$$[Cu^{2+}] = 1.8 \times 10^{-5} \text{ M}$$

d. The endpoint is at 3.15 mL, at which point the NH_3 has been neutralized:

$$0.100 \text{ L solution} \times 0.100 \text{ mol L}^{-1} \text{ NH}_3 = C \times 0.00315 \text{ L HNO}_3 \text{ solution}$$

$$C = 3.2 \text{ M}$$

e. In the original titration, before the endpoint, the Cu(II) is almost all complexed, so:

$$K_f = 1.7 \times 10^{13} = \frac{[Cu(NH_3)_4^{2+}]}{[Cu^{2+}][NH_3]^4} = \frac{[1.8 \times 10^{-5}]}{[Cu^{2+}][NH_3]^4}$$

$$[Cu^{2+}] = 1.1 \times 10^{-18}[NH_3]^{-4}$$

$$E = (-0.0128)\ln((1.1 \times 10^{-18})[NH_3]^{-4})$$

$$E = 0.53 + 0.51 \bullet \ln[NH_3]$$

Repeating the calculation for Ag(I), which differs in the magnitude and expression for K_f and has $n = 1$ rather than $n = 2$:

$$K_f = 1.7 \times 10^{7} = \frac{[Ag(NH_3)_2^{+}]}{[Ag^{+}][NH_3]^2} = \frac{[1.8 \times 10^{-5}]}{[Ag^{+}][NH_3]^2}$$

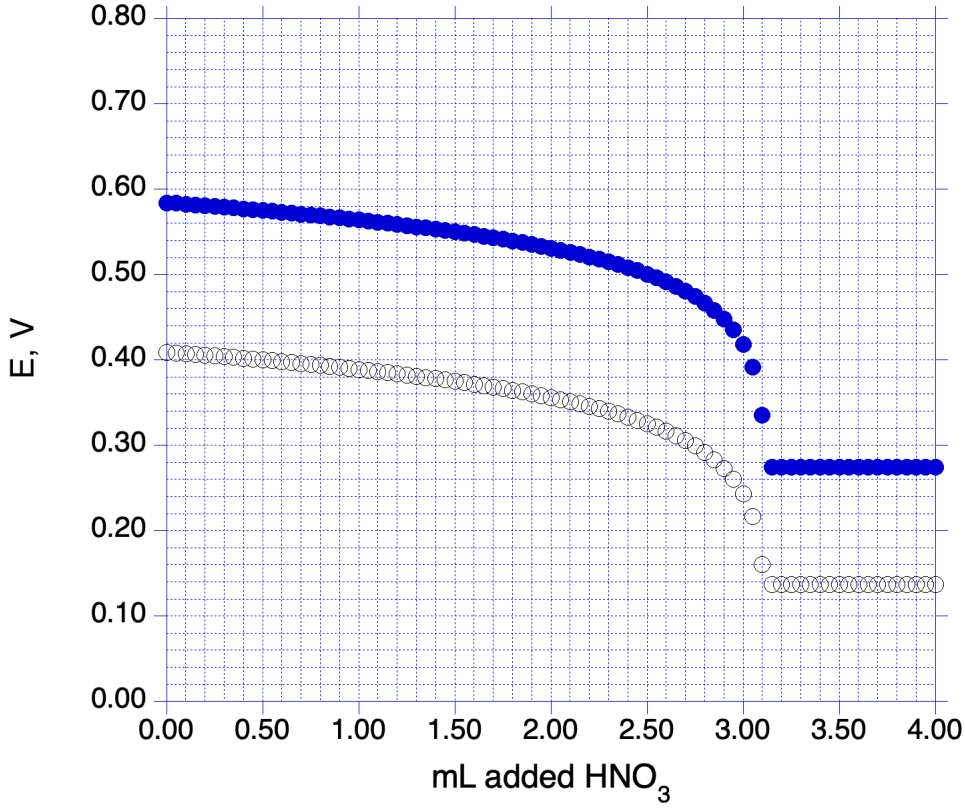
$$[Ag^{+}] = 1.1 \times 10^{-12}[NH_3]^{-2}$$

$$E = (-0.0257)\ln((1.1 \times 10^{-12})[NH_3]^{-2})$$

$$E = 0.71 + 0.51 \bullet \ln[NH_3]$$

So before the endpoint, the Ag experiment will give potentials that are 0.18 V higher than the correspoding values for the Cu experiment.

After the endpoint, the only difference between the Cu and Ag experiments is that $n = 1$ for Ag (vs. $n = 2$ for Cu). This results in a doubling of the cell potential for Ag. So:

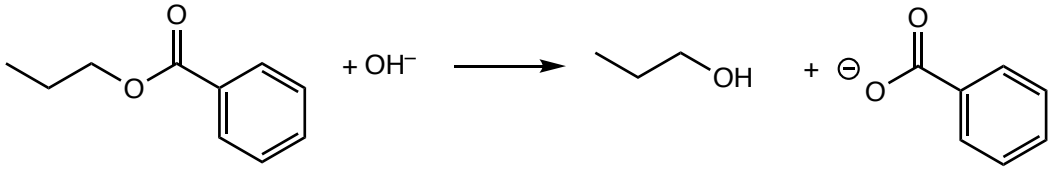

0.80
0.70
0.60
0.50
0.40
0.30
0.20
0.10
0.00
E, V
0.00
0.50
1.00
1.50
2.00
2.50
3.00
3.50
4.00
mL added HNO3

5. a. $NH_3 + CH_3COOH \rightarrow NH_4^+ + CH_3COO^-$

b. $IO_3^- + H^+ + I^- \rightarrow I_3^- + H_2O$ (I_2 also acceptable in place of I_3^-)

c. $MnO_2 + H^+ + Cl^- \rightarrow Mn^{2+} + H_2O + Cl_2$

d.



e. $CaO + C \rightarrow CaC_2 + CO$

f. $^{124}I \rightarrow {}^{124}Te$

6. a. Electron energies are proportional to $-Z_{eff}^2/n^2$. For the valence electrons, Z_{eff} only increases slightly going down a column of the periodic table, so electrons with larger values of n have higher energies and thus are easier to ionize.

b. The $2s^1$ state of H has an energy = –1312 kJ mol^{-1} + 984 kJ mol^{-1} = –328 kJ mol^{-1}. This is higher in energy than the valence electron in Cs at –376 kJ mol^{-1}, so the electron transfer to Cs^+ will release 48 kJ mol^{-1} of energy.

c. In all cases except H, the *ns* electron can be promoted to an *np* orbital, which is significantly lower in energy than the $(n+1)s$ orbital. There is no $1p$ orbital, so this is not possible for H.

d. In all cases except H, the $(n+1)p$ orbital is modestly higher in energy than the $(n+1)s$ orbital, giving rise to an excited state of modestly higher energy. For H, there is a $2p$ orbital, but in one-electron atoms the energy depends only on n, not l, so its energy is the same as that of the $2s$ state.

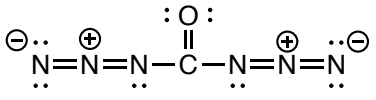
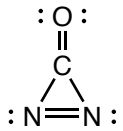
e. For Li – Rb, the MCl(*s*) compounds form ionic lattices with the rock salt structure. As the cations increase in size going down the column, the lattices expand and hence the molar density decreases. HCl(*s*) is a molecular crystal, and the weaker intermolecular forces give relatively long intermolecular distances and hence a less dense packing. CsCl(*s*) adopts a different lattice than the rock salt lattice (it is commonly called the CsCl lattice), which allows it to pack more densely than the rock salt lattice with a cation the size of cesium would.

f. β^- decay forms ^{137}Ba.

g. $E = \Delta mc^2$. $\Delta m = -1.26 \times 10^{-3}$ amu $\times$ $(1.661 \times 10^{-27}$ kg amu$^{-1})$ $= -2.09 \times 10^{-30}$ kg

$E = (2.09 \times 10^{-30}$ kg$)(2.998 \times 10^8$ m s$^{-1})^2 = 1.88 \times 10^{-13}$ J $= 1.88 \times 10^{-16}$ kJ

$(1.88 \times 10^{-16}$ kJ$)(6.022 \times 10^{23}$ mol$^{-1}) = 1.13 \times 10^8$ kJ mol^{-1}

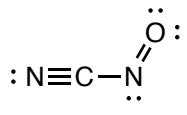
7. a.  

Other resonance structures are acceptable in both cases.

b. $\Delta H° = \Sigma(\text{BDE of bonds broken}) - \Sigma(\text{BDE of bonds formed})$
$\Delta H° = \{(N{=}N) + (C{=}O) + 2 \times (C{-}N)\} - \{(C{\equiv}O) + (N{\equiv}N)\}$
$\Delta H° = \{418 + 741 + 2 \times 290\} - \{1080 + 949\}$ kJ mol^{-1}
$\Delta H° = -290$ kJ mol^{-1}

c. The reaction is more exothermic than expected, indicating that the bonds are weaker in the reactant than would be expected based on typical bond dissociation enthalpies. This is likely due to the three-membered ring in the structure. This means that the bonds in the ring cannot achieve ideal bond angles, so they are not as strong as expected.

d. $\Delta S°$ is highly positive since two molecules are produced from one. Since $\Delta G° = \Delta H° - T\Delta S°$, $\Delta G° < \Delta H°$.

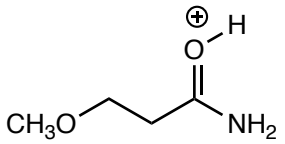
e.  , linear at carbon and bent at the middle nitrogen.

f. Entropically, there should be little difference between the molecules. Enthalpically, one can estimate $\Delta H°$ of isomerization from the diazinone to NCNO:
$\Delta H° = \{(N{=}N) + (C{=}O) + 2 \times (C{-}N)\} - \{(C{\equiv}N) + (C{-}N) + (N{=}O)\}$
$\Delta H° = \{418 + 741 + 2 \times 290\} - \{891 + 290 + 480\}$ kJ mol^{-1}
$\Delta H° = 78$ kJ mol^{-1}

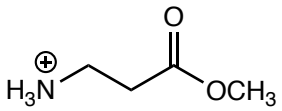
Even considering that diazirinone is ~57 kJ mol^{-1} less stable than one would expect (from the results of b./c.), formation of NCNO is still expected to be endothermic, and thus diazirinone is expected to be more stable.

8. a. Compound **II** is most basic. Nitrogen is the least electronegative atom with a lone pair in each of the three structures, but in **I** that lone pair is engaged in resonance with the carbonyl group; since the resonance is lost on protonation, that nitrogen is not basic. The oxime **III** is basic at nitrogen, but the greater amount of *s* character in the lone pair and the fact that the nitrogen is bonded to an electronegative oxygen atom, make it less basic than the amine in **II**.

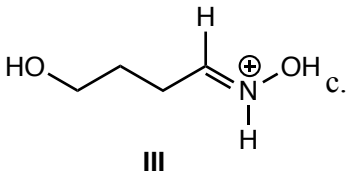
b.



I



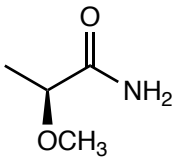
II

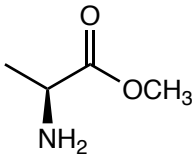


III

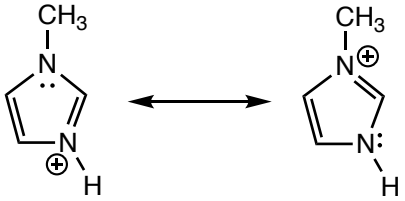
c.

c. Many possible answers, including





d. The imidazole **V** is much more basic than the pyrrole **IV**. Protonation of the imidazole at the unmethylated nitrogen results in better resonance in the conjugate acid than was present in the conjugate base. No such enhancement of resonance is possible in **IV** (in fact, resonance that is present in the neutral compound is lost on protonation at nitrogen, which means that pyrrole actually protonates preferentially at carbon).



e. Since reaction with bromine takes place at carbon, the additional N in the imidazole **V** is electron-withdrawing and deactivating, since its lone pair is in the plane of the ring and so cannot stabilize the cationic intermediate in the reaction. In contrast, the lone pair of the nitrogen on pyrrole is stabilizing to the intermediate: