

USA-2 C-0 C-1

**USA-2 C-0 C**  
Nikhil Seshadri

**ICHO**  
**General instructions**  
**Cover sheet**

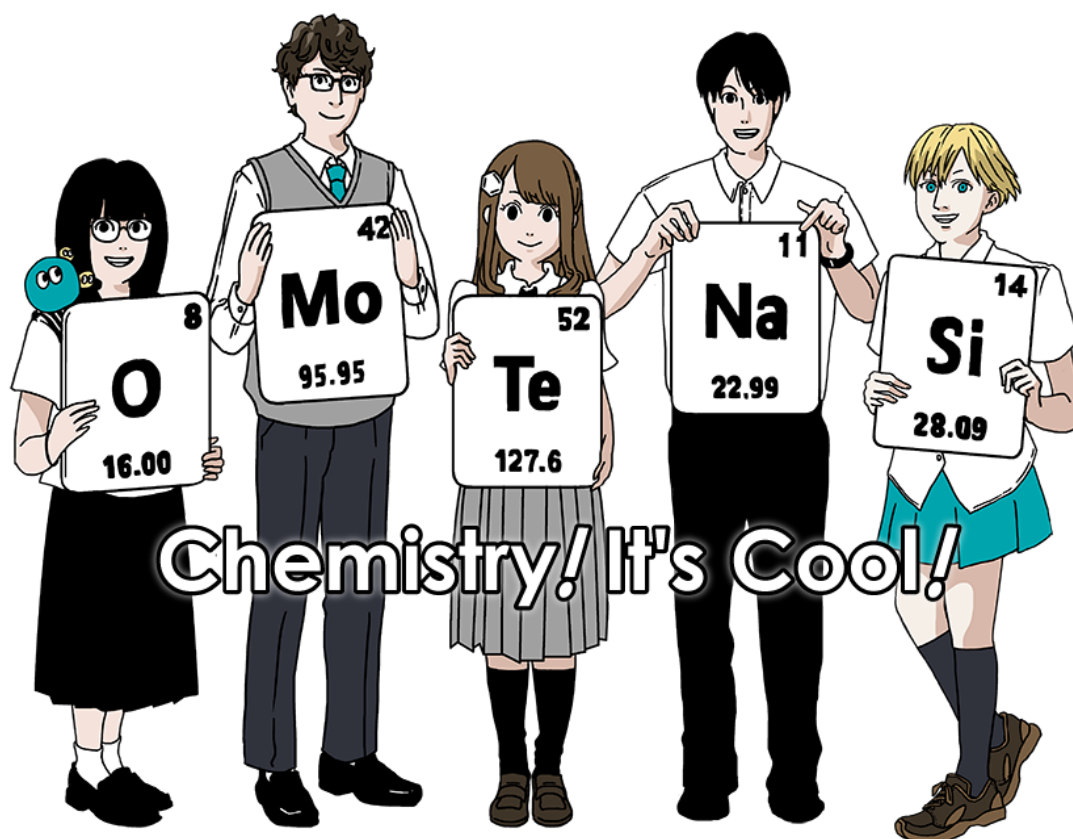
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International Chemistry Olympiad 2021 Japan

53rd ICHO2021 Japan

25th July – 2nd August, 2021

<https://www.icho2021.org>





USA-2 C-0 G-2

# G0-2

USA (United States of America)

## General Instructions

- You are allowed to use pen only to write your answers.
- Your calculator must be non-programmable.
- This examination has **9 problems**.
- You can solve the problems in any order.
- You will have **5 hours** to solve all problems.
- You can **begin** working only after the **START** command is given by the invigilator.
- All results must be written in the appropriate answer boxes with pen on the **answer sheets**. If you need scratch paper, use the back of the question sheets. Remember that answers written outside the answer boxes will not be graded.
- Write relevant calculations in the appropriate boxes when necessary. Work must be shown to receive full credit for correct answers.
- The invigilator will announce a **30-minute** warning before the **STOP** command.
- You **must stop** working when the **STOP** command is given. Failure to stop writing will lead to the nullification of your examination.
- The official English version of this examination is available by request for clarification only.
- You are not allowed to leave your seat without permission from the invigilator. If you need any assistance (broken calculator, need to use a restroom, etc.), raise your hand to get the attention of the invigilator.

**GOOD LUCK!**

## Problems and Grading Information

	Title	Total Score	Percentage
1	Hydrogen at a Metal Surface	24	11
2	Isotope Time Capsule	35	11
3	Lambert–Beer Law?	22	8
4	The Redox Chemistry of Zinc	32	11
5	Mysterious Silicon	60	12
6	The Solid-State Chemistry of Transition Metals	45	13
7	Playing with Non-benzenoid Aromaticity	36	13
8	Dynamic Organic Molecules and Their Chirality	26	11
9	Likes and Dislikes of Capsules	23	10
Total			100

## Physical Constants and Equations

### Constants

Speed of light in vacuum	$c = 2.99792458 \times 10^8 \text{ m s}^{-1}$
Planck constant	$h = 6.62607015 \times 10^{-34} \text{ J s}$
Elementary charge	$e = 1.602176634 \times 10^{-19} \text{ C}$
Electron mass	$m_e = 9.10938370 \times 10^{-31} \text{ kg}$
Electric constant (permittivity of vacuum)	$\varepsilon_0 = 8.85418781 \times 10^{-12} \text{ F m}^{-1}$
Avogadro constant	$N_A = 6.02214076 \times 10^{23} \text{ mol}^{-1}$
Boltzmann constant	$k_B = 1.380649 \times 10^{-23} \text{ J K}^{-1}$
Faraday constant	$F = N_A \times e = 9.64853321233100184 \times 10^4 \text{ C mol}^{-1}$
Gas constant	$R = N_A \times k_B = 8.31446261815324 \text{ J K}^{-1} \text{ mol}^{-1}$ $= 8.2057366081 \times 10^{-2} \text{ L atm K}^{-1} \text{ mol}^{-1}$
Unified atomic mass unit	$u = 1 \text{ Da} = 1.66053907 \times 10^{-27} \text{ kg}$
Standard pressure	$p = 1 \text{ bar} = 10^5 \text{ Pa}$
Atmospheric pressure	$p_{\text{atm}} = 1.01325 \times 10^5 \text{ Pa}$
Zero degree Celsius	$0^\circ \text{C} = 273.15 \text{ K}$
Ångstrom	$1 \text{ Å} = 10^{-10} \text{ m}$
Picometer	$1 \text{ pm} = 10^{-12} \text{ m}$
Electronvolt	$1 \text{ eV} = 1.602176634 \times 10^{-19} \text{ J}$
Part-per-million	$1 \text{ ppm} = 10^{-6}$
Part-per-billion	$1 \text{ ppb} = 10^{-9}$
Part-per-trillion	$1 \text{ ppt} = 10^{-12}$
pi	$\pi = 3.141592653589793$
The base of the natural logarithm (Euler's number)	$e = 2.718281828459045$



## Equations

The ideal gas law	$PV = nRT$ , where $P$ is the pressure, $V$ is the volume, $n$ is the amount of substance, $T$ is the absolute temperature of ideal gas.
Coulomb's law	$F = k_e \frac{q_1 q_2}{r^2}$ , where $F$ is the electrostatic force, $k_e (\simeq 9.0 \times 10^9 \text{ N m}^2 \text{ C}^{-2})$ is Coulomb's constant, $q_1$ and $q_2$ are the magnitudes of the charges, and $r$ is the distance between the charges.
The first law of thermodynamics	$\Delta U = q + w$ , where $\Delta U$ is the change in the internal energy, $q$ is the heat supplied, $w$ is the work done.
Enthalpy $H$	$H = U + PV$
Entropy based on Boltzmann's principle $S$	$S = k_B \ln W$ , where $W$ is the number of microstates.
The change of entropy $\Delta S$	$\Delta S = \frac{q_{\text{rev}}}{T}$ , where $q_{\text{rev}}$ is the heat for the reversible process.
Gibbs free energy $G$	$G = H - TS$ $\Delta_r G^\circ = -RT \ln K = -zFE^\circ$ , where $K$ is the equilibrium constant, $z$ is the number of electrons, $E^\circ$ is the standard electrode potential.
Reaction quotient $Q$	$\Delta_r G = \Delta_r G^\circ + RT \ln Q$ For a reaction $aA + bB \rightleftharpoons cC + dD$ $Q = \frac{[C]^c [D]^d}{[A]^a [B]^b}$ , where $[A]$ is the concentration of A.

Heat change $\Delta q$	$\Delta q = nc_m \Delta T$ , where $c_m$ is the temperature-independent molar heat capacity.
Nernst equation for re- dox reaction	$E = E^\circ + \frac{RT}{zF} \ln \frac{C_{\text{ox}}}{C_{\text{red}}}$ , where $C_{\text{ox}}$ is the concentration of oxidized substance, $C_{\text{red}}$ is the concentration of reduced substance.
Arrhenius equation	$k = A \exp\left(-\frac{E_a}{RT}\right)$ , where $k$ is the rate constant, $A$ is the pre-exponential factor, $E_a$ is the activation energy. $\exp(x) = e^x$
Lambert-Beer equation	$A = \varepsilon lc$ , where $A$ is the absorbance, $\varepsilon$ is the molar absorption coefficient, $l$ is the optical path length, $c$ is the concentration of the solution.
Henderson-Hasselbalch equation	For an equilibrium $\text{HA} \rightleftharpoons \text{H}^+ + \text{A}^-$ , where equilibrium constant is $K_a$ , $\text{pH} = \text{p}K_a + \log\left(\frac{[\text{A}^-]}{[\text{HA}]}\right)$
Energy of a photon	$E = h\nu = h\frac{c}{\lambda}$ , where $\nu$ is the frequency, $\lambda$ is the wavelength of the light.
The sum of a geometric series	When $x \neq 1$ , $1 + x + x^2 + \dots + x^n = \sum_{i=0}^n x^i = \frac{1 - x^{n+1}}{1 - x}$
Approximation equation that can be used to solve problems	When $x \ll 1$ , $\frac{1}{1 - x} \simeq 1 + x$

## Periodic Table

1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	
1 H Hydrogen 1.008																	2 He Helium 4.003	
3 Li Lithium 6.968	4 Be Beryllium 9.012																9 F Fluorine 18.998	10 Ne Neon 20.180
11 Na Sodium 22.990	12 Mg Magnesium 24.306																17 Cl Chlorine 35.452	18 Ar Argon 39.948
19 K Potassium 39.098	20 Ca Calcium 40.078	21 Sc Scandium 44.956	22 Ti Titanium 47.867	23 V Vanadium 50.942	24 Cr Chromium 51.996	25 Mn Manganese 54.938	26 Fe Iron 55.845	27 Co Cobalt 58.933	28 Ni Nickel 58.693	29 Cu Copper 63.546	30 Zn Zinc 65.38	31 Ga Gallium 69.723	32 Ge Germanium 72.630	33 As Arsenic 74.922	34 Se Selenium 78.971	35 Br Bromine 79.904	36 Kr Krypton 83.798	
37 Rb Rubidium 85.468	38 Sr Strontium 87.62	39 Y Yttrium 88.906	40 Zr Zirconium 91.224	41 Nb Niobium 92.906	42 Mo Molybdenum 95.95	43 Tc Technetium [99]	44 Ru Ruthenium 101.07	45 Rh Rhodium 102.906	46 Pd Palladium 106.42	47 Ag Silver 107.868	48 Cd Cadmium 112.414	49 In Indium 114.818	50 Sn Tin 118.710	51 Sb Antimony 121.760	52 Te Tellurium 127.60	53 I Iodine 126.904	54 Xe Xenon 131.293	
55 Cs Caesium 132.905	56 Ba Barium 137.327	57-71 La-Lu Lanthanoids	72 Hf Hafnium 178.49	73 Ta Tantalum 180.948	74 W Tungsten 183.84	75 Re Rhenium 186.207	76 Os Osmium 190.23	77 Ir Iridium 192.217	78 Pt Platinum 195.084	79 Au Gold 196.967	80 Hg Mercury 200.592	81 Tl Thallium 204.384	82 Pb Lead 207.2	83 Bi Bismuth 208.98	84 Po Polonium [210]	85 At Astatine [210]	86 Rn Radon [222]	
87 Fr Francium [223]	88 Ra Radium [226]	89-103 Ac-Lr Actinoids	104 Rf Rutherfordium [267]	105 Db Dubnium [268]	106 Sg Seaborgium [271]	107 Bh Bohrium [272]	108 Hs Hassium [277]	109 Mt Meitnerium [276]	110 Ds Darmstadtium [281]	111 Rg Roentgenium [280]	112 Cn Copernicium [285]	113 Nh Nihonium [278]	114 Fl Flerovium [289]	115 Mc Moscovium [289]	116 Lv Livermorium [293]	117 Ts Tennessine [293]	118 Og Oganesson [294]	
57-71 La-Lu Lanthanoids		58 Ce Cerium 140.116	59 Pr Praseodymium 140.908	60 Nd Neodymium 144.242	61 Pm Promethium [145]	62 Sm Samarium 150.36	63 Eu Europium 151.964	64 Gd Gadolinium 157.25	65 Tb Terbium 158.925	66 Dy Dysprosium 162.500	67 Ho Holmium 164.930	68 Er Erbium 167.259	69 Tm Thulium 168.934	70 Yb Ytterbium 173.045	71 Lu Lutetium 174.967			
89-103 Ac-Lr Actinoids		89 Ac Actinium [227]	90 Th Thorium 232.038	91 Pa Protactinium 231.036	92 U Uranium 238.029	93 Np Neptunium [237]	94 Pu Plutonium [239]	95 Am Americium [243]	96 Cm Curium [247]	97 Bk Berkelium [247]	98 Cf Californium [252]	99 Es Einsteinium [252]	100 Fm Fermium [257]	101 Md Mendelevium [258]	102 No Nobelium [259]	103 Lr Lawrencium [262]		

Key:

113 Nh Nihonium [278]	atomic number	Symbol	name	atomic weight [in parenthesis for the radioactive element]
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# <sup>1</sup>H NMR Chemical Shifts



$\Delta\delta$  for one alkyl group-substitution: *ca.* +0.4 ppm

USA-2 C-1 C-1

**USA-2 C-1 C**  
Nikhil Seshadri

**ICHO**  
**Problem 1**  
**Cover sheet**

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## Hydrogen at a Metal Surface

11 % of the total							
Question	A.1	A.2	B.1	B.2	B.3	B.4	Total
Points	6	4	5	3	3	3	24
Score							



Hydrogen is expected to be a future energy source that does not depend on fossil fuels. Here, we will consider the hydrogen-storage process in a metal, which is related to hydrogen-transport and hydrogen-storage technology.

### Part A

As hydrogen is absorbed into the bulk of a metal surface, let us first consider the adsorption process of hydrogen at the metal surface,  $\text{H}_2(\text{g}) \rightarrow 2\text{H}(\text{ad})$ , where the gaseous and adsorbed states of hydrogen are represented as (g) and (ad), respectively. Hydrogen molecules ( $\text{H}_2$ ) that reach the metal surface (M) dissociate at the surface and are adsorbed as H atoms (Fig. 1). Here, the potential energy of  $\text{H}_2$  is represented by two variables: the interatomic distance,  $d$ , and the height relative to the surface metal atom,  $z$ . It is assumed that the axis along the two H atoms is parallel to the surface and that the center of gravity is always on the vertical dotted line in Figure 1.

Figure 2 shows the potential energy contour plot for the dissociation at the surface. The numerical values represent the potential energy in units of kJ per mole of  $\text{H}_2$ . The solid line spacing is  $20 \text{ kJ mol}^{-1}$ , the dashed line spacing is  $100 \text{ kJ mol}^{-1}$ , and the spacing between solid and dashed lines is  $80 \text{ kJ mol}^{-1}$ . The zero-point vibration energy is ignored.

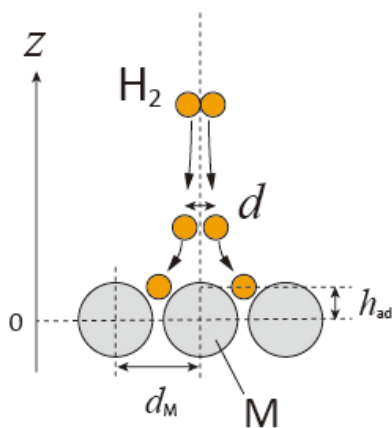


Figure 1. Definition of variables. Drawing is not to scale.

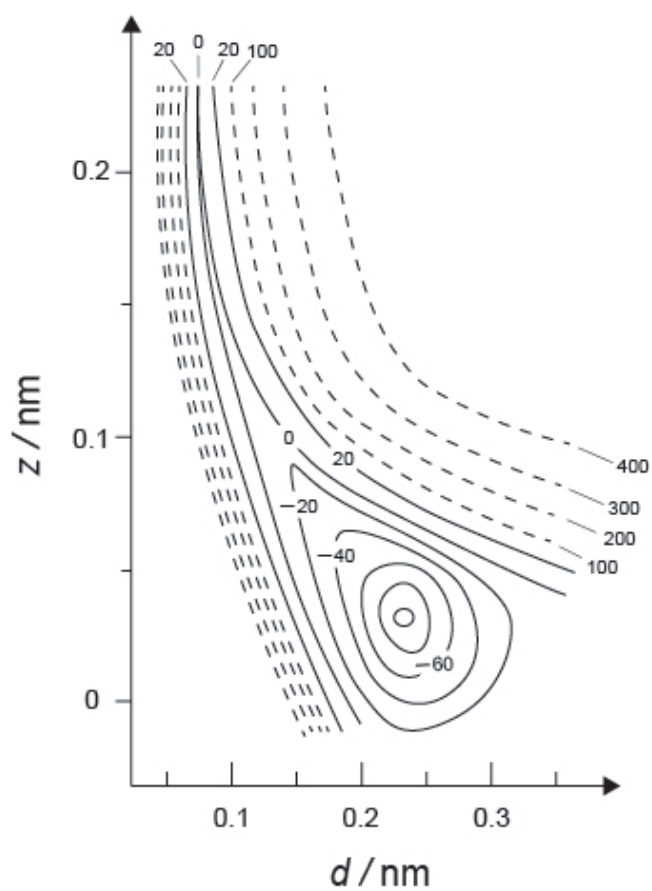


Figure 2.

**A.1** For each of the following items (i)–(iii), **SELECT** the closest value from A–G. 6pt

(i) The interatomic distance for a gaseous  $\text{H}_2$  molecule

(ii) The interatomic distance between metal atoms ( $d_{\text{M}}$  in Figure 1)

(iii) The distance of adsorbed H atoms from the surface ( $h_{\text{ad}}$  in Figure 1)

A. 0.03 nm	B. 0.07 nm	C. 0.11 nm	D. 0.15 nm
E. 0.19 nm	F. 0.23 nm	G. 0.27 nm	

**A.2** For each of the following items (i)–(ii), **SELECT** the closest value from A–H. 4pt

(i) the energy required for the dissociation of gaseous  $\text{H}_2$  to gaseous H  
[ $\text{H}_2(\text{g}) \rightarrow 2\text{H}(\text{g})$ ]

(ii) the energy released during the adsorption of a gaseous  $\text{H}_2$  [ $\text{H}_2(\text{g}) \rightarrow 2\text{H}(\text{ad})$ ]

A. 20 $\text{kJ mol}^{-1}$	B. 40 $\text{kJ mol}^{-1}$	C. 60 $\text{kJ mol}^{-1}$	D. 100 $\text{kJ mol}^{-1}$
E. 150 $\text{kJ mol}^{-1}$	F. 200 $\text{kJ mol}^{-1}$	G. 300 $\text{kJ mol}^{-1}$	H. 400 $\text{kJ mol}^{-1}$



## Part B

The adsorbed hydrogen atoms are then either absorbed into the bulk, or recombine and desorb back into the gas phase, as shown in the reactions (1a) and (1b). H(ab) represents a hydrogen atom absorbed in the bulk.



The reaction rates per surface site for adsorption, desorption, and absorption are  $r_1[\text{s}^{-1}]$ ,  $r_2[\text{s}^{-1}]$  and  $r_3[\text{s}^{-1}]$ , respectively. They are expressed as:

$$r_1 = k_1 P_{\text{H}_2} (1 - \theta)^2 \quad (2)$$

$$r_2 = k_2 \theta^2 \quad (3)$$

$$r_3 = k_3 \theta \quad (4)$$

where  $k_1 [\text{s}^{-1} \text{Pa}^{-1}]$ ,  $k_2 [\text{s}^{-1}]$  and  $k_3 [\text{s}^{-1}]$  are the reaction rate constants and  $P_{\text{H}_2}$  is the pressure of  $\text{H}_2$ . Among the sites available on the surface,  $\theta$  ( $0 \leq \theta \leq 1$ ) is the fraction occupied by H atoms. It is assumed that adsorption and desorption are fast compared to absorption ( $r_1, r_2 \gg r_3$ ) and that  $\theta$  remains constant.

**B.1**  $r_3$  can be expressed as:

5pt

$$r_3 = \frac{k_3}{1 + \sqrt{\frac{1}{P_{\text{H}_2} C}}} \quad (5)$$

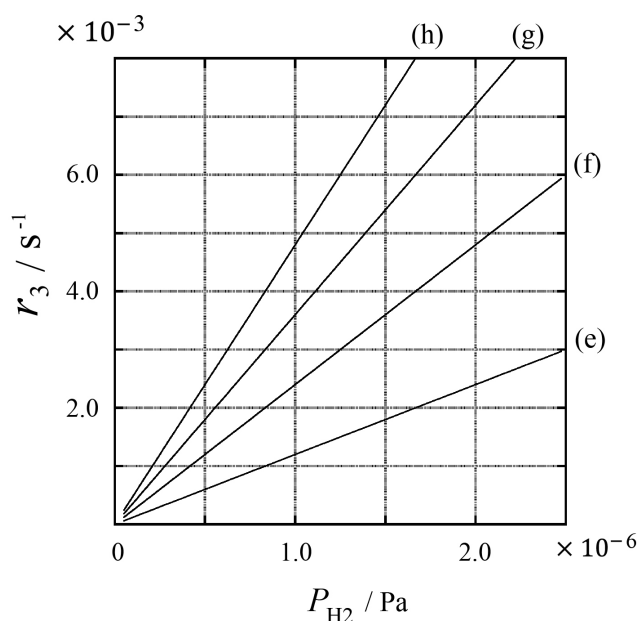
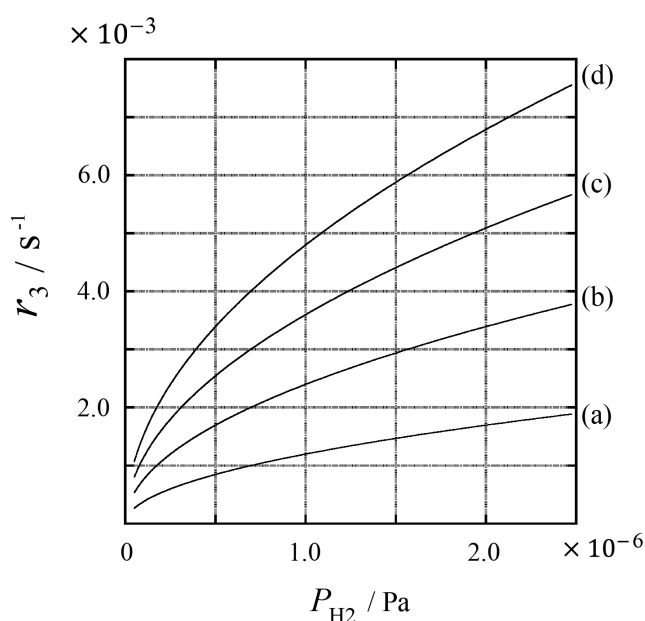
**EXPRESS**  $C$  using  $k_1$  and  $k_2$ .

A metal sample with a surface area of  $S = 1.0 \times 10^{-3} \text{ m}^2$  was placed in a container ( $1\text{L} = 1.0 \times 10^{-3} \text{ m}^3$ ) with  $\text{H}_2$  ( $P_{\text{H}_2} = 1.0 \times 10^2 \text{ Pa}$ ). The density of hydrogen-atom adsorption sites on the surface was  $N = 1.3 \times 10^{18} \text{ m}^{-2}$ . The surface temperature was kept at  $T = 400 \text{ K}$ . As the reaction (1) proceeded,  $P_{\text{H}_2}$  decreased at a constant rate of  $v = 4.0 \times 10^{-4} \text{ Pa s}^{-1}$ . Assume that  $\text{H}_2$  is an ideal gas and that the volume of the metal sample is negligible.

**B.2** **CALCULATE** the amount of H atoms in moles absorbed per unit area of the surface per unit time,  $A$  [ $\text{mol s}^{-1} \text{ m}^{-2}$ ]. 3pt

**B.3** At  $T = 400 \text{ K}$ ,  $C$  equals  $1.0 \times 10^2 \text{ Pa}^{-1}$ . **CALCULATE** the value of  $k_3$  at  $400 \text{ K}$ . (If you did not obtain the answer to **B.2**, use  $A = 3.6 \times 10^{-7} \text{ mol s}^{-1} \text{ m}^{-2}$ .) 3pt

**B.4** At a different temperature,  $C = 2.5 \times 10^3 \text{ Pa}^{-1}$  and  $k_3 = 4.8 \times 10^{-2} \text{ s}^{-1}$ . For  $r_3$  as a function of  $P_{\text{H}_2}$  at this temperature, **SELECT** the correct curve from (a)–(h). 3pt





USA-2 C-1 A-1

**A1-1**  
USA (United States of America)

## Hydrogen at a Metal Surface

### Part A

**A.1** (6 pt)

(i)	(ii)	(iii)

**A.2** (4 pt)

(i)	(ii)



USA-2 C-1 A-2

# A1-2

USA (United States of America)

## Part B

**B.1** (5 pt)

$C =$  \_\_\_\_\_

**B.2** (3 pt)

$A =$  \_\_\_\_\_  $\text{mol s}^{-1} \text{m}^{-2}$



USA-2 C-1 A-3

# A1-3

USA (United States of America)

**B.3** (3 pt)

$k_3 =$  \_\_\_\_\_  $s^{-1}$

**B.4** (3 pt)

\_\_\_\_\_

USA-2 C-2 C-1

**USA-2 C-2 C**  
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**ICHO**  
**Problem 2**  
**Cover sheet**

Please return this cover sheet together with all the related question sheets.

## Isotope Time Capsule

11 % of the total					
Question	A.1	A.2	A.3	A.4	Total
Points	8	8	10	9	<b>35</b>
Score					



Molecular entities that differ only in isotopic composition, such as  $\text{CH}_4$  and  $\text{CH}_3\text{D}$ , are called isotopologues.

Isotopologues are considered to have the same chemical characteristics. In nature, however, there are slight differences between isotopologues.

Assume that all of the substances shown in this Question are in the gas phase.

Let us consider the following equilibrium:



The entropy,  $S$ , increases as the number of possible microscopic states of a system,  $W$ , increases:

$$S = k_B \ln W \quad (2)$$

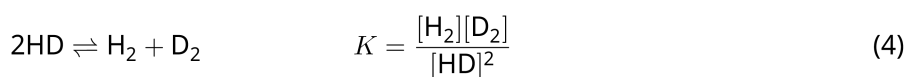
$W = 1$  for  $^{12}\text{C}^{16}\text{O}_2$  and  $^{12}\text{C}^{18}\text{O}_2$ . In contrast,  $W = 2$  for a  $^{12}\text{C}^{16}\text{O}^{18}\text{O}$  molecule because the oxygen atoms are distinguishable in this molecule. As the right-hand side of the equilibrium shown in equation 1 has two  $^{12}\text{C}^{16}\text{O}^{18}\text{O}$  molecules,  $W = 2^2 = 4$ .

- A.1** The enthalpy change,  $\Delta H$ , of equation 3 is positive regardless of the temperature. 8pt



**CALCULATE** the equilibrium constant,  $K$ , for equation 3 at very low temperature (think of  $T \rightarrow 0$ ) and again at very high temperature (think of  $T \rightarrow +\infty$ ). Assume that the reaction remains unchanged at these temperatures and that  $\Delta H$  converges to a constant value for high temperature.

$\Delta H$  of the following process can be explained by molecular vibrations.



At  $T = 0$  K, the vibrational energy of a diatomic molecule whose vibration frequency is  $\nu$  [ $\text{s}^{-1}$ ] is expressed as:

$$E = \frac{1}{2} h \nu \quad (5)$$

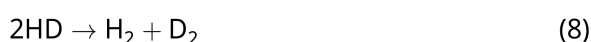
$$\nu = \frac{1}{2\pi} \sqrt{\frac{k}{\mu}} \quad (6)$$

In equation 6,  $k$  is the force constant and  $\mu$  is the reduced mass.

Reduced mass is expressed in terms of the mass of the two atoms in the diatomic molecule,  $m_1$  and  $m_2$ , according to:

$$\mu = \frac{m_1 m_2}{m_1 + m_2} \quad (7)$$

- A.2** The wavenumber corresponding to the vibration of  $\text{H}_2$  is  $4161.0 \text{ cm}^{-1}$ . **CALCULATE**  $\Delta H$  of the following equation at  $T = 0$  K in units of  $\text{J mol}^{-1}$ . 8pt



Assume that:

- only the vibrational energy contributes to  $\Delta H$ .
- the  $k$  values for  $\text{H}_2$ ,  $\text{HD}$ , and  $\text{D}_2$  are identical.
- the mass of H is 1 Da and the mass of D is 2 Da.





USA-2 C-2 Q-3

# Q2-3

USA (United States of America)

The molar ratio of  $\text{H}_2$ , HD, and  $\text{D}_2$  depends on the temperature in a system in equilibrium. Here,  $\Delta_{\text{D}_2}$  is defined as the change of the molar ratio of  $\text{D}_2$ .

$$\Delta_{\text{D}_2} = \frac{R_{\text{D}_2}}{R_{\text{D}_2}^*} - 1 \quad (9)$$

Here,  $R_{\text{D}_2}$  refers to  $\frac{[\text{D}_2]}{[\text{H}_2]}$  in the sample and  $R_{\text{D}_2}^*$  to  $\frac{[\text{D}_2]}{[\text{H}_2]}$  at  $T \rightarrow +\infty$ . Note that the distribution of isotopes becomes random at  $T \rightarrow +\infty$ .

**A.3**    **CALCULATE**  $\Delta_{\text{D}_2}$  with natural D abundance when the isotopic exchange is in equilibrium at the temperature where  $K$  (in equation 4) is 0.300. Assume that the natural abundance ratios of D and H are  $1.5576 \times 10^{-4}$  and  $(1 - 1.5576 \times 10^{-4})$ , respectively. 10pt

In general, the molar ratio of the doubly substituted isotopologue, which contains two heavy isotope atoms in one molecule, increases with decreasing temperature. Let us consider the molar ratio of  $\text{CO}_2$  molecules with molecular weights of 44 and 47, which are described as  $\text{CO}_2[44]$  and  $\text{CO}_2[47]$  below. The quantity  $\Delta_{47}$  is defined as:

$$\Delta_{47} = \frac{R_{47}}{R_{47}^*} - 1 \quad (10)$$

$R_{47}$  refers to  $\frac{[\text{CO}_2[47]]}{[\text{CO}_2[44]]}$  in the sample and  $R_{47}^*$  to  $\frac{[\text{CO}_2[47]]}{[\text{CO}_2[44]]}$  at  $T \rightarrow +\infty$ . The natural abundances of carbon and oxygen atoms are shown below; ignore isotopes that are not shown here.

	$^{12}\text{C}$	$^{13}\text{C}$
natural abundance	0.988888	0.011112

	$^{16}\text{O}$	$^{17}\text{O}$	$^{18}\text{O}$
natural abundance	0.997621	0.0003790	0.0020000

The temperature dependence of  $\Delta_{47}$  is determined as follows, where  $T$  is given as the absolute temperature in units of K:

$$\Delta_{47} = \frac{36.2}{T^2} + 2.920 \times 10^{-4} \quad (11)$$

- A.4** The  $R_{47}$  of fossil plankton obtained from the Antarctic seabed was  $4.50865 \times 10^{-5}$ . **CALCULATE** the approximate temperature using this  $R_{47}$ . This temperature is interpreted as the air temperature during the era in which the plankton lived. Consider only the most common isotopologue of  $\text{CO}_2[47]$  for the calculation. 9pt



USA-2 C-2 A-1

**A2-1**  
USA (United States of America)

## Isotope Time Capsule

**A.1** (8 pt)

$T \rightarrow 0 : K =$  \_\_\_\_\_ ,  $T \rightarrow +\infty : K =$  \_\_\_\_\_



USA-2 C-2 A-2

# A2-2

USA (United States of America)

**A.2** (8 pt)

$\Delta H =$  \_\_\_\_\_  $\text{J mol}^{-1}$



USA-2 C-2 A-3

# A2-3

USA (United States of America)

**A.3** (10 pt)

$\Delta_{D_2} =$  \_\_\_\_\_



USA-2 C-2 A-4

**A2-4**  
USA (United States of America)

**A.4** (9 pt)

$T =$  \_\_\_\_\_ K

USA-2 C-3 C-1

**USA-2 C-3 C**  
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**ICHO**  
**Problem 3**  
**Cover sheet**

Please return this cover sheet together with all the related question sheets.

## Lambert-Beer Law?

8 % of the total				
Question	A.1	B.1	B.2	Total
Points	10	6	6	22
Score				

In this problem, ignore the absorption of the cell and the solvent. The temperatures of all solutions and gases are kept constant at 25 °C.

### Part A

An aqueous solution **X** was prepared using HA and NaA. The concentrations  $[A^-]$ ,  $[HA]$ , and  $[H^+]$  in solution **X** are  $1.00 \times 10^{-2} \text{ mol L}^{-1}$ ,  $1.00 \times 10^{-3} \text{ mol L}^{-1}$ , and  $1.00 \times 10^{-4} \text{ mol L}^{-1}$ , respectively, which are correlated via the following acid-base equilibrium:



For part A, the optical path length is  $l$ . Ignore the density change upon dilution. Assume that no chemical reactions other than equation 1 occur.

- A.1** The absorbance of **X** was  $A_1$  at a wavelength of  $\lambda_1$ . Then, solution **X** was diluted to twice its initial volume using hydrochloric acid with pH = 2.500. After dilution, the absorbance was still  $A_1$  at  $\lambda_1$ . **DETERMINE** the ratio  $\varepsilon_{HA}/\varepsilon_{A^-}$ , where  $\varepsilon_{HA}$  and  $\varepsilon_{A^-}$  represent the absorption coefficients of HA and of  $A^-$ , respectively, at  $\lambda_1$ . 10pt

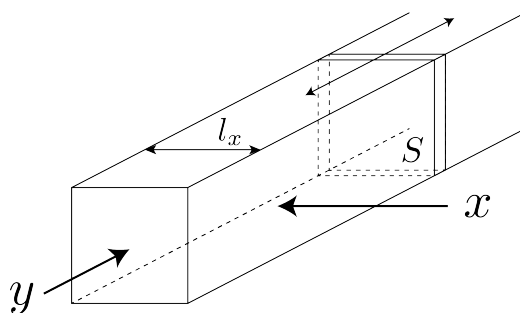


**Part B**

Let us consider the following equilibrium in the gas phase.



Pure gas D is filled into a cuboid container that has a transparent movable wall with a cross-section of  $S$  (see the figure below) at a pressure  $P$ . Equilibrium is established while the total pressure is kept at  $P$ . The absorbance of the gas is  $A = \varepsilon(n/V)l$ , where  $\varepsilon$  is the absorption coefficient,  $n$  is the amount of gas in moles,  $V$  is the volume of gas, and  $l$  is the optical path length. Assume that all components of the gas mixture behave as ideal gases.



Use the following definitions if necessary.

	Initial state		After equilibrium	
	D	M	D	M
Partial pressure	$P$	0	$p_D$	$p_M$
Amount in moles	$n_0$	0	$n_D$	$n_M$
Volume	$V_0$		$V$	

**B.1** The absorbance of the gas at  $\lambda_{B1}$  measured from direction  $x$  was  $A_{B1}$  both at the initial state ( $l = l_{x0}$ ) and after the equilibrium ( $l = l_x$ ). **DETERMINE** the ratio  $\varepsilon_D/\varepsilon_M$  at  $\lambda_{B1}$ , where  $\varepsilon_D$  and  $\varepsilon_M$  represent the absorption coefficients of D and M, respectively. 6pt

**B.2** The absorbance of the gas at  $\lambda_{B2}$  measured from direction  $y$  was  $A_{B2}$  both at the initial state ( $l = l_{y0}$ ) and after the equilibrium ( $l = l_y$ ). **DETERMINE** the ratio  $\varepsilon_D/\varepsilon_M$  at  $\lambda_{B2}$ . 6pt



USA-2 C-3 A-1

**A3-1**  
USA (United States of America)

## Lambert-Beer Law?

### Part A

**A.1** (10 pt)

(Continued on the next page)



USA-2 C-3 A-2

# A3-2

USA (United States of America)

A.1 (cont.)

$\varepsilon_{\text{HA}}/\varepsilon_{\text{A}^-} =$

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USA-2 C-3 A-3

# A3-3

USA (United States of America)

## Part B

**B.1** (6 pt)

$\epsilon_D/\epsilon_M =$  \_\_\_\_\_



USA-2 C-3 A-4

# A3-4

USA (United States of America)

**B.2** (6 pt)

$\varepsilon_D/\varepsilon_M =$  \_\_\_\_\_

USA-2 C-4 C-1

**USA-2 C-4 C**  
Nikhil Seshadri

**ICHO**  
**Problem 4**  
**Cover sheet**

Please return this cover sheet together with all the related question sheets.

## The Redox Chemistry of Zinc

11 % of the total							
Question	A.1	A.2	B.1	B.2	B.3	B.4	Total
Points	6	5	4	3	5	9	32
Score							



Zinc has long been used in alloys for brass and steel materials. The zinc contained in industrial wastewater is removed by precipitation to detoxify the water, and the precipitate obtained is reduced to recover and reuse it as metallic zinc.

### Part A

The dissolution equilibrium of zinc hydroxide  $\text{Zn}(\text{OH})_2(\text{s})$  at 25 °C and the relevant equilibrium constants are given in equations 1–4.



The solubility of zinc,  $S$ , (concentration of zinc in a saturated aqueous solution) is given in equation 5.

$$S = [\text{Zn}^{2+}(\text{aq})] + [\text{Zn}(\text{OH})_2(\text{aq})] + [\text{Zn}(\text{OH})_4^{2-}(\text{aq})] \quad (5)$$

**A.1** When the equilibria in equations 1–4 are established, **CALCULATE** the pH range in which  $[\text{Zn}(\text{OH})_2(\text{aq})]$  is the greatest among  $[\text{Zn}^{2+}(\text{aq})]$ ,  $[\text{Zn}(\text{OH})_2(\text{aq})]$  and  $[\text{Zn}(\text{OH})_4^{2-}(\text{aq})]$ . 6pt

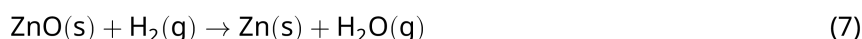
**A.2** A saturated aqueous solution of  $\text{Zn}(\text{OH})_2(\text{s})$  with pH = 7.00 was prepared and filtered. NaOH was added to this filtrate to increase its pH to 12.00. **CALCULATE** the mole percent of zinc that precipitates when increasing the pH from 7.00 to 12.00. Ignore the volume and temperature changes. 5pt

## Part B

Next, the recovered zinc hydroxide is heated to obtain zinc oxide according to the reaction below:



The zinc oxide is then reduced to metallic zinc by reaction with hydrogen:



**B.1** In order for reaction (7) to proceed at a constant hydrogen pressure of 1 bar, it is necessary to reduce the partial pressure of the generated water vapor. **CALCULATE** the upper limit for the partial pressure of water vapor to allow reaction (7) to proceed at 300 °C. The Gibbs formation energies of zinc oxide and water vapor at 300 °C and 1 bar for all gaseous species are  $\Delta G_{\text{ZnO}}(300^\circ\text{C}) = -2.90 \times 10^2 \text{ kJ mol}^{-1}$  and  $\Delta G_{\text{H}_2\text{O}}(300^\circ\text{C}) = -2.20 \times 10^2 \text{ kJ mol}^{-1}$ , respectively. 4pt

Metallic zinc is used as a negative electrode (anode) material for metal-air batteries. The electrode consists of Zn and ZnO. It uses the following redox reaction to generate electricity with the electromotive force (e.m.f.) at 25 °C and pressure of 1 bar,  $E^\circ$ .



**B.2** A zinc–air battery was discharged at 20 mA for 24 hours. **CALCULATE** the change in mass of the negative electrode (anode) in the battery. 3pt





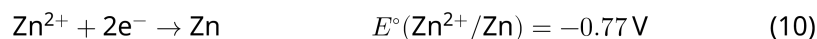
Mt. Fuji

- B.3** Consider the change of e.m.f. of a zinc–air battery depending on the environment. **CALCULATE** the e.m.f. at the summit of Mt. Fuji, where the temperature and altitude are  $-38^{\circ}\text{C}$  (February) and 3776 m, respectively. The atmospheric pressure is represented by equation 9 below at altitude  $h$  [m] and temperature  $T$  [ $^{\circ}\text{C}$ ]. 5pt

$$P [\text{bar}] = 1.013 \times \left( 1 - \frac{0.0065h}{T + 0.0065h + 273.15} \right)^{5.257} \quad (9)$$

The molar ratio of oxygen in the atmosphere is 21%. The Gibbs energy change of reaction (8) is  $\Delta G_{\text{ZnO}}(-38^{\circ}\text{C}) = -3.26 \times 10^2 \text{ kJ mol}^{-1}$  at  $-38^{\circ}\text{C}$  and 1 bar.

- B.4** **CALCULATE** the Gibbs energy change for reaction (6) at  $25^{\circ}\text{C}$ . Note that the standard reduction potentials,  $E^{\circ}(\text{Zn}^{2+}/\text{Zn})$  and  $E^{\circ}(\text{O}_2/\text{H}_2\text{O})$  at  $25^{\circ}\text{C}$  and 1 bar are given as (10) and (11), respectively. 9pt





USA-2 C-4 A-1

**A4-1**  
USA (United States of America)

## The Redox Chemistry of Zinc

### Part A

**A.1** (6 pt)

\_\_\_\_\_ < pH < \_\_\_\_\_



USA-2 C-4 A-2

**A4-2**  
USA (United States of America)

**A.2** (5 pt)

\_\_\_\_\_  
%



USA-2 C-4 A-3

# A4-3

USA (United States of America)

## Part B

**B.1** (4 pt)

$p_{\text{H}_2\text{O}} =$  \_\_\_\_\_ bar

**B.2** (3 pt)

\_\_\_\_\_ g



USA-2 C-4 A-4

**A4-4**  
USA (United States of America)

**B.3** (5 pt)

\_\_\_\_\_ V



USA-2 C-4 A-5

# A4-5

USA (United States of America)

**B.4** (9 pt)

$\Delta G^\circ =$  \_\_\_\_\_  $\text{J mol}^{-1}$

USA-2 C-5 C-1

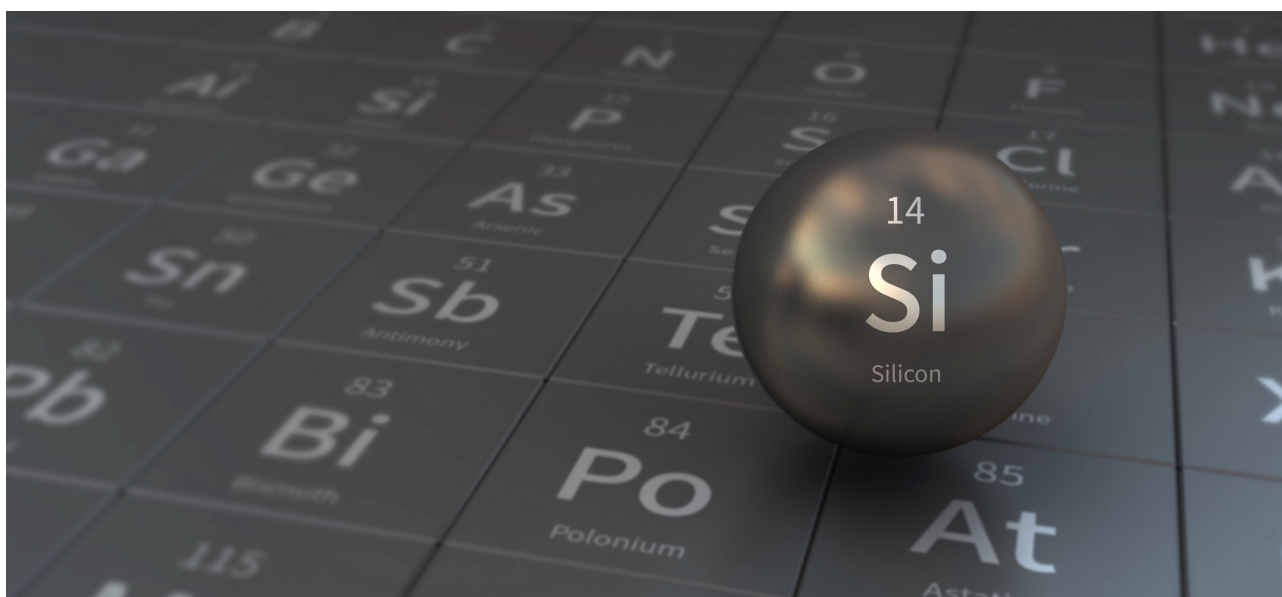
**USA-2 C-5 C**  
Nikhil Seshadri

**ICHO**  
**Problem 5**  
**Cover sheet**

Please return this cover sheet together with all the related question sheets.

## Mysterious Silicon

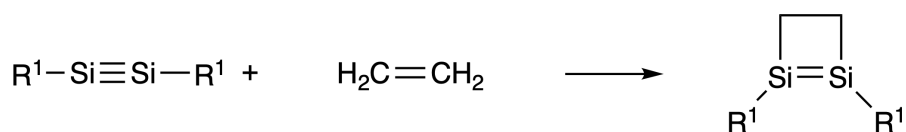
12 % of the total								
Question	A.1	A.2	A.3	A.4	B.1	B.2	B.3	Total
Points	9	7	6	10	5	15	8	60
Score								



Although silicon is also a group 14 element like carbon, their properties differ significantly.

### Part A

Unlike the carbon–carbon triple bond, the silicon–silicon triple bond in a written as  $R^1-Si \equiv Si-R^1$  (R: organic substituent), is extremely reactive. For example, it reacts with ethylene to form a cyclic product that contains a four-membered ring.



When  $R^1-Si \equiv Si-R^1$  is treated with an alkyne ( $R^2-C \equiv C-R^2$ ), the four-membered-ring compound **A** is formed as an initial intermediate. Further reaction of another molecule of  $R^2-C \equiv C-R^2$  with **A** affords isomers **B** and **C**, both of which have cyclic, benzene-like conjugated structures, so-called ‘disilabenzenes’ that contain a six-membered ring and can be written as  $(R^1-Si)_2(R^2-C)_4$ .





The  $^{13}\text{C}$  NMR analysis of the corresponding six-membered ring skeletons  $\text{Si}_2\text{C}_4$  shows two signals for **B** and one signal for **C**.

**A.1** **DRAW** the structures of **A**, **B**, and **C** using  $\text{R}^1$ ,  $\text{R}^2$ , Si, and C. (Only one resonance structure is needed, if applicable.) 9pt

**A.2** **CALCULATE** the aromatic stabilization energy (ASE) for benzene and compound **C** (where  $\text{R}^1 = \text{R}^2 = \text{H}$ ) as positive values. The enthalpy change of some hydrogenation reactions of unsaturated systems is shown below (Figure 1). 7pt

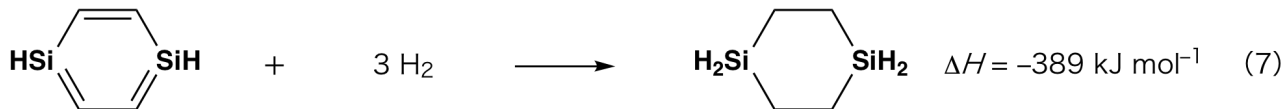
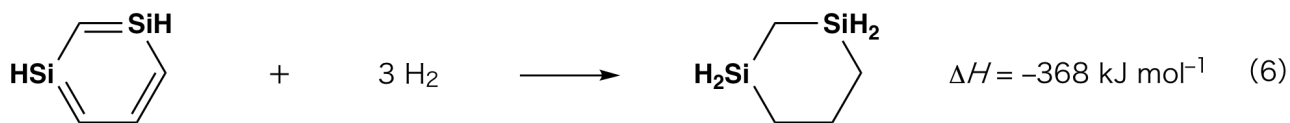
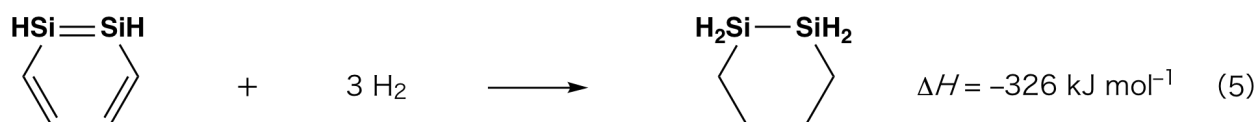
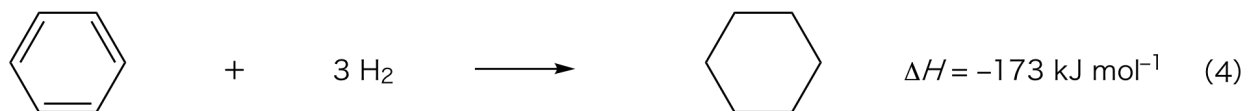
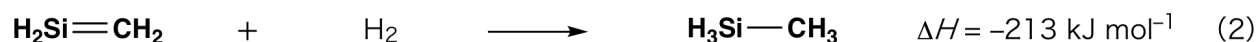


Figure 1.

When a xylene solution of **C** is heated, it undergoes isomerization to give an equilibrium mixture of compounds **D** and **E**. The mole ratio is **D** : **E** = 1 : 40.0 at 50.0 °C, and **D** : **E** = 1 : 20.0 at 120.0 °C.

**A.3 CALCULATE**  $\Delta H$  for the transformation of **D** to **E**. Assume that  $\Delta H$  does not depend on temperature. 6pt

The isomerization from **C** to **D** and **D** to **E** proceeds via transformations of  $\pi$ -bonds into  $\sigma$ -bonds without breaking any  $\sigma$ -bonds. A  $^{13}\text{C}$  NMR analysis revealed one signal for the  $\text{Si}_2\text{C}_4$  skeleton of **D** and two signals for that of **E**. The skeleton of **D** does not contain any three-membered rings, while **E** has two three-membered rings that share an edge.

**A.4 DRAW** the structures of **D** and **E** using  $\text{R}^1$ ,  $\text{R}^2$ , Si, and C. 10pt

## Part B

Silicon is able to form highly coordinated compounds (> four substituents) with electronegative elements such as fluorine. Metal fluorides are often used as fluorination reagents and highly coordinated silicon fluorides also act as fluorination reagents.

The fluorination reaction of  $\text{CCl}_4$  using  $\text{Na}_2\text{SiF}_6$  was carried out as follows.

### Standardization of $\text{Na}_2\text{SiF}_6$ solution :

#### Preparation

- Aqueous solution **F**: 0.855 g of  $\text{Na}_2\text{SiF}_6$  ( $188.053 \text{ g mol}^{-1}$ ) dissolved in water (total volume: 200 mL).
- Aqueous solution **G**: 6.86 g of  $\text{Ce}_2(\text{SO}_4)_3$  ( $568.424 \text{ g mol}^{-1}$ ) dissolved in water (total volume: 200 mL).

#### Procedure

- Precipitation titration of a solution **F** (50.0 mL) by dropwise adding solution **G** in the presence of xylene orange, which coordinates to  $\text{Ce}^{3+}$ , as an indicator. After adding 18.8 mL of solution **G**, the color of the solution changes from yellow to magenta. The generated precipitate is a binary compound that contains  $\text{Ce}^{3+}$ , and the only resulting silicon compound is  $\text{Si}(\text{OH})_4$ .

**B.1 WRITE** the balanced equation for the reaction of  $\text{Na}_2\text{SiF}_6$  with  $\text{Ce}_2(\text{SO}_4)_3$ . 5pt

### Reaction of $\text{CCl}_4$ with $\text{Na}_2\text{SiF}_6$ :

(Substance losses, e.g. by evaporation, are negligible during the following steps.)

- $\text{Na}_2\text{SiF}_6$  ( $x \text{ [g]}$ ) was added to  $\text{CCl}_4$  (500.0 g) and heated to 300 °C in a sealed, pressure-resistant reaction vessel. The unreacted  $\text{Na}_2\text{SiF}_6$  and generated  $\text{NaCl}$  were removed by filtration. The filtrate was diluted to a total volume of 1.00 L with  $\text{CCl}_4$  (solution **H**). The  $^{29}\text{Si}$  and  $^{19}\text{F}$  NMR spectra of solution **H** showed  $\text{SiF}_4$  as the only silicon compound. In the  $^{19}\text{F}$  NMR spectrum, in addition to  $\text{SiF}_4$ , signals corresponding to  $\text{CFCl}_3$ ,  $\text{CF}_2\text{Cl}_2$ ,  $\text{CF}_3\text{Cl}$ , and  $\text{CF}_4$  were observed (cf. Table 1). The integration ratios in the  $^{19}\text{F}$  NMR spectrum are proportional to the number of fluorine nuclei.

Table 1

$^{19}\text{F}$ NMR data	$\text{CFCl}_3$	$\text{CF}_2\text{Cl}_2$	$\text{CF}_3\text{Cl}$	$\text{CF}_4$
Integration ratio	45.0	65.0	18.0	2.0

$\text{SiF}_4$  is hydrolyzed to form  $\text{H}_2\text{SiF}_6$  according to the following equation:



- Solution **H** (10 mL) was added to an excess amount of water, which resulted in the complete hydrolysis of  $\text{SiF}_4$ . After separation, the  $\text{H}_2\text{SiF}_6$  generated from the hydrolysis in the aqueous solution was neutralized and completely converted to  $\text{Na}_2\text{SiF}_6$  (aqueous solution **J**).
- The precipitate of unreacted  $\text{Na}_2\text{SiF}_6$  and  $\text{NaCl}$ , which was removed by filtration in the initial step (underlined above), was completely dissolved in water to give an aqueous solution (solution **K**; 10.0 L).
- Then, additional precipitation titrations using solution **G** were carried out. The entire amount of solution **J** required 61.6 mL of titrant to reach the endpoint. Separately, 100 mL of solution **K** used 44.4 mL of titrant to reach the endpoint. It should be noted here that the coexistence of  $\text{NaCl}$  or  $\text{SiO}_2$  has no effect on the precipitation titration.

**B.2**    **CALCULATE** the mass of the  $\text{NaCl}$  produced in the reaction vessel (underlined above), and **CALCULATE** the mass ( $x$  [g]) of the  $\text{Na}_2\text{SiF}_6$  used as a starting material.    15pt

**B.3**    77.8% of the  $\text{CCl}_4$  used as a starting material was unreacted. **CALCULATE** the mass of  $\text{CF}_3\text{Cl}$  generated.    8pt



USA-2 C-5 A-1

**A5-1**  
USA (United States of America)

## Mysterious Silicon

### Part A

**A.1** (9 pt)

**A** (3 pt)

**B** (3 pt)

**C** (3 pt)

**A.2** (7 pt)

$\text{C}_6\text{H}_6$  :  $\text{kJ mol}^{-1}$ , **C** :  $\text{kJ mol}^{-1}$



USA-2 C-5 A-2

**A5-2**  
USA (United States of America)

**A.3** (6 pt)

$\Delta H =$  \_\_\_\_\_  $\text{kJ mol}^{-1}$

**A.4** (10 pt)

**D** (5 pt)

**E** (5 pt)



USA-2 C-5 A-3

**A5-3**  
USA (United States of America)

**Part B**

**B.1** (5 pt)

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**B.2** (15 pt)

(Continued on the next page)



USA-2 C-5 A-4

**A5-4**  
USA (United States of America)

**B.2 (cont.)**

NaCl : \_\_\_\_\_ g, Na<sub>2</sub>SiF<sub>6</sub> : \_\_\_\_\_ g



USA-2 C-5 A-5

**A5-5**  
USA (United States of America)

**B.3** (8 pt)

$\text{CF}_3\text{Cl}$  : \_\_\_\_\_ g



USA-2 C-6 C-1

**USA-2 C-6 C**  
Nikhil Seshadri

**IChO**  
**Problem 6**  
**Cover sheet**

Please return this cover sheet together with all the related question sheets.

## The Solid-State Chemistry of Transition Metals

13 % of the total											
Question	A.1	A.2	A.3	B.1	B.2	B.3	B.4	C.1	C.2	C.3	Total
Points	6	3	3	6	4	4	4	5	5	5	<b>45</b>
Score											



Volcano at Sakurajima island

### Part A

Japan is one of the countries with the largest number of volcanos worldwide. When silicate minerals crystallize from magma, some of the transition-metal ions ( $M^{n+}$ ) in the magma are incorporated into the silicate minerals. The  $M^{n+}$  studied in this problem are coordinated by oxide ions ( $O^{2-}$ ) and adopt a four-coordinate tetrahedral ( $T_d$ ) geometry in the magma. In the silicate minerals, the ions form six-coordinate octahedral ( $O_h$ ) geometry. Both types of complexes exhibit a high-spin electron configuration. The distribution coefficient of  $M^{n+}$  between the silicate minerals and magma,  $D$ , can be expressed by:

$$D = \frac{[M]_s}{[M]_l}$$

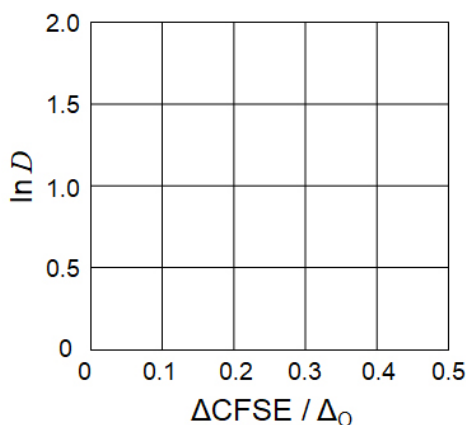
where  $[M]_s$  and  $[M]_l$  are the concentrations of  $M^{n+}$  in the silicate minerals and the magma, respectively. The table below shows the  $D$  values of  $Cr^{2+}$  and  $Mn^{2+}$  as examples.

	$Cr^{2+}$	$Mn^{2+}$
$D$	7.2	1.1

$\Delta_O$  is the energy separation of the d-orbitals of  $M^{n+}$ , and  $CFSE^O$  is the crystal-field stabilization energy in a  $O_h$  field. Let  $\Delta_T$  and  $CFSE^T$  be those in a  $T_d$  field.

- A.1** **CALCULATE**  $\Delta CFSE$ , defined as  $|CFSE^O - CFSE^T|$  in terms of  $\Delta_O$  for  $Cr^{2+}$ ,  $Mn^{2+}$ , and  $Co^{2+}$ ; assume  $\Delta_T = 4/9\Delta_O$ . 6pt

- A.2** A linear relationship is observed by plotting  $\ln D$  against  $\Delta CFSE / \Delta_O$  in the Cartesian coordinate system shown below. **CALCULATE** the approximate value of  $D$  for  $Co^{2+}$ . 3pt



Metal oxides  $MO$  ( $M$ : Ca, Ti, V, Mn, or Co) crystallize in a rock-salt structure wherein the  $M^{n+}$  adopts an  $O_h$  geometry with a high-spin electron configuration. The lattice enthalpy of these oxides is primarily determined by the Coulombic interactions (due to the radius and charge of the ions) with some contribution from the CFSE of  $M^{n+}$  in the  $O_h$  field.

- A.3** **CHOOSE** the appropriate set of lattice enthalpies [ $\text{kJ mol}^{-1}$ ] from one of the options (a) to (f). 3pt

	CaO	TiO	VO	MnO	CoO
(a)	3460	3878	3913	3810	3916
(b)	3460	3916	3878	3810	3913
(c)	3460	3913	3916	3810	3878
(d)	3810	3878	3913	3460	3916
(e)	3810	3916	3878	3460	3913
(f)	3810	3913	3916	3460	3878

**Part B**

A mixed oxide **A**, containing  $\text{La}^{3+}$  and  $\text{Cu}^{2+}$ , crystallizes in a tetragonal unit cell shown in Figure 1. In the  $[\text{CuO}_6]$  octahedron, the Cu–O length along the z-axis ( $l_z$ ) is longer than that of the x-axis ( $l_x$ ), and  $[\text{CuO}_6]$  is distorted from the regular  $O_h$  geometry. This distortion removes the degeneracy of the  $e_g$  orbitals ( $d_{x^2-y^2}$  and  $d_{z^2}$ ).

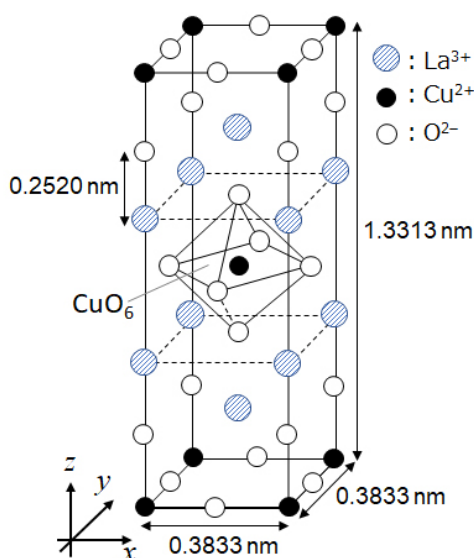


Figure 1.

**A** can be synthesized by thermal decomposition (pyrolysis) of complex **B**, which is formed by mixing metal chlorides in dilute aqueous ammonia solution containing squaric acid ( $\text{C}_4\text{H}_2\text{O}_4$ ), a diacid. Upon pyrolysis in dry air to 200 °C, **B** loses 29.1% of its mass due to the loss of crystallization water. Another weight loss is observed when heating is continued to 700 °C due to the release of  $\text{CO}_2$ . The total weight loss during the formation of **A** from **B** is 63.6%. It should be noted that only water and  $\text{CO}_2$  are released in the pyrolysis reaction.

**B.1** **WRITE** the chemical formula for **A** and **B**.

6pt

**B.2** **CALCULATE**  $l_x$  and  $l_z$  using Figure 1.

4pt

**B.3** For  $\text{Cu}^{2+}$  in the distorted  $[\text{CuO}_6]$  octahedron in **A** of Figure 1, **WRITE** the names of the split  $e_g$  orbitals ( $d_{x^2-y^2}$  and  $d_{z^2}$ ) on lines (i) and (ii), and **PLACE** electrons on the energy diagram in the dotted box on your answer sheet.

4pt

**A** is an insulator. One hole is generated in the crystal lattice of **A** when one  $\text{La}^{3+}$  is substituted with one  $\text{Sr}^{2+}$ . As a result, the  $\text{Sr}^{2+}$ -doped **A** conducts electricity and shows superconductivity below 38 K. When the substitution described takes place in **A**,  $2.05 \times 10^{27}$  holes  $\text{m}^{-3}$  were generated.

**B.4** **CALCULATE** the percentage of  $\text{Sr}^{2+}$  substituted for  $\text{La}^{3+}$  based on the mole ratio in the substitution. Note that the valencies of the constituent ions and the crystal structure are not altered by the substitution. 4pt

### Part C

$\text{Cu}_2(\text{CH}_3\text{CO}_2)_4$  is composed of four  $\text{CH}_3\text{CO}_2^-$  coordinated to two  $\text{Cu}^{2+}$  (Figure 2A).  $\text{Cu}_2(\text{CH}_3\text{CO}_2)_4$  exhibits high levels of structural symmetry, with two axes passing through the carbon atoms of the four  $\text{CH}_3\text{CO}_2^-$  and an axis passing through the two  $\text{Cu}^{2+}$ , all of which are oriented orthogonal relative to each other. When a dicarboxylate ligand is used instead of  $\text{CH}_3\text{CO}_2^-$ , a “cage complex” is formed. The cage complex  $\text{Cu}_4(\text{L1})_4$  is composed of planar dicarboxylate **L1** (Figure 2B) and  $\text{Cu}^{2+}$  (Figure 2C). The structure of the cage complex is determined by the angle  $\theta$  between the coordination directions of the two carboxylates, indicated by the arrows in Figure 2B.  $\theta$  is  $0^\circ$  for **L1**. Hydrogen atoms are not shown in Figure 2.

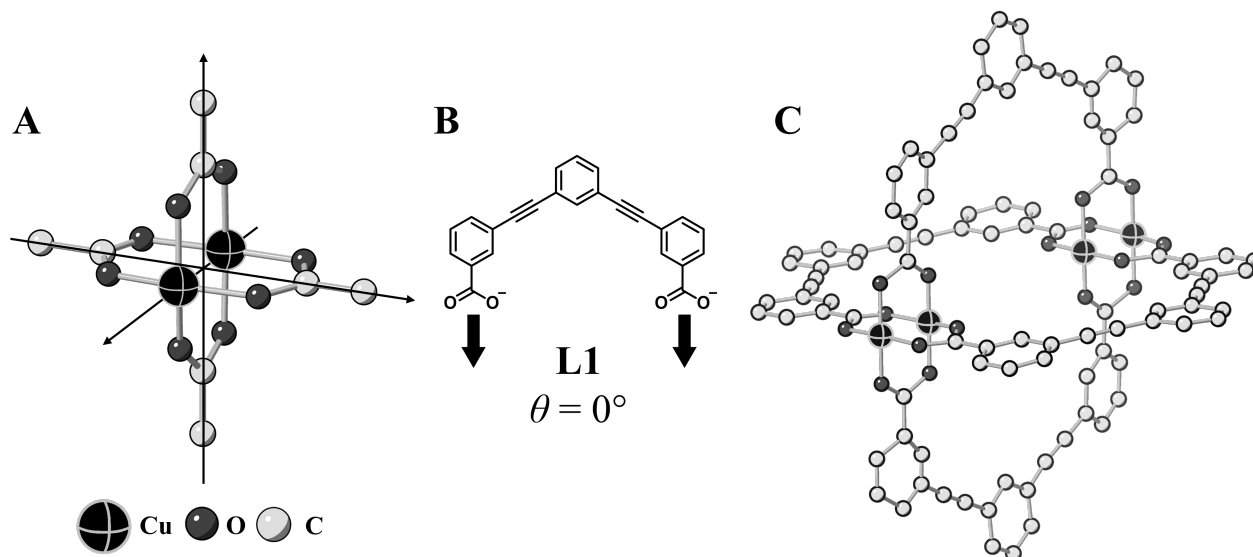
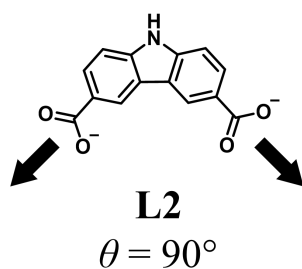


Figure 2.

- C.1** The  $\theta$  of the planar dicarboxylate **L2** below is fixed to  $90^\circ$ . If the composition of the cage complex formed from **L2** and  $\text{Cu}^{2+}$  is  $\text{Cu}_n(\text{L2})_m$ , **GIVE** the smallest integer combination of  $n$  and  $m$ . Assume that only the  $\text{CO}_2^-$  groups of **L2** coordinate to  $\text{Cu}^{2+}$  ions. 5pt



A zinc complex,  $\text{Zn}_4\text{O}(\text{CH}_3\text{CO}_2)_6$ , contains four tetrahedral  $\text{Zn}^{2+}$ , six  $\text{CH}_3\text{CO}_2^-$ , and one  $\text{O}^{2-}$  (Figure 3A). In  $\text{Zn}_4\text{O}(\text{CH}_3\text{CO}_2)_6$ , the  $\text{O}^{2-}$  is located at the origin, and the three axes passing through the carbon atoms of  $\text{CH}_3\text{CO}_2^-$  are oriented orthogonal relative to each other. When *p*-benzenedicarboxylate (Figure 3B, **L3**,  $\theta = 180^\circ$ ) is used instead of  $\text{CH}_3\text{CO}_2^-$ , the  $\text{Zn}^{2+}$  clusters are linked to each other to form a crystalline solid (**X**) that is called a “porous coordination polymer” (Figure 3C). The composition of **X** is  $[\text{Zn}_4\text{O}(\text{L3})_3]_n$ , and it has a cubic crystal structure with nano-sized pores. One pore is represented as a sphere in Figure 3D, and each tetrahedral  $\text{Zn}^{2+}$  cluster is represented as a dark gray polyhedron in Figures 3C and 3D. Hydrogen atoms are not shown in Figure 3.

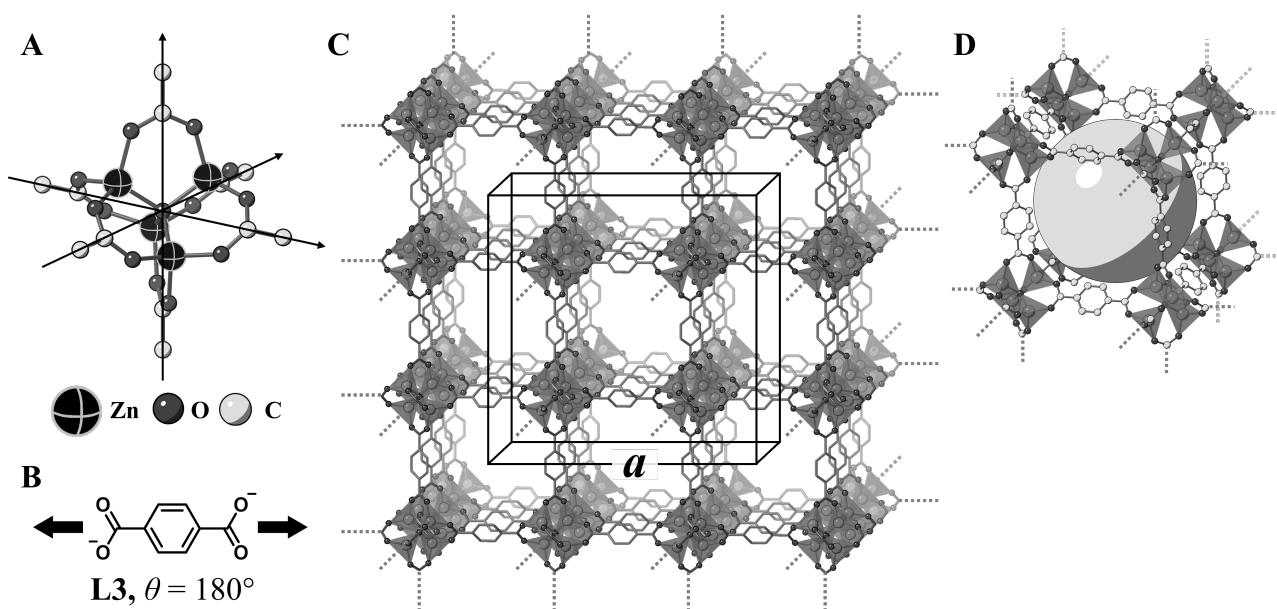


Figure 3.

**C.2** **X** has a cubic unit cell with a side length of  $a$  (Figure 3C) and a density of  $0.592 \text{ g cm}^{-3}$ . **CALCULATE**  $a$  in [cm]. 5pt

**C.3** **X** contains a considerable number of pores, and 1 g of **X** can accommodate  $3.0 \times 10^2 \text{ mL}$  of  $\text{CO}_2$  gas in the pores at 1 bar and  $25^\circ\text{C}$ . **CALCULATE** the average number of  $\text{CO}_2$  molecules per pore. 5pt



USA-2 C-6 A-1

**A6-1**  
USA (United States of America)

## The Solid-State Chemistry of Transition Metals

### Part A

**A.1** (6 pt)

$\text{Cr}^{2+}$  : \_\_\_\_\_  $\Delta_o$ ,  $\text{Mn}^{2+}$  : \_\_\_\_\_  $\Delta_o$ ,  $\text{Co}^{2+}$  : \_\_\_\_\_  $\Delta_o$



**A.2** (3 pt)



$D$  : \_\_\_\_\_

**A.3** (3 pt)

\_\_\_\_\_



USA-2 C-6 A-3

# A6-3

USA (United States of America)

## Part B

**B.1** (6 pt)

A : \_\_\_\_\_, B : \_\_\_\_\_

**B.2** (4 pt)

$l_x =$  \_\_\_\_\_ nm,  $l_z =$  \_\_\_\_\_ nm

**B.3** (4 pt)

(i) : \_\_\_\_\_, (ii) : \_\_\_\_\_



**B.4** (4 pt)

\_\_\_\_\_ %



USA-2 C-6 A-5

# A6-5

USA (United States of America)

## Part C

**C.1** (5 pt)

$n =$  \_\_\_\_\_,  $m =$  \_\_\_\_\_

**C.2** (5 pt)

$a =$  \_\_\_\_\_ cm



USA-2 C-6 A-6

# A6-6

USA (United States of America)

**C.3** (5 pt)

\_\_\_\_\_

USA-2 C-7 C-1

**USA-2 C-7 C**  
Nikhil Seshadri

**IChO**  
**Problem 7**  
**Cover sheet**

Please return this cover sheet together with all the related question sheets.

## Playing with Non-benzenoid Aromaticity

13 % of the total					
Question	A.1	A.2	A.3	B.1	Total
Points	5	2	19	10	<b>36</b>
Score					

Prof. Nozoe (1902–1996) started the research field of non-benzenoid aromatic compounds, which are now ubiquitous in organic chemistry.



Photo courtesy: Tohoku Univ.

### Part A

Lineariifolianone is a natural product with a unique structure that was first isolated from *Inula linariifolia*. From valencene (**1**), a one-step conversion gives compound **2**. A three-step conversion of **2**, via **3**, yields ketone **4**. Eremophilene (**5**) is converted into **6** by performing the same four-step conversion.



*Inula linariifolia*



**A.1** **DRAW** the structures of **2** and **6** and clearly identify the stereochemistry where necessary. 5pt





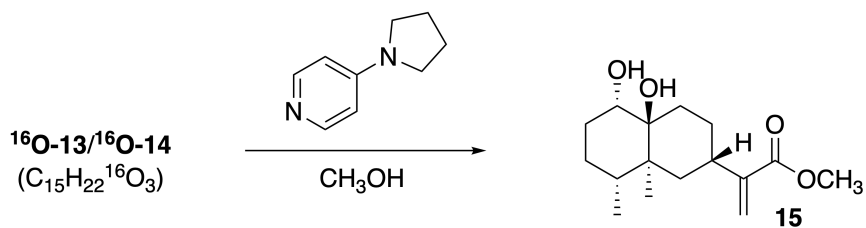
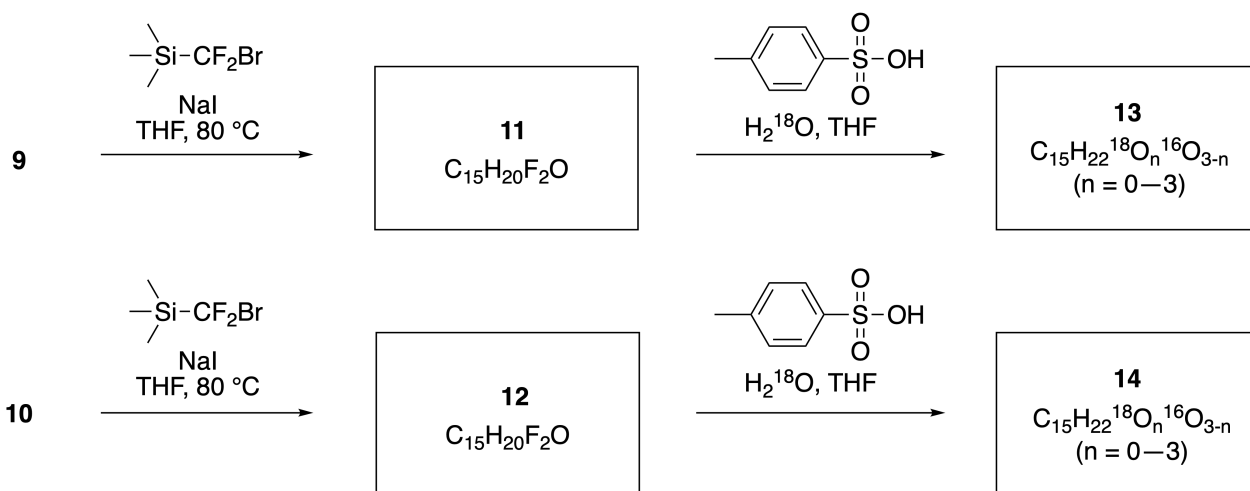
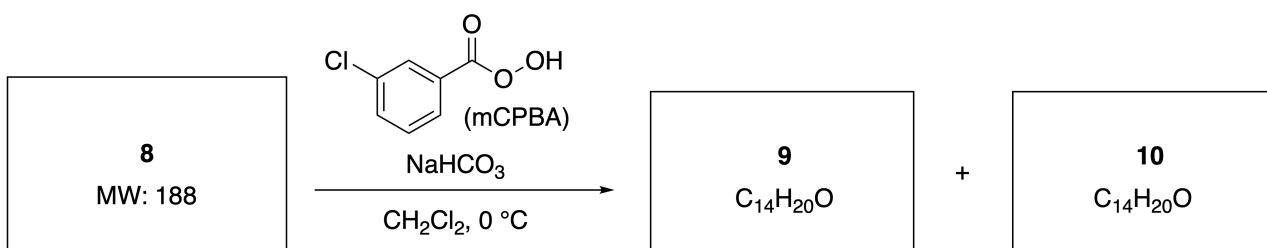
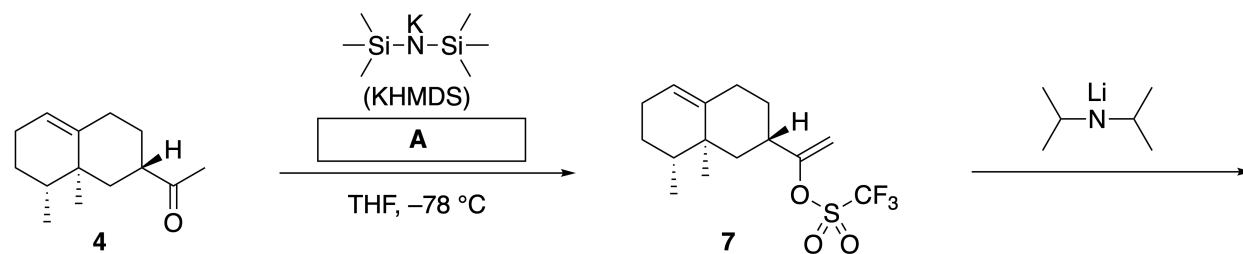
USA-2 C-7 Q-3

# Q7-3

USA (United States of America)

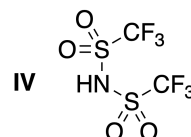
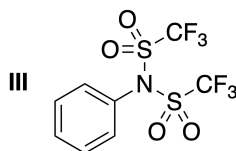
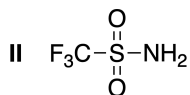
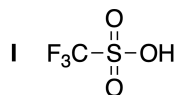
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Ketone **4** is ultimately converted into ester **15**. Compound **8** (molecular weight: 188) retains all the stereocenters in **7**. Compounds **9** and **10** have five stereocenters and no carbon-carbon double bonds. Assume that  $\text{H}_2^{18}\text{O}$  is used instead of  $\text{H}_2^{16}\text{O}$  for the synthesis of  $^{18}\text{O}$ -labelled-linearifolianones **13** and **14** from **11** and **12**, respectively. Compounds **13** and **14** are  $^{18}\text{O}$ -labelled isotopomers. Ignoring isotopic labelling, both **13** and **14** provide the same product **15** with identical stereochemistry.



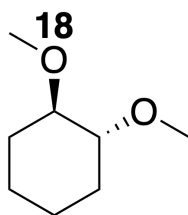
**A.2** **CHOOSE** the appropriate structure for reagent **A**.

2pt



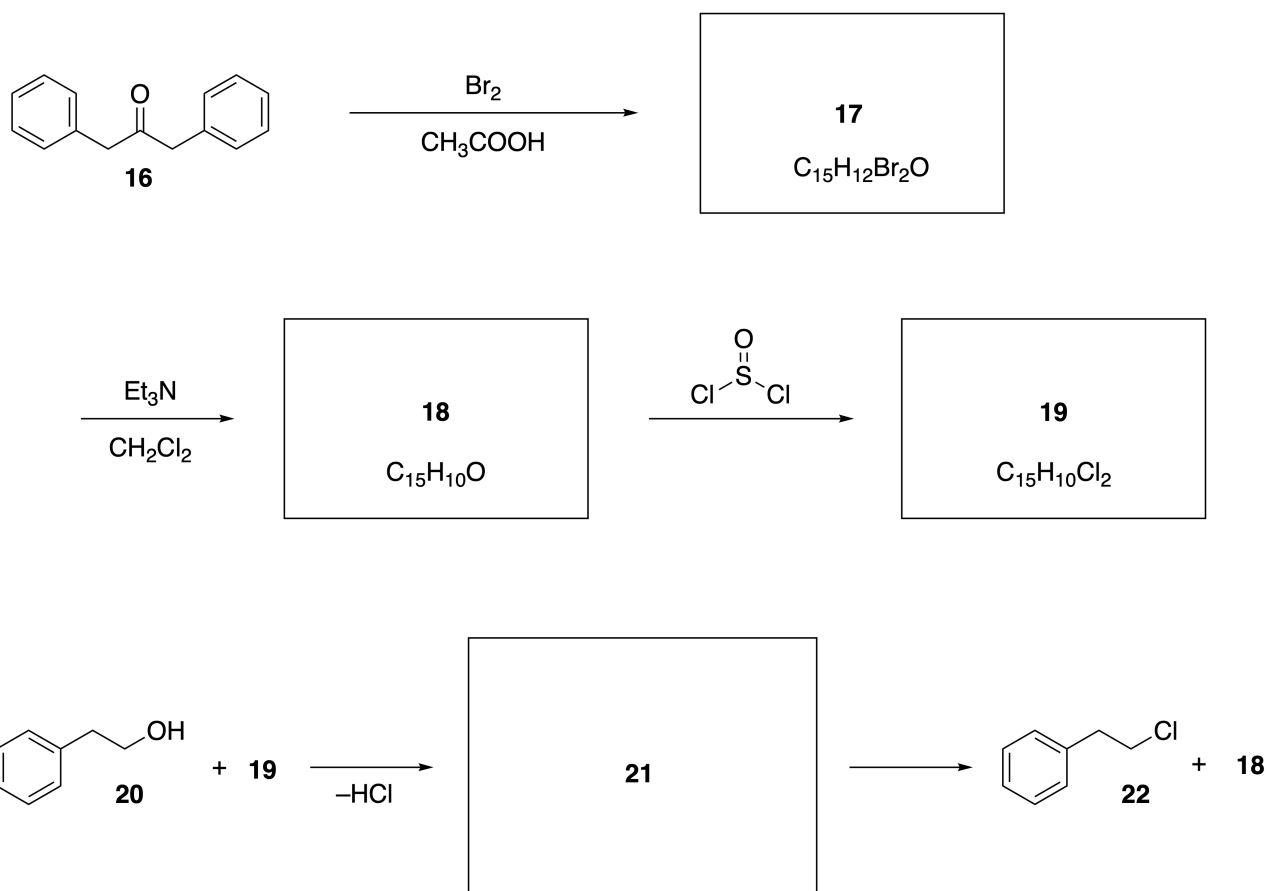
**A.3** **DRAW** the structures of **8–14** and clearly identify the stereochemistry where necessary. Also, **LABEL** the  $^{18}\text{O}$  atoms in compounds **13** and **14** using the notation shown below:

19pt



**Part B**

Compound **19** is synthesized as shown below. In relation to non-benzenoid aromaticity, **19** can be used as an activator for alcohols, and **20** was converted to **22** via the ion-pair intermediate **21**. Although the formation of **21** was observed by NMR, **21** gradually decomposes to give **18** and **22**.



$^1\text{H}$  NMR ( $\text{CD}_3\text{CN}$ , ppm) **20**:  $\delta$  7.4–7.2 (5H), 3.7 (2H), 2.8 (2H), 2.2 (1H)

**21**:  $\delta$  8.5–7.3 (15H), 5.5 (2H), 3.4 (2H)

**B.1** **DRAW** the structures of **17–19** and **21**. Ignore stereochemistry.

10pt



USA-2 C-7 A-1

**A7-1**  
USA (United States of America)

## Playing with Non-benzenoid Aromaticity

### Part A

**A.1** (5 pt)

**2** (2 pt)

**6** (3 pt)

**A.2** (2 pt)

**A.3** (19 pt)

**8** (3 pt)



**9** (2 pt)

**10** (2 pt)



**11** (2 pt)

**12** (2 pt)



**13** (4 pt)

**14** (4 pt)



USA-2 C-7 A-3

**A7-3**  
USA (United States of America)

**Part B**

**B.1** (10 pt)

**17** (2 pt)

**18** (2 pt)

**19** (3 pt)

**21** (3 pt)

USA-2 C-8 C-1

**USA-2 C-8 C**  
Nikhil Seshadri

**ICHO**  
**Problem 8**  
**Cover sheet**

Please return this cover sheet together with all the related question sheets.

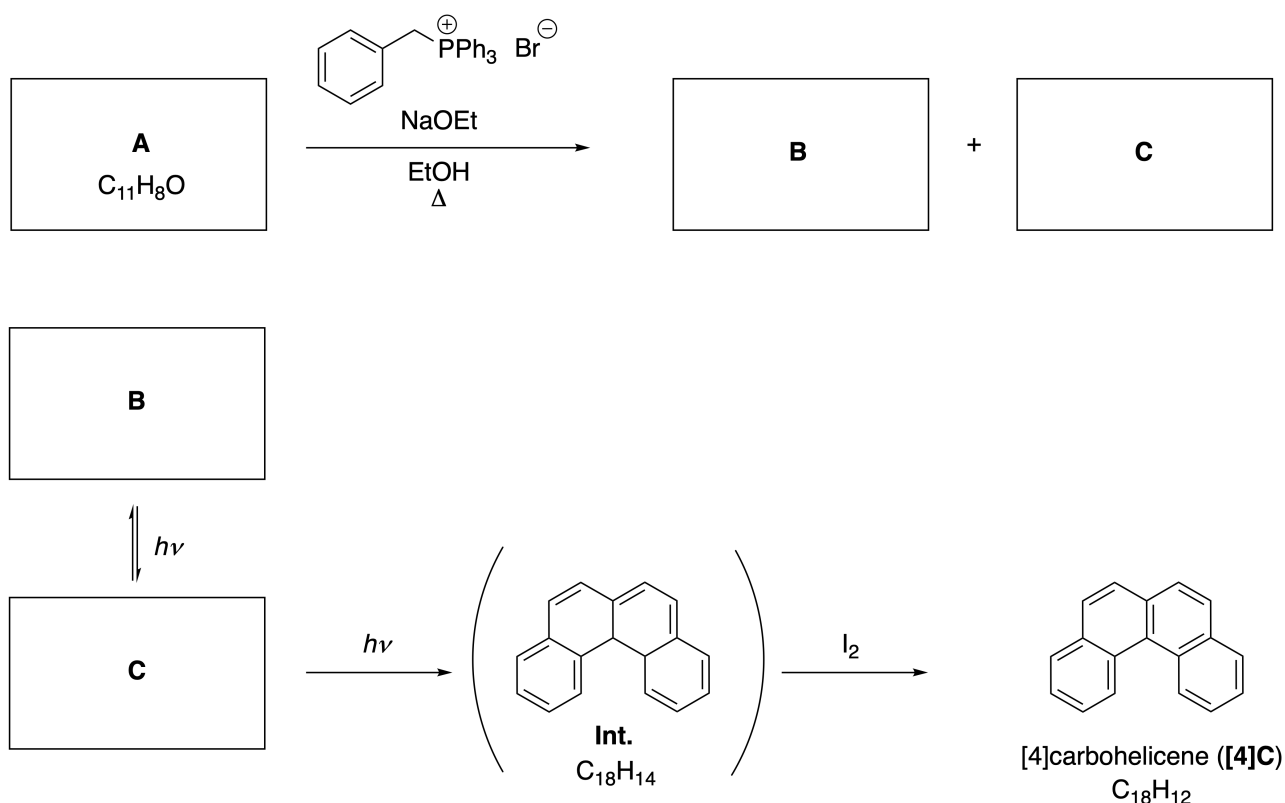


## Dynamic Organic Molecules and Their Chirality

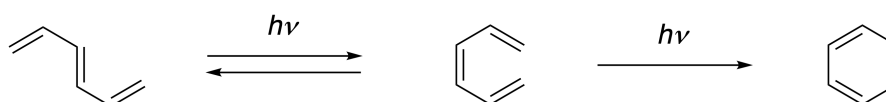
11 % of the total						
Question	A.1	A.2	A.3	B.1	B.2	Total
Points	9	3	7	3	4	<b>26</b>
Score						

### Part A

Polycyclic aromatic hydrocarbons with successive ortho-connections are called [n]carbohelicenes (n represents the number of six-membered rings; see below). [4]Carbohelicene (**[4]C**) is efficiently prepared according to the synthesis shown below. The key photochemical reaction proceeds via the intermediate (**Int.**) that is then easily oxidized by iodine.



The photochemical reaction proceeds in a manner similar to the following example.

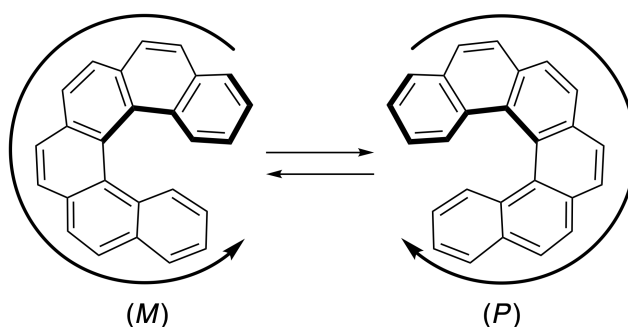


**Note:** For all of Question 8, please draw alternating single and double bonds in your answers to the problems as depicted in the examples of carbohelicene. Do not use circles for conjugated  $\pi$  systems.

**A.1** **DRAW** the structures of **A–C**. Stereoisomers should be distinguished. 9pt

**A.2** Attempts to synthesize [5]carbohelicene from the same phosphonium salt and an appropriate starting compound resulted in the formation of only a trace amount of [5]carbohelicene. Instead, product **D** whose molecular weight was 2 Da lower than that of [5]carbohelicene was isolated. The  $^1\text{H}$  NMR chemical shifts of **D** are listed below. **DRAW** the structure of **D**.  
[**D** ( $\delta$ , ppm in  $\text{CS}_2$ , r.t.), 8.85 (2H), 8.23 (2H), 8.07 (2H), 8.01 (2H), 7.97 (2H), 7.91 (2H)] 3pt

[5]- and larger [n]carbohelicenes have helical chirality and interconversion between enantiomers of these helicenes is very slow at room temperature. The chirality of [n]carbohelicenes is defined as (*M*) or (*P*) as shown below.



[n]Carbohelicenes with n larger than 4 can be enantiomerically separated by chiral column chromatography, which was developed by Prof. Yoshio Okamoto.

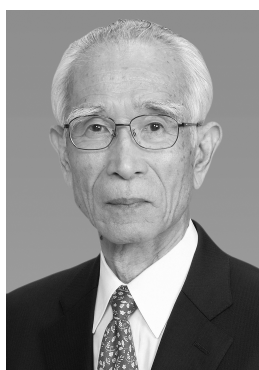
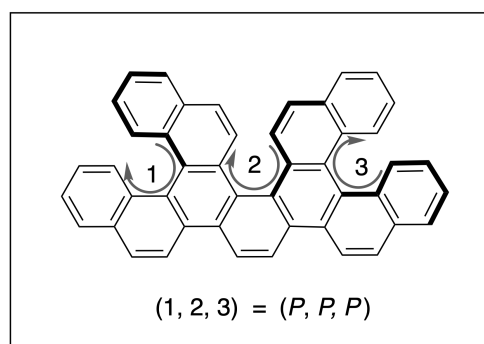
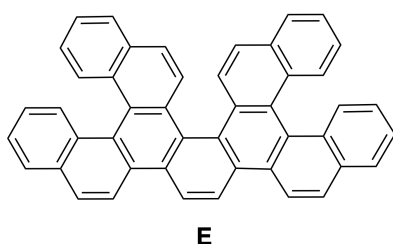
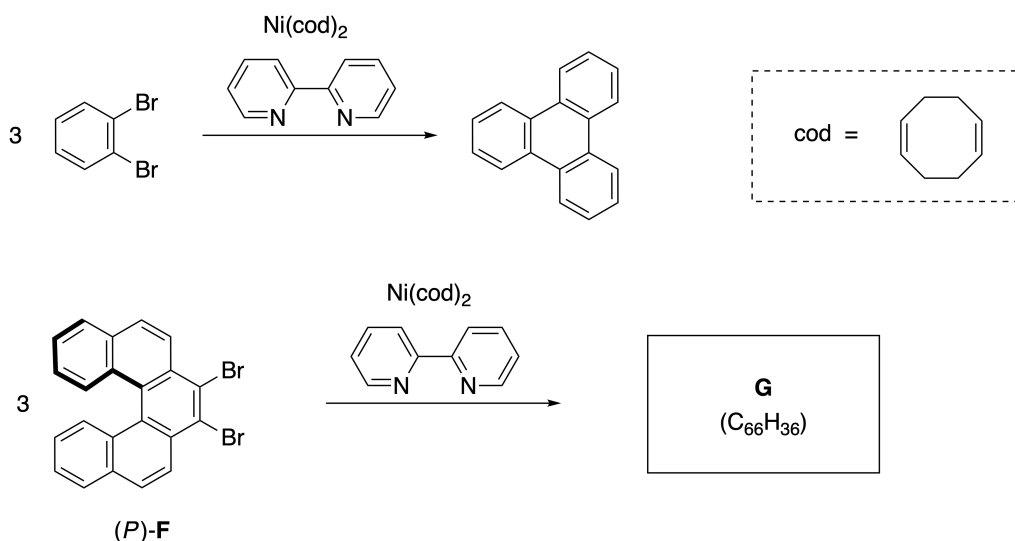


Photo courtesy: The Japan Prize Foundation

Multiple helicenes are molecules that contain two or more helicene-like structures. Considering helical chirality, several stereoisomers exist in a multiple helicene. For example, compound **E** contains three [5]carbohelicene-like moieties in one molecule. One of the stereoisomers is described as (*P*, *P*, *P*) and shown below.

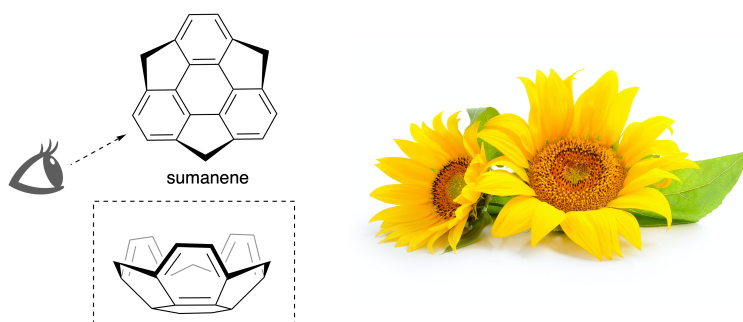


- A.3** The nickel-mediated trimerization of 1,2-dibromobenzene generates triphenylene. When the same reaction is applied to an enantiomer of **F**, (*P*)-**F**, multiple helicene **G** ( $C_{66}H_{36}$ ) is obtained. Interconversion between stereoisomers does not occur during the reaction. **DRAW** one possible stereoisomer of **G** with the chirality defined as in the example above, including numerical labels. **LIST ALL** remaining stereoisomers with location numbers and *M* and *P* labels according to the same numbering. For instance, the other stereoisomers of **E** would be listed as (1, 2, 3) = (*P*, *M*, *P*), (*P*, *M*, *M*), (*P*, *P*, *M*), (*M*, *M*, *M*), (*M*, *M*, *P*), (*M*, *P*, *P*), and (*M*, *P*, *M*). 7pt

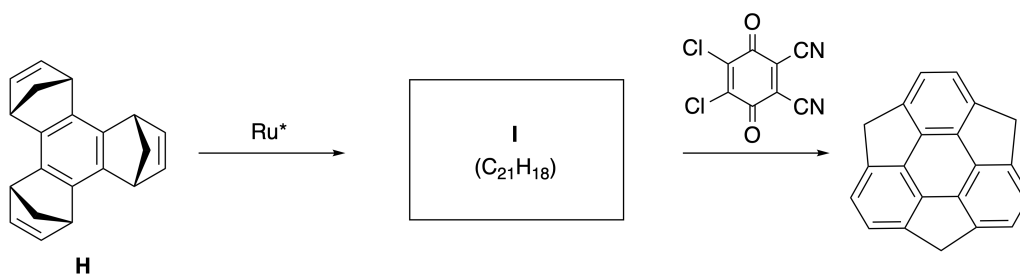
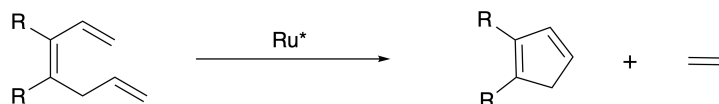
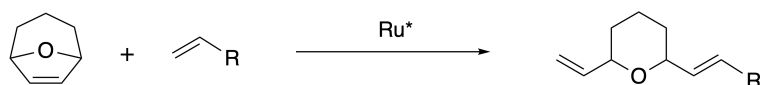


**Part B**

Sumanene is a bowl-shaped hydrocarbon that was first reported in Japan in 2003. The name "sumanene" comes from a Sanskrit-Hindi word "suman" that means sunflower. The synthesis of sumanene was originally completed by a reaction sequence consisting of a ring-opening and a ring-closing metathesis.

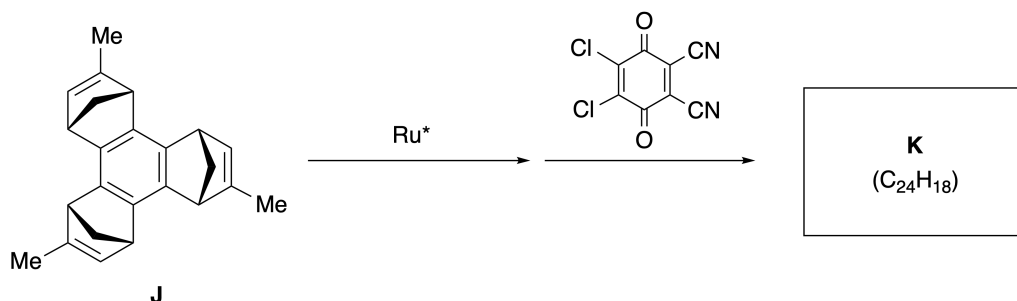


Representative metathesis reactions, catalyzed by a ruthenium catalyst ( $\text{Ru}^*$ ), are shown below.



**B.1** **DRAW** the structure of intermediate **I** (ignore stereochemistry).

3pt



- B.2** Starting with the optically active precursor **J**, the same reaction sequence gives the optically active sumanene derivative **K**. The stereocenters in **J** are unchanged during the metathesis reaction. **DRAW** the structure of **K** with appropriate stereochemistry. 4pt



USA-2 C-8 A-1

**A8-1**  
USA (United States of America)

## Dynamic Organic Molecules and Their Chirality

### Part A

**A.1** (9 pt)

**A** (3 pt)

**B** (3 pt)

**C** (3 pt)

**A.2** (3 pt)



USA-2 C-8 A-2

**A8-2**  
USA (United States of America)

**A.3** (7 pt)



USA-2 C-8 A-3

# A8-3

USA (United States of America)

## Part B

**B.1** (3 pt)

**B.2** (4 pt)



USA-2 C-9 C-1

**USA-2 C-9 C**  
Nikhil Seshadri

**ICHO**  
**Problem 9**  
**Cover sheet**

Please return this cover sheet together with all the related question sheets.

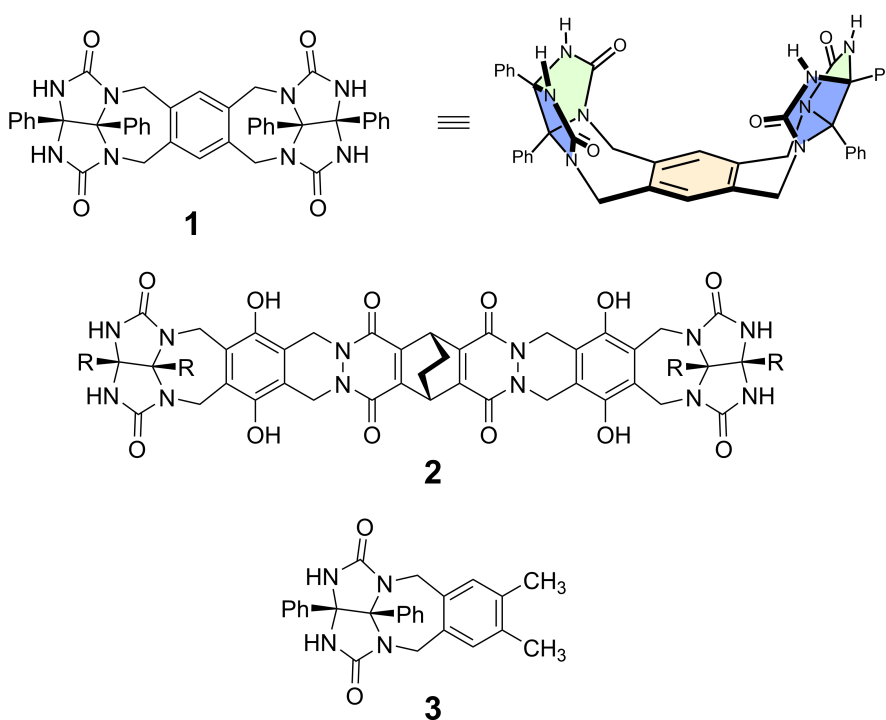
## Likes and Dislikes of Capsule

10 % of the total						
Question	A.1	A.2	A.3	A.4	A.5	Total
Points	13	2	2	3	3	<b>23</b>
Score						

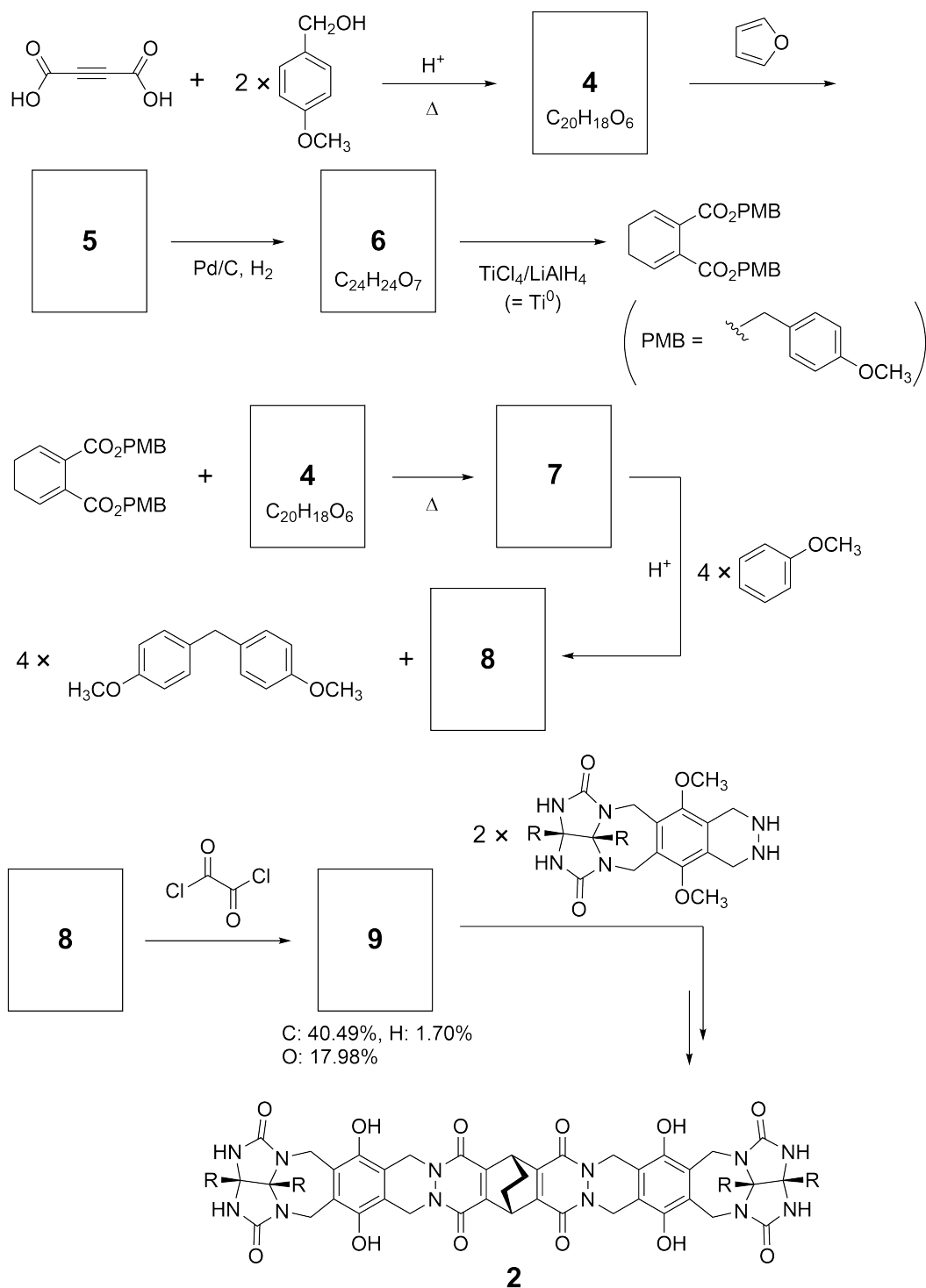
Good kids don't do this, but if you unseam a tennis ball, you can disassemble it into two U-shaped pieces.



Based on this idea, compounds **1** and **2** were synthesized as U-shaped molecules with different sizes. Compound **3** was prepared for comparison to **1**. The encapsulation behavior of these compounds was investigated.



The synthetic route to **2** is shown below. The composition of compound **9** by mass is C: 40.49%, H: 1.70%, and O: 17.98%.





USA-2 C-9 Q-3

# Q9-3

USA (United States of America)

- A.1** **DRAW** the structures of **4–9**; ignore stereochemistry. Use "PMB" as a substituent instead of drawing the whole structure of the *p*-methoxybenzyl group shown in the scheme above. 13pt

In the mass spectrum of **1**, the ion peak corresponding to its dimer ( $1_2$ ) was clearly observed, whereas an ion peak for  $3_2$  was not observed in the spectrum of **3**. In the  $^1\text{H}$  NMR spectra of a solution of  $1_2$ , all the NH protons were observed to be chemically equivalent. The chemical shift was significantly different from that of the NH protons of **3**. These data indicate that hydrogen bonds are formed between the NH groups of **1** and atoms **X** of another molecule of **1** to form the dimeric capsule.

- A.2** **CIRCLE** all the appropriate atom(s) **X** in compound **1**. 2pt

- A.3** **WRITE** the number of hydrogen bonds in the dimeric capsule ( $1_2$ ). 2pt

The dimeric capsule of **1** ( $1_2$ ) has an internal space where an appropriate small molecule Z can be encapsulated. This phenomenon is expressed by the following equation:

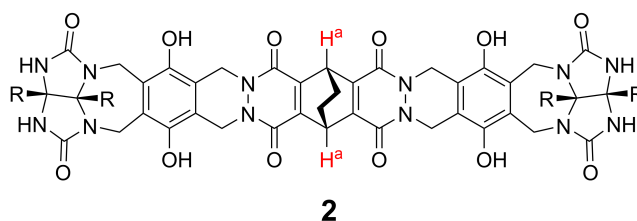


The equilibrium constant of the encapsulation of Z into  $1_2$  is given below:

$$K_a = \frac{[Z@1_2]}{[Z][1_2]} \quad (2)$$

Encapsulation of a molecule into a capsule could be monitored by NMR spectroscopy. For example,  $1_2$  in  $C_6D_6$  gave different signals in the  $^1H$  NMR spectra before and after addition of  $CH_4$ .

Compound **2** also forms a rigid and large dimeric capsule ( $2_2$ ). The  $^1H$  NMR spectrum of  $2_2$  was measured in  $C_6D_6$ ,  $C_6D_5F$ , and a  $C_6D_6/C_6D_5F$  solvent mixture, with all other conditions kept constant. The chemical shifts for the  $H^a$  protons of **2** in the solvents given above are summarized below. No other signals due to the  $H^a$  protons in **2** were observed (except for those listed). Assume that the interior of the capsule is always filled with the largest possible number of solvent molecules and that each signal corresponds to one species of the filled capsule.



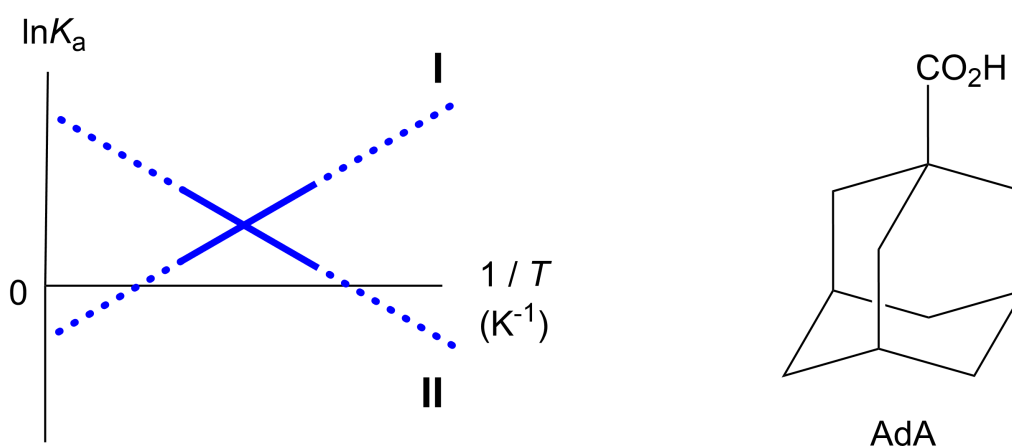
solvent	$\delta$ (ppm) of $H^a$
$C_6D_6$	4.60
$C_6D_5F$	4.71
$C_6D_6 / C_6D_5F$	4.60, 4.71, 4.82

**A.4 DETERMINE** the number of  $C_6D_6$  and  $C_6D_5F$  molecules encapsulated in  $2_2$  giving each  $H^a$  signal. 3pt

$^1\text{H}$  NMR measurements in  $\text{C}_6\text{D}_6$  revealed that  $2_2$  can incorporate one molecule of 1-adamantanecarboxylic acid (AdA), and the association constants ( $K_a$ ), expressed below, were determined at various temperatures.  $[\text{solvent}@2_2]$  denotes a species containing one or more solvent molecules.

$$K_a = \frac{[\text{Z}@2_2]}{[\text{Z}][\text{solvent}@2_2]} \quad (3)$$

Similarly,  $K_a$  values of  $\text{CH}_4$  and  $1_2$  (equation 2) at various temperatures in  $\text{C}_6\text{D}_6$  were also determined by  $^1\text{H}$  NMR measurements. The plots of the two association constants (as  $\ln K_a$  vs  $1/T$ ) are shown below.



**A.5** **WRITE** the correct letter, A or B, to fill in (1)–(5) in the following paragraph. 3pt  
 No  $\text{C}_6\text{D}_6$  molecule is encapsulated in  $1_2$ . In line **II**, the entropy change ( $\Delta S$ ) is ( 1 ) and enthalpy change ( $\Delta H$ ) is ( 2 ), indicating that the driving force for the encapsulation in line **II** is ( 3 ). Therefore, line **I** corresponds to ( 4 ), and line **II** corresponds to ( 5 ).

	A	B
(1)	positive	negative
(2)	positive	negative
(3)	$\Delta S$	$\Delta H$
(4)	$1_2$ and $\text{CH}_4$	$2_2$ and AdA
(5)	$1_2$ and $\text{CH}_4$	$2_2$ and AdA



USA-2 C-9 A-1

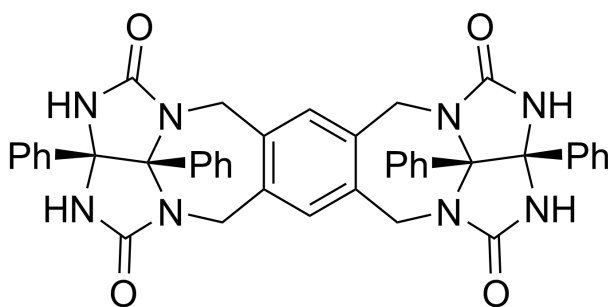
**A9-1**  
USA (United States of America)

## Likes and Dislikes of Capsule

**A.1** (13 pt)

<b>4</b> (2 pt)	<b>5</b> (3 pt)
<b>6</b> (2 pt)	<b>7</b> (2 pt)
<b>8</b> (2 pt)	<b>9</b> (2 pt)

**A.2** (2 pt)



**A.3** (2 pt)

**A.4** (3 pt)

$\delta$ (ppm) of H <sup>a</sup>	numbers of C <sub>6</sub> D <sub>6</sub>	numbers of C <sub>6</sub> D <sub>5</sub> F
4.60 ppm		
4.71 ppm		
4.82 ppm		

**A.5** (3 pt)

(1) : \_\_\_\_\_ (2) : \_\_\_\_\_ (3) : \_\_\_\_\_

(4) : \_\_\_\_\_ (5) : \_\_\_\_\_