IChO
General instructions
Cover sheet

Please return this cover sheet together with all the related question sheets.
Chemistry! It's Cool!
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GOOD LUCK!

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### 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, \( k_e (\approx 9.0 \times 10^9 \text{ N m}^2 \text{ C}^{-2}) \) 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 \( G \)

\[ G = H - TS \]
\[ \Delta_r G^\circ = -RT \ln K = -zF E^\circ \]
where \( K \) is the equilibrium constant, \( z \) is the number of electrons, \( E^\circ \) is the standard electrode potential.

### Reaction quotient \( Q \)

For a reaction
\[ aA + bB \rightleftharpoons cC + dD \]
\[ Q = \frac{[C]^c[D]^d}{[A]^a[B]^b} \]
where \([A]\) is the concentration of \( A \).
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<td>where ( c_m ) is the temperature-independent molar heat capacity.</td>
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<td>( E = E^\circ + \frac{RT}{z \mathcal{F}} \ln \frac{C_{\text{ox}}}{C_{\text{red}}} )</td>
<td>where ( C_{\text{ox}} ) is the concentration of oxidized substance, ( C_{\text{red}} ) is the concentration of reduced substance.</td>
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<td>Arrhenius equation</td>
<td>( k = A \exp \left( - \frac{E_a}{RT} \right) )</td>
<td>where ( k ) is the rate constant, ( A ) is the pre-exponential factor, ( E_a ) is the activation energy.</td>
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<td>Lambert–Beer equation</td>
<td>( A = \varepsilon l c )</td>
<td>where ( A ) is the absorbance, ( \varepsilon ) is the molar absorption coefficient, ( l ) is the optical path length, ( c ) is the concentration of the solution.</td>
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<td>Henderson–Hasselbalch equation</td>
<td>For an equilibrium ( \text{HA} \rightleftharpoons \text{H}^+ + \text{A}^- )</td>
<td>where equilibrium constant is ( K_a ), ( \text{pH} = pK_a + \log \left( \frac{[\text{A}^-]}{[\text{HA}]} \right) )</td>
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**Key:**
- **Atomic Number:** The number of protons in the nucleus.
- **Symbol:** The chemical symbol for the element.
- **Name:** The official name of the element.
- **Atomic Weight:** Mass in atomic mass units (amu).
- **Group:** Elements in the same column have similar chemical properties.
- **Period:** Elements in the same row have similar chemical properties.

**Table of Elements:**
- **Groups:** 1A, 2A, 3A, ..., 18A
- **Periods:** 1, 2, 3, ..., 7

**Notable Elements:**
- **La-Lu:** Lanthanoids
- **Ac-Lr:** Actinoids

**Atomic Properties:**
- **Atomic Number (Z):** The number of protons in the nucleus.
- **Mass Number (A):** The sum of protons and neutrons.
- **Electron Configuration:** The arrangement of electrons in the atomic orbitals.

**Periodic Table Notes:**
- **Group Periodicity:** Elements in the same group have similar chemical properties.
- **Periodic Table Trends:** Trends in chemical behavior and reactivity across Periods and Groups.

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**Note:** This table provides a snapshot of the periodic table, highlighting key elements and their properties. For a complete understanding, refer to the full periodic table in a comprehensive chemistry textbook or resource.
$^{1}H$ NMR Chemical Shifts

$\Delta \delta$ for one alkyl group-substitution: ca. +0.4 ppm
International Chemistry Olympiad 2021 Japan
53rd IChO2021 Japan
25th July - 2nd August, 2021
https://www.icho2021.org

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\[ \Delta U = q + w \]
where \( \Delta U \) is the change in the internal energy, \( q \) is the heat supplied, \( w \) is the work done.

**Enthalpy**  
\[ H = U + PV \]

**Entropy based on Boltzmann's principle**  
\[ S = k_B \ln W \]
where \( W \) is the number of microstates.

**The change of entropy**  
\[ \Delta S = \frac{\Delta r G}{T} \]
where \( \Delta r G \) is the change of Gibbs free energy.

**Gibbs free energy**  
\[ G = H - TS \]
\[ \Delta_r G = -RT \ln K = -zFE^o \]
where \( K \) is the equilibrium constant, \( z \) is the number of electrons, \( E^o \) is the standard electrode potential.

**Reaction quotient**  
\[ \Delta_r G = \Delta_r G^o + RT \ln Q \]
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.
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### Key
- **Periodic Table of Elements**
- **Atomic Number**
- **Symbol**
- **Atomic Weight**
- **Group**
- **Period**

### Notes
- This table provides a comprehensive overview of the periodic elements, including their atomic numbers, symbols, and atomic weights.
- Elements are arranged in order of increasing atomic number.
- Groups and periods are clearly marked for easy reference.

---

### Additional Information
- **ICChO**
- **G0-6**
- **English-3 (India)**

---

### References
- [IUPAC Periodic Table](https://www.iupac.org/tc33/periodic_table/)
- [Periodic Table](https://en.wikipedia.org/wiki/Periodic_table)

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### Credits
- **Created by:** [Author(s)]
- **Last Updated:** [Date]

---

### Acknowledgements
- Special thanks to [Contributors] for their valuable contributions.
$^{1}H$ NMR Chemical Shifts

$\Delta \delta$ for one alkyl group-substitution: ca. +0.4 ppm
IChO
Problem 1
Cover sheet

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

**Part A**

As hydrogen is absorbed into the bulk of a metal via its surface, let us first consider the adsorption process of hydrogen at the metal surface, \( \text{H}_2(g) \rightarrow 2\text{H}(\text{ad}) \), 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 Fig. 1. Fig. 2 shows the potential energy contour plot for the dissociation at the surface. The numerical values represent the potential energy in units of \( \text{kJ} \) 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.
Fig. 1: Definition of variables. Drawing is not in scale.

Fig. 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 H\(_2\) molecule
(ii) The interatomic distance between metal atoms (\(d_M\) in Fig. 1)
(iii) The distance of adsorbed H atoms from the surface (\(h_{ad}\) in Fig. 1)

<table>
<thead>
<tr>
<th></th>
<th>A. 0.03 nm</th>
<th>B. 0.07 nm</th>
<th>C. 0.11 nm</th>
<th>D. 0.15 nm</th>
<th>E. 0.19 nm</th>
<th>F. 0.23 nm</th>
<th>G. 0.27 nm</th>
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### 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 H\(_2\) to gaseous H
\[H_2(g) \rightarrow 2H(g)\]
(ii) the energy released during the adsorption of a gaseous H\(_2\)
\[H_2(g) \rightarrow 2H(ad)\]

<table>
<thead>
<tr>
<th></th>
<th>A. 20 kJ mol(^{-1})</th>
<th>B. 40 kJ mol(^{-1})</th>
<th>C. 60 kJ mol(^{-1})</th>
<th>D. 100 kJ mol(^{-1})</th>
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<td>E. 150 kJ mol(^{-1})</td>
<td>F. 200 kJ mol(^{-1})</td>
<td>G. 300 kJ mol(^{-1})</td>
<td>H. 400 kJ mol(^{-1})</td>
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</table>
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.

\[ \text{H}_2(\text{g}) \xrightleftharpoons[k_2]{k_1} 2\text{H(ad)} \]  
\[ \text{H(ad)} \xrightarrow{k_3} \text{H(ab)} \]  

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

\[ r_1 = k_1 P_{\text{H}_2} (1 - \theta)^2 \]  
\[ r_2 = k_2 \theta^2 \]  
\[ r_3 = k_3 \theta \]

where \( k_1 \) [s\(^{-1}\) Pa\(^{-1}\)], \( k_2 \) [s\(^{-1}\)] and \( k_3 \) [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 ≤ \( \theta \) ≤ 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:

\[ r_3 = \frac{k_3}{1 + \sqrt{\frac{1}{P_{\text{H}_2}C}}} \]  

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 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 $T$, $C = 2.5 \times 10^3 \text{ Pa}^{-1}$ and $k_3 = 4.8 \times 10^{-2} \text{ s}^{-1}$ are given. For $r_3$ as a function of $P_{\text{H}_2}$ at this temperature, select the correct plot from (a)–(h). 3pt
Hydrogen at a Metal Surface

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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 -storage technology.

Part A

As hydrogen is absorbed into the bulk of a metal via its 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 dependent on two variables: the inter-atomic distance, \( d \), and the height relative to the surface metal atom, \( z \). Assume 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 Fig. 1.

Fig. 2 shows the potential energy contour plot for the dissociation at the surface. The numerical values represent the potential energy in kJ per mole of \( \text{H}_2 \). The spacing between solid lines is 20 kJ mol\(^{-1}\), between dashed lines is 100 kJ mol\(^{-1}\), and between solid and dashed lines is 80 kJ mol\(^{-1}\). Ignore the zero-point vibration energy.
Fig. 1 Definition of variables. Drawing is not to scale.

Fig. 2
A.1 For each of the following items (i)–(iii), select the closest value from A–G. 6pt
(i) The inter-atomic distance for a gaseous H₂ molecule
(ii) The inter-atomic distance between metal atoms ($d_{M}$ in Fig. 1)
(iii) The distance of adsorbed H atoms from the surface ($h_{ad}$ in Fig. 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 H₂ to gaseous H

$[H_2(g) \rightarrow 2H(g)]$

(ii) the energy released during the adsorption of a gaseous H₂ $[H_2(g) \rightarrow 2H(\text{ad})]$

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

\[
\text{H}_2(g) \xrightleftharpoons[k_2]{k_1} 2\text{H(ad)} \quad (1a)
\]

\[
\text{H(ad)} \xrightarrow{k_3} \text{H(ab)} \quad (1b)
\]

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:

\[
r_1 = k_1 P_H^2 (1 - \theta)^2 \quad (2)
\]

\[
r_2 = k_2 \theta^2 \quad (3)
\]

\[
r_3 = k_3 \theta \quad (4)
\]

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 \(P_H\) is the pressure of \(\text{H}_2\).

Among the sites available on the surface, \(\theta \text{[0} \leq \theta \leq 1\text{]}\) is the fraction occupied by H atoms. Assume 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:

\[
r_3 = \frac{k_3}{1 + \sqrt{\frac{1}{P_H C}}} \quad (5)
\]

**Express** \(C\) using \(k_1\) and \(k_2\).
A metal sample with a surface area of $S = 1.0 \times 10^{-3}$ m$^2$ was placed in a container (1 L = $1.0 \times 10^{-3}$ m$^3$) with H$_2$ ($P_{H_2} = 1.0 \times 10^2$ Pa). The density of hydrogen-atom adsorption sites on the surface was $N = 1.3 \times 10^{18}$ m$^{-2}$. The surface temperature was kept at $T = 400$ K. As the set of reactions (1) proceeded, $P_{H_2}$ decreased at a constant rate of $v = 4.0 \times 10^{-4}$ Pa s$^{-1}$. Assume that 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, $A$ [mol s$^{-1}$ m$^{-2}$].

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

**B.4** At a different $T$, $C = 2.5 \times 10^3$ Pa$^{-1}$ and $k_3 = 4.8 \times 10^{-2}$ s$^{-1}$. From plots (a)–(h), select the correct plot for $r_3$ as a function of $P_{H_2}$ at this temperature.
## Hydrogen at a Metal Surface

### Part A

**A.1** (6 pt)

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**A.2** (4 pt)

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Part B

B.1 (5 pt)

\[ C = \ \text{__________} \]

B.2 (3 pt)

\[ A = \ \text{__________} \text{ mol s}^{-1} \text{ m}^{-2} \]
B.3 (3 pt)

\[ k_3 = \quad \text{s}^{-1} \]

B.4 (3 pt)

____________________
Please return this cover sheet together with all the related question sheets.
Isotope Time Capsule

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Molecular entities that differ only in isotopic composition, such as CH₄ and CH₃D, are called isotopologues. Isotopologues are considered to have the same chemical characteristics. In nature, however, there exists a slight difference.

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

Let us consider the following equilibrium:

\[ ^{12}\text{C}^{16}\text{O}_2 + ^{12}\text{C}^{18}\text{O}_2 \rightleftharpoons 2^{12}\text{C}^{16}\text{O}^{18}\text{O} \]

\[ K = \frac{[^{12}\text{C}^{16}\text{O}^{18}\text{O}]^2}{[^{12}\text{C}^{16}\text{O}_2][^{12}\text{C}^{18}\text{O}_2]} \]

The entropy, \( S \), increases with increasing the number of possible microscopic states of a system, \( W \):

\[ S = k_B \ln W \]

\( W = 1 \) 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 eq. 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 eq. 3 is positive regardless of the temperature.

$$H_2 + DI \rightleftharpoons HD + HI$$  \hspace{1cm} (3)

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

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

$$2HD \rightleftharpoons H_2 + D_2 \hspace{1cm} K = \frac{[H_2][D_2]}{[HD]^2}$$  \hspace{1cm} (4)

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

$$E = \frac{1}{2} \hbar \nu$$  \hspace{1cm} (5)

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

Wherein $k$ is the force constant and $\mu$ the reduced mass, which is expressed in terms of the mass of the two atoms in the diatomic molecule, $m_1$ and $m_2$, according to:

$$\mu = \frac{m_1 m_2}{m_1 + m_2}$$  \hspace{1cm} (7)

A.2  The vibration of $H_2$ is at 4161.0 cm$^{-1}$ when reported as a wavenumber. 8pt **Calculate** the $\Delta H$ of the following equation at $T = 0 \text{ K}$ in units of J mol$^{-1}$.

$$2HD \rightarrow H_2 + D_2$$  \hspace{1cm} (8)

Assume that:

- only the vibrational energy contributes to the $\Delta H$.
- the $k$ values for $H_2$, HD, and $D_2$ are identical.
- the mass of H to be 1 Da and the mass of D to be 2 Da.
The molar ratio of H\textsubscript{2}, HD, and D\textsubscript{2} depends on the temperature in a system in equilibrium. Here, \( \Delta_{D_2} \) is defined as the change of the molar ratio of D\textsubscript{2}.

\[
\Delta_{D_2} = \frac{R_{D_2}}{R_{D_2}^*} - 1
\]  

(9)

Here, \( R_{D_2} \) refers to \( \frac{[D_2]}{[H_2]} \) in the sample and \( R_{D_2}^* \) to \( \frac{[D_2]}{[H_2]} \) at \( T \rightarrow +\infty \). It should be noted here that the distribution of isotopes becomes random at \( T \rightarrow +\infty \).

A.3 **Calculate** \( \Delta_{D_2} \) with natural D abundance when the isotopic exchange is in equilibrium at the temperature where \( K \) in eq. 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.
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 CO$_2$ molecules with molecular weights of 44 and 47, which are described as CO$_2$(44) and CO$_2$(47) below. The quantity $\Delta_{47}$ is defined as:

$$\Delta_{47} = \frac{R_{47}}{R^*_47} - 1$$

(10)

$R_{47}$ refers to $[\text{CO}_2(47)]$ in the sample and $R^*_47$ to $[\text{CO}_2(47)]$ at $T \to +\infty$. The natural abundances of carbon and oxygen atoms are shown below; ignore isotopes that are not shown here.

<table>
<thead>
<tr>
<th></th>
<th>$^{12}\text{C}$</th>
<th>$^{13}\text{C}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>natural abundance</td>
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<td>0.011112</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th></th>
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<th>$^{18}\text{O}$</th>
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</thead>
<tbody>
<tr>
<td>natural abundance</td>
<td>0.997621</td>
<td>0.0003790</td>
<td>0.0020000</td>
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</table>

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

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

(11)

A.4 The $R_{47}$ of fossil plankton obtained from the Antarctic seabed was $4.50865 \times 10^{-5}$. Estimate the 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 CO$_2$(47) for the calculation.
Molecular entities that differ only in isotopic composition, such as CH₄ and CH₃D, are called isotopologues. Isotopologues are considered to have the same chemical characteristics. In nature, however, there exists a slight difference.

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

Let us consider the following equilibrium:

\[ ^{12}\text{C}^{16}\text{O}_2 + ^{12}\text{C}^{18}\text{O}_2 \rightleftharpoons 2^{12}\text{C}^{16}\text{O}^{18}\text{O} \]

\[ K = \frac{[^{12}\text{C}^{16}\text{O}^{18}\text{O}]^2}{[^{12}\text{C}^{16}\text{O}_2][^{12}\text{C}^{18}\text{O}_2]} \]  \hspace{1cm} (1)

The entropy, \( S \), increases with increasing the number of possible microscopic states of a system, \( W \):

\[ S = k_B \ln W \]  \hspace{1cm} (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 eq. 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 eq. 3 is positive regardless of the temperature.

$$
H_2 + DI \rightleftharpoons HD + HI
$$

\[ \text{(3)} \]

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

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

$$
2HD \rightleftharpoons H_2 + D_2 \quad K = \frac{[H_2][D_2]}{[HD]^2}
$$

\[ \text{(4)} \]

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

$$
E = \frac{1}{2} h\nu
$$

\[ \text{(5)} \]

$$
\nu = \frac{1}{2\pi} \sqrt{\frac{k}{\mu}}
$$

\[ \text{(6)} \]

wherein $k$ is the force constant and $\mu$ the reduced mass, which is expressed in terms of the mass of the two atoms in the diatomic molecule, $m_1$ and $m_2$, according to the following expression:

$$
\mu = \frac{m_1 m_2}{m_1 + m_2}
$$

\[ \text{(7)} \]

A.2  The vibration of $H_2$ is observed at 4161.0 cm$^{-1}$ (as wavenumber). **Calculate** the $\Delta H$ of the following equation at $T = 0$ K in units of J mol$^{-1}$.

$$
2HD \rightarrow H_2 + D_2
$$

\[ \text{(8)} \]

Assume that:
- only the vibrational energy contributes to the $\Delta H$.
- the $k$ values for $H_2$, $HD$, and $D_2$ are identical.
- the mass of H is 1 Da and of D is 2 Da.
The molar ratio of H$_2$, HD, and D$_2$ depends on the temperature in a system in equilibrium. Here, $\Delta_{D_2}$ is defined as the change of the molar ratio of D$_2$.

$$\Delta_{D_2} = \frac{R_{D_2}}{R_{D_2}^*} - 1$$  \hspace{1cm} (9)

Here, $R_{D_2}$ refers to $\left[ \frac{D_2}{H_2} \right]$ in the sample and $R_{D_2}^*$ to $\left[ \frac{D_2}{H_2} \right]$ at $T \to +\infty$. It should be noted here that the distribution of isotopes becomes random at $T \to +\infty$.

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

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$$\Delta_{47} = \frac{36.2}{T^2} + 2.920 \times 10^{-4}$$  \hspace{1cm} (11)$$

**A.4** The $R_{47}$ of a fossil plankton obtained from the Antarctic seabed was $4.50865 \times 10^{-5}$. **Estimate** the temperature using this $R_{47}$ value. This temperature can be interpreted as the air temperature during the era in which the plankton lived. Consider only the most common isotopologue of CO$_2[47]$ for the calculation.
A.1 (8 pt)

\[ T \to 0 : K = \quad , \quad T \to +\infty : K = \]
ΔΗ = _______ J mol⁻¹
Δ₂ = \[ \text{_________} \]
\[ T = K \]
Please return this cover sheet together with all the related question sheets.
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 the 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 \( \lambda_1 \).
Part B
Let us consider the following equilibrium in the gas phase.

\[ \text{D} \rightleftharpoons 2\text{M} \quad (2) \]

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 \( P \), and equilibrium is established while the total pressure is kept at \( P \). The absorbance of the gas is \( A = \epsilon \frac{n}{V} l \), where \( \epsilon \), \( n \), \( V \), and \( l \) are the absorption coefficient, amount of the gas in moles, volume of the gas, and optical path length, respectively. Assume that all components of the gas mixture behave as ideal gases.

Use the following definitions if necessary.

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<tr>
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<th>Initial state</th>
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<td>( p_D )</td>
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<tr>
<td>Amount in moles</td>
<td>( n_0 )</td>
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</tr>
<tr>
<td>Volume</td>
<td>( V_0 )</td>
<td>( V )</td>
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B.1 The absorbance of the gas at \( \lambda_{B1} \) measured from direction \( x \) (\( l = l_x \)) was \( A_{B1} \) both at the initial state and after the equilibrium. **Determine** the ratio \( \epsilon_D / \epsilon_M \) at \( \lambda_{B1} \), where \( \epsilon_D \) and \( \epsilon_M \) represent the absorption coefficients of D and of M, respectively.

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 \( \epsilon_D / \epsilon_M \) at \( \lambda_{B2} \).
Lambert–Beer Law?

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

**Part A**

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

$$HA \rightleftharpoons A^- + H^+ \quad K = \frac{[A^-][H^+]}{[HA]}$$

The optical path length is $l$ for Part A. Ignore the density change upon dilution. Assume that no chemical reactions other than eq 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 the 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.

\[
D \rightleftharpoons 2M \tag{2}
\]

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 in the container while the total pressure is kept at \(P\). The absorbance of the gas is \(A = \varepsilon(n/V)l\), where \(\varepsilon\), \(n\), \(V\), and \(l\) are the absorption coefficient, amount of the gas in moles, volume of the gas, and optical path length, respectively. Assume that all components of the gas mixture behave as ideal gases.

![Diagram of a cuboid container with a transparent movable wall](image)

Use the following definitions if necessary.

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

B.2 The absorbance of the gas at \(\lambda_{B2}\) measured along direction \(y\) was \(A_{B2}\) both at the initial state (\(l = l_y\)) and after the equilibrium (\(l = l_y\)). Determine the ratio \(\varepsilon_D/\varepsilon_M\) at \(\lambda_{B2}\).
Lambert–Beer Law?

Part A

A.1 (10 pt)

(Continued on the next page)
Part B

B.1 (6 pt)

$\varepsilon_D / \varepsilon_M =$

__________________________
$\varepsilon_D / \varepsilon_M =$
Please return this cover sheet together with all the related question sheets.
Zinc has long been used as alloys for brass and steel materials. The zinc contained in industrial wastewater is separated by precipitation to detoxify the water, and the obtained precipitate is reduced to recover and reuse it as metallic zinc.

**Part A**

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

\[
\text{Zn(OH)}_2(s) \rightleftharpoons \text{Zn}^{2+}(aq) + 2\text{OH}^-(aq) \quad K_{sp} = 1.74 \times 10^{-17} \quad (1)
\]

\[
\text{Zn(OH)}_2(s) \rightleftharpoons \text{Zn(OH)}_2(aq) \quad K_1 = 2.62 \times 10^{-6} \quad (2)
\]

\[
\text{Zn(OH)}_2(s) + 2\text{OH}^-(aq) \rightleftharpoons \text{Zn(OH)}_4^{2-}(aq) \quad K_2 = 6.47 \times 10^{-2} \quad (3)
\]

\[
\text{H}_2\text{O}(l) \rightleftharpoons \text{H}^+(aq) + \text{OH}^-(aq) \quad K_w = 1.00 \times 10^{-14} \quad (4)
\]
The solubility, $S$, of zinc (concentration of zinc in a saturated aqueous solution) is given in eq. 5.

$$S = [\text{Zn}^{2+}(\text{aq})] + [\text{Zn(OH)}_2(\text{aq})] + [\text{Zn(OH)}_4^{2-}(\text{aq})]$$  \hspace{1cm} (5)

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

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

**Part B**

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

$$\text{Zn(OH)}_2(\text{s}) \rightarrow \text{ZnO(\text{s}) + H}_2\text{O(l)}$$  \hspace{1cm} (6)

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

$$\text{ZnO(\text{s}) + H}_2(\text{g}) \rightarrow \text{Zn(\text{s}) + H}_2\text{O(g)}$$  \hspace{1cm} (7)

B.1 In order for reaction (7) to proceed at a hydrogen pressure kept at 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. Here, the Gibbs formation energies of zinc oxide and water vapor at 300°C and 1 bar for all gaseous species are $\Delta G_{\text{ZnO(300°C)}} = -2.90 \times 10^2 \text{kJ mol}^{-1}$ and $\Delta G_{\text{H}_2\text{O(300°C)}} = -2.20 \times 10^2 \text{kJ mol}^{-1}$, respectively.

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, $E^\circ$.

$$\text{Zn(s) + } \frac{1}{2}\text{O}_2(\text{g}) \rightarrow \text{ZnO(\text{s})} \hspace{1cm} E^\circ = 1.65 \text{V}$$  \hspace{1cm} (8)

B.2 A zinc-air battery was discharged at 20 mA for 24 hours. **Calculate** the change in mass of the negative electrode (anode) of the battery.
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 °C (February) and 3776 m, respectively. The atmospheric pressure is represented by

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

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

B.4 **Calculate** the Gibbs energy change for reaction (6) at 25 °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 °C and 1 bar are given as (10) and (11), respectively.

\[
\text{Zn}^{2+} + 2e^- \rightarrow \text{Zn} \quad E^{\circ}(\text{Zn}^{2+}/\text{Zn}) = -0.77 \text{V} \quad (10)
\]

\[
\text{O}_2 + 4\text{H}^+ + 4e^- \rightarrow 2\text{H}_2\text{O} \quad E^{\circ}(\text{O}_2/\text{H}_2\text{O}) = 1.23 \text{V} \quad (11)
\]
The Redox Chemistry of Zinc

Zinc has long been used to form alloys like brass and in the steel industry. The zinc in industrial wastewater is separated by precipitation to detoxify the water, and the obtained precipitate is reduced to recover and reuse it as metallic zinc.

**Part A**

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

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**Part B**

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

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$$\Delta G_{\text{ZnO}}(300°\text{C}) = -2.90 \times 10^2 \text{ kJ mol}^{-1} \quad \Delta G_{\text{H}_2\text{O}}(300°\text{C}) = -2.20 \times 10^2 \text{ kJ mol}^{-1}$$

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$$\text{Zn}^{2+} + 2e^- \rightarrow \text{Zn} \quad \quad E^\circ(\text{Zn}^{2+}/\text{Zn}) = -0.77\,\text{V}$$

(10)

$$\text{O}_2 + 4\text{H}^+ + 4e^- \rightarrow 2\text{H}_2\text{O} \quad \quad E^\circ(\text{O}_2/\text{H}_2\text{O}) = 1.23\,\text{V}$$

(11)
The Redox Chemistry of Zinc

Part A

A.1 (6 pt)

< pH <
Part B

B.1 (4 pt)

\[ \frac{p_{H_2O}}{} \text{ bar} \]

B.2 (3 pt)

\[ \text{g} \]
B.3 (5 pt)

V
\[ \Delta G^\circ = \text{J mol}^{-1} \]
Please return this cover sheet together with all the related question sheets.
Mysterious Silicon

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<td>5</td>
<td>15</td>
<td>8</td>
<td>60</td>
</tr>
</tbody>
</table>

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 compound formulated as $R^1\text{Si}≡\text{Si}≡R^1$ ($R$: organic substituent) is extremely reactive. For example, it reacts with ethylene to form a cyclic product that contains a four-membered ring.

$$\begin{align*}
R^1\text{Si}≡\text{Si}≡R^1 & \quad + \quad \text{H}_2\text{C}≡\text{CH}_2 \\
\Rightarrow & \quad \text{R}^1\text{Si}≡\text{Si}≡\text{R}^1
\end{align*}$$

When $R^1\equiv\text{Si}≡\text{Si}≡R^1$ is treated with an alkyne ($R^2\text{C}≡\text{C}≡R^2$), the four-membered-ring compound $A$ is formed as an initial intermediate. Further reaction of another molecule of $R^2\text{C}≡\text{C}≡R^2$ with $A$ affords isomers $B$ and $C$, both of which have benzene-like cyclic conjugated structures, so-called ‘disilabenzenes’ that contain a six-membered ring and can be formulated as $(R^1\text{Si})_2(R^2\text{C})_4$. 
The $^{13}$C NMR analysis of the corresponding six-membered ring skeletons $Si_2C_4$ shows two signals for $B$ and one signal for $C$.

**A.1** Draw the structural formulae of $A$, $B$, and $C$ using $R^1$, $R^2$, $Si$, and $C$, with one of the possible resonance structures.

**A.2** Calculate the aromatic stabilization energy (ASE) for benzene and $C$ (in the case of $R^1 = R^2 = H$) as positive values, considering the enthalpy change in some hydrogenation reactions of unsaturated systems shown below (Fig. 1).

\[
\begin{align*}
\text{H}_2\text{C} &\equiv \text{CH}_2 \quad + \quad \text{H}_2 \quad \longrightarrow \quad \text{H}_3\text{C} \equiv \text{CH}_3 \quad \Delta H = -135 \text{ kJ mol}^{-1} \quad (1) \\
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\text{H} &\equiv \text{Si} \quad + \quad 3 \text{ H}_2 \quad \longrightarrow \quad \text{H}_3\text{Si} \equiv \text{SiH}_2 \quad \Delta H = -173 \text{ kJ mol}^{-1} \quad (4) \\
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\end{align*}
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When a xylene solution of C is heated, it undergoes isomerization to give an equilibrium mixture of compounds D and E. The molar ratio is \( \text{D} : \text{E} = 1 : 40.0 \) at 50.0 °C and \( \text{D} : \text{E} = 1 : 20.0 \) 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.

The isomerization from C to D and 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 structural formulae of D and E using \( R_1 \), \( R_2 \), Si, and C.

Part B
Silicon is able to form highly coordinated compounds (> four substituents) with electronegative elements such as fluorine. As metal fluorides are often used as fluorination reagents, 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 \( \text{F} \): 0.855 g of \( \text{Na}_2\text{SiF}_6 \) (188.053 g mol\(^{-1}\)) dissolved in water (total volume: 200 mL).
    Aqueous solution \( \text{G} \): 6.86 g of \( \text{Ce}_2(\text{SO}_4)_3 \) (568.424 g mol\(^{-1}\)) dissolved in water (total volume: 200 mL).
  - Procedure
    Precipitation titration of a solution \( \text{F} \) (50.0 mL) by dropwise adding solution \( \text{G} \) in the presence of xilenol orange, which coordinates to \( \text{Ce}^{3+} \), as an indicator. After adding 18.8 mL of solution \( \text{G} \), 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 \( \text{Si(OH)}_4 \).

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

- **Reaction of \( \text{CCl}_4 \) with \( \text{Na}_2\text{SiF}_6 \)**:
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\( \text{Na}_2\text{SiF}_6(\text{x g}) \) 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 \( \text{H} \)). The \(^{29}\text{Si} \) and \(^{19}\text{F} \) NMR spectra of solution \( \text{H} \) 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 \( \text{CCl}_3 \), \( \text{CF}_2\text{Cl}_2 \), \( \text{CF}_3\text{Cl} \), 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.

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<tr>
<th>(^{19}\text{F} ) NMR data</th>
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SiF₄ is hydrolyzed to form H₂SiF₆ according to the following eq. 8:

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Solution H (10 mL) was added to an excess amount of water, which resulted in the complete hydrolysis of SiF₄. After separation, the H₂SiF₆ generated from the hydrolysis in the aqueous solution was neutralized and completely converted to Na₂SiF₆ (aqueous solution J).

The precipitate of unreacted Na₂SiF₆ and NaCl, which was removed by filtration in the initial step (underlined), 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, and the endpoints of the titrations with G were as follows:
- For solution J (entire amount): 61.6 mL.
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It should be noted here that the coexistence of NaCl or SiO₂ has no effect on the precipitation titration.

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| B.3 | 77.8% of the CCl₄ used as a starting material was unreacted. **Calculate** the mass of CF₃Cl generated. 8pt |
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 compound formulated as \( R^1\text{Si} \equiv \text{Si} \equiv R^1 \) (R: organic substituent) is extremely reactive. For example, it reacts with ethylene to form a cyclic product that contains a four-membered ring.

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R^1\text{Si} \equiv \text{Si} \equiv R^1 + H_2\text{C} \equiv \text{CH}_2 \rightarrow \text{Si} \equiv \text{Si} \quad \text{(R)}
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</tr>
</tbody>
</table>
# Mysterious Silicon

## Part A

**A.1** (9 pt)

<table>
<thead>
<tr>
<th>A (3 pt)</th>
<th>B (3 pt)</th>
<th>C (3 pt)</th>
</tr>
</thead>
</table>

**A.2** (7 pt)

$C_6H_6 : \text{kJ mol}^{-1}$, $C : \text{kJ mol}^{-1}$
A.3 (6 pt)

\[ \Delta H = \text{kJ mol}^{-1} \]

A.4 (10 pt)

D (5 pt)  E (5 pt)
Part B

B.1 (5 pt)

B.2 (15 pt)

(Continued on the next page)
B.2 (cont.)

\[
\begin{align*}
\text{NaCl} &: \quad g, \quad \text{Na}_2\text{SiF}_6 &: \quad g
\end{align*}
\]
B.3 (8 pt)

CF$_3$Cl: ___________ g
Please return this cover sheet together with all the related question sheets.
### Part A

Japan is one of the countries with the highest numbers of volcanos worldwide. When silicate minerals crystallize from magma, a part of the transition-metal ions ($M^{n+}$) in the magma is incorporated into the silicate minerals. The $M^{n+}$ studied in the problem are coordinated by oxide ions ($O^{2-}$) and adopt a four-coordinate tetrahedral ($T_d$) geometry in the magma and six-coordinate octahedral ($O_h$) geometry in the silicate minerals, both of which 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.

<table>
<thead>
<tr>
<th></th>
<th>Cr$^{2+}$</th>
<th>Mn$^{2+}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$D$</td>
<td>7.2</td>
<td>1.1</td>
</tr>
</tbody>
</table>
Let $\Delta_O$ and $\text{CFSE}^O$ be the energy separation of the d-orbitals of $M^{n^+}$ and the crystal-field stabilization energy in a $O_h$ field, respectively. Let $\Delta_T$ and $\text{CFSE}^T$ be those in a $T_d$ field.

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

**A.2** A linear relationship is observed by plotting $\ln D$ against $\Delta \text{CFSE} / \Delta_O$ in the Cartesian coordinate system shown below. Estimate $D$ for Co$^{2+}$.

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 mainly governed by the Coulomb interactions based on the radius and charge of the ions and some contributions from the CFSE of $M^{n^+}$ in the $O_h$ field.

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

<table>
<thead>
<tr>
<th></th>
<th>CaO</th>
<th>TiO</th>
<th>VO</th>
<th>MnO</th>
<th>CoO</th>
</tr>
</thead>
<tbody>
<tr>
<td>(a)</td>
<td>3460</td>
<td>3878</td>
<td>3913</td>
<td>3810</td>
<td>3916</td>
</tr>
<tr>
<td>(b)</td>
<td>3460</td>
<td>3916</td>
<td>3878</td>
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</table>
Part B

A mixed oxide \( \text{A} \), which contains \( \text{La}^{3+} \) and \( \text{Cu}^{2+} \), crystallizes in a tetragonal unit cell shown in Fig. 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 \( d_{z^2} \)).

\[ \text{Fig. 1} \]

\( \text{A} \) can be synthesized by thermal decomposition (pyrolysis) of complex \( \text{B} \), which is formed by mixing metal chlorides in dilute aqueous ammonia solution containing squaric acid \( \text{C}_4\text{H}_2\text{O}_4 \), i.e., a diacid. The pyrolysis behavior of \( \text{B} \) in dry air shows a weight loss of 29.1% up to 200 °C due to the loss of crystallization water, followed by another weight loss up to 700 °C due to the release of CO\(_2\). The total weight loss during the formation of \( \text{A} \) from \( \text{B} \) is 63.6%. It should be noted that only water and CO\(_2\) are released in the pyrolysis reaction.

### B.1 Write the chemical formulae for \( \text{A} \) and \( \text{B} \). 6pt

### B.2 Calculate \( l_x \) and \( l_z \) using Fig. 1. 4pt

### B.3 For \( \text{Cu}^{2+} \) in the distorted \( [\text{CuO}_6] \) octahedron in \( \text{A} \) of Fig. 1, write the names of the split \( e_g \) orbitals (\( d_{x^2-y^2} \) and \( d_{z^2} \)) in (i) and (ii), and draw the electron configuration in the dotted box in your answer sheet. 4pt
**A** is an insulator. When one $\text{La}^{3+}$ is substituted with one $\text{Sr}^{2+}$, one hole is generated in the crystal lattice that can conduct electricity. As a result, the $\text{Sr}^{2+}$-doped $\text{A}$ shows superconductivity below 38 K. When a substitution reaction took place for $\text{A}$, $2.05 \times 10^{27}$ holes $\text{m}^{-3}$ were generated.

<table>
<thead>
<tr>
<th>B.4 <strong>Calculate</strong> the percentage of $\text{Sr}^{2+}$ substituted for $\text{La}^{3+}$ based on the mole ratio in the substitution reaction. Note that the valences of the constituent ions and the crystal structure are not altered by the substitution reaction.</th>
</tr>
</thead>
</table>

**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 $\text{Cu}^{2+}$ (Fig. 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 $\text{Cu}_4(L1L1L1)_4$ is composed of planar dicarboxylate $L1$ (Fig. 2B) and $\text{Cu}^{2+}$ (Fig. 2C). The angle $\theta$ between the coordination directions of the two carboxylates, indicated by the arrows in Fig. 2B, determines the structure of the cage complex. The $\theta$ is $0^\circ$ for $L1$. Note that hydrogen atoms are not shown in Fig. 2.

---

![Fig. 2](image-url)
C.1 The $\theta$ of the planar dicarboxylate $L_2$ below is fixed to $90^\circ$. If the composition of the cage complex formed from $L_2$ and $Cu^{2+}$ is $Cu_n(L_2)_m$, give the smallest integer combination of $n$ and $m$. Assume that only the $CO_2^-$ groups of $L_2$ form a coordination bond to $Cu^{2+}$ ions.

![Diagram of $L_2$ with $\theta = 90^\circ$]
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 $\text{O}^{2-}$ (Fig. 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 (Fig. 3B, $\text{L}_3$, $\theta = 180^\circ$) 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 ($\text{X}$) that is called a “porous coordination polymer” (Fig. 3C). The composition of $\text{X}$ is $[\text{Zn}_4\text{O(\text{L}_3\text{L}_3\text{L}_3)}_3]_n$, and it has a cubic crystal structure with nano-sized pores. One pore is represented as a sphere in Fig. 3D, and each tetrahedral $\text{Zn}^{2+}$ cluster is represented as a dark gray polyhedron in Fig. 3C and 3D. Note that hydrogen atoms are not shown in Fig. 3.

**Fig. 3**

**C.2** X has a cubic unit cell with a side length of $a$ (Fig. 3C) and a density of 0.592 g cm$^{-3}$. Calculate $a$ in [cm].

**C.3** X contains a considerable number of pores, and 1 g of X can accommodate $3.0 \times 10^2$ mL of $\text{CO}_2$ gas in the pores at 1 bar and 25 °C. Calculate the average number of $\text{CO}_2$ molecules per pore.
The Solid-State Chemistry of Transition Metals

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<th>A.3</th>
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Volcano at Sakurajima island

Part A

Japan is one of the countries with the highest numbers of volcanos worldwide. When silicate minerals crystallize from magma, a part of the transition-metal ions (M$^{n+}$) in the magma is incorporated into the silicate minerals. The M$^{n+}$ studied in the problem are coordinated by oxide ions (O$^{2-}$) and adopt a four-coordinate tetrahedral ($T_d$) geometry in the magma and six-coordinate octahedral ($O_h$) geometry in the silicate minerals, both of which 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 $[M]_s$ is the concentrations of M$^{n+}$ in the silicate minerals and $[M]_l$ is the concentrations of M$^{n+}$ in the magma. The table below shows the $D$ values of the Cr$^{2+}$ and Mn$^{2+}$ ions as examples.

<table>
<thead>
<tr>
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<th>Cr$^{2+}$</th>
<th>Mn$^{2+}$</th>
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<tbody>
<tr>
<td>$D$</td>
<td>7.2</td>
<td>1.1</td>
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</table>
Let $\Delta_O$ and $\text{CFSE}^O$ be the energy separation of the d-orbitals of $M^{n+}$ and the crystal-field stabilization energy in a $O_h$ field, respectively. Let $\Delta_T$ and $\text{CFSE}^T$ be those in a $T_d$ field.

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

A linear relationship is observed by plotting $\ln D$ against $\Delta\text{CFSE} / \Delta_O$ in the Cartesian coordinate system shown below. Estimate $D$ for $Co^{2+}$.

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 mainly governed by the Coulomb interactions based on the radius and charge of the ions and some contributions from the CFSE of $M^{n+}$ in the $O_h$ field.

**A.3 Choose** the appropriate set of lattice enthalpies [kJ mol$^{-1}$] from options (a) to (f) for the series of metal oxides given.

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<th></th>
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<tr>
<td>(b)</td>
<td>3460</td>
<td>3916</td>
<td>3878</td>
<td>3810</td>
<td>3913</td>
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<tr>
<td>(c)</td>
<td>3460</td>
<td>3913</td>
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<td>3810</td>
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<tr>
<td>(f)</td>
<td>3810</td>
<td>3913</td>
<td>3916</td>
<td>3460</td>
<td>3878</td>
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</table>
A mixed oxide $A$, which contains $\text{La}^{3+}$ and $\text{Cu}^{2+}$, crystallizes in a tetragonal unit cell shown in Fig. 1. In the $[\text{CuO}_6]$ octahedron, the Cu–O length along the $z$-axis ($l_z$) is longer than that along 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 $d_{z^2}$).

The mixed oxide $A$ 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 $\text{C}_4\text{H}_2\text{O}_4$, i.e., a diacid. The pyrolysis behavior of $B$ in dry air shows a weight loss of 29.1% up to 200 °C due to the loss of crystallization water, followed by another weight loss up 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 formulae for $A$ and $B$. | 6pt |
| B.2 | Calculate $l_x$ and $l_z$ using Fig. 1. | 4pt |
| B.3 | For $\text{Cu}^{2+}$ in the distorted $[\text{CuO}_6]$ octahedron in $A$ of Fig. 1, write the names of the split $e_g$ orbitals ($d_{x^2-y^2}$ and $d_{z^2}$) in (i) and (ii), and draw the electron configuration in the dotted box in your answer sheet. | 4pt |
**A** is an insulator. When one La$^{3+}$ is substituted with one Sr$^{2+}$, one hole is generated in the crystal lattice that can conduct electricity. As a result, the Sr$^{2+}$-doped A shows superconductivity below 38 K. When a substitution reaction took place for A, $2.05 \times 10^{27}$ holes m$^{-3}$ were generated.

### B.4 Calculate the percentage of Sr$^{2+}$ substituted for La$^{3+}$ based on the mole ratio in the substitution reaction. Note that the valences of the constituent ions and the crystal structure are not altered by the substitution reaction.

**Part C**

Cu$_2$(CH$_3$CO$_2$)$_4$ is composed of four CH$_3$CO$_2^-$ coordinated to two Cu$^{2+}$ (Fig. 2A). Cu$_2$(CH$_3$CO$_2$)$_4$ exhibits high levels of structural symmetry, with two axes passing through the carbon atoms of the four CH$_3$CO$_2^-$ and an axis passing through the two Cu$^{2+}$, all of which are oriented orthogonal relative to each other. When a dicarboxylate ligand is used instead of CH$_3$CO$_2^-$, a “cage complex” is formed. The cage complex Cu$_4$(L1)$_4$ is composed of planar dicarboxylate L1 (Fig. 2B) and Cu$^{2+}$ (Fig. 2C). The angle $\theta$ between the coordination directions of the two carboxylates, indicated by the arrows in Fig. 2B, determines the structure of the cage complex. The $\theta$ is $0^\circ$ for L1. Note that hydrogen atoms are not shown in Fig. 2.
C.1 The $\theta$ of the planar dicarboxylate $L_2$ below is fixed to 90°. If the composition of the cage complex formed from $L_2$ and Cu$^{2+}$ is $Cu_n(L_2)_m$, give the smallest integer combination of $n$ and $m$. Assume that only the CO$_2^-$ groups of $L_2$ form a coordination bond to Cu$^{2+}$ ions.
A zinc complex, Zn₄O(CH₃CO₂)₆, contains four tetrahedral Zn²⁺, six CH₃CO₂⁻, and one O²⁻ (Fig. 3A). In Zn₄O(CH₃CO₂)₆, the O²⁻ is located at the origin, and the three axes passing through the carbon atoms of CH₃CO₂⁻ are oriented orthogonal relative to each other. When p-benzenedicarboxylate (Fig. 3B, L₃, θ = 180°) is used instead of CH₃CO₂⁻, the Zn²⁺ clusters are linked to each other to form a crystalline solid (X) that is called a “porous coordination polymer” (Fig. 3C). The composition of X is [Zn₄O(L₃)₃]ₓ, and it has a cubic crystal structure with nano-sized pores. One pore is represented as a sphere in Fig. 3D, and each tetrahedral Zn²⁺ cluster is represented as a dark gray polyhedron in Fig. 3C and 3D. Note that hydrogen atoms are not shown in Fig. 3.

**Fig. 3**

C.2 The crystalline solid X has a cubic unit cell with a side length of a (Fig. 3C) and a density of 0.592 g cm⁻³. **Calculate** a in [cm].

C.3 X contains a considerable number of pores, and 1 g of X can accommodate 3.0 × 10² mL of CO₂ gas in the pores at a pressure of 1 bar and at a temperature of 25 °C. **Calculate** the average number of CO₂ molecules per pore.
The Solid-State Chemistry of Transition Metals

Part A

A.1 (6 pt)

\[ \text{Cr}^{2+} : \Delta_0, \text{Mn}^{2+} : \Delta_0, \text{Co}^{2+} : \Delta_0 \]
A.2 (3 pt)

D: ____________________

A.3 (3 pt)

_______
Part B

B.1 (6 pt)

A: _______________________, B: _______________________

B.2 (4 pt)

\( l_x = \quad \text{nm}, \quad l_z = \quad \text{nm} \)
B.3 (4 pt)

(i) : _______________________, (ii) : _______________________

B.4 (4 pt)
Part C

C.1 (5 pt)

\[ n = \quad , m = \quad \]

C.2 (5 pt)

\[ a = \quad \text{cm} \]
C.3 (5 pt)
IChO
Problem 7
Cover sheet

Please return this cover sheet together with all the related question sheets.
Playing with Non-benzenoid Aromaticity

<table>
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Prof. Nozoe (1902–1996) opened 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, which was isolated from *Inula linariifolia*. From valencene (1), a one-step conversion yields 2, before a three-step conversion via 3 yields ketone 4. Eremophilene (5) is converted into 6 by performing the same four-step conversion.
A.1 Draw the structures of 2 and 6 and clearly identify the stereochemistry where necessary. 5pt

Then, ketone 4 is 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-linearifolanones 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 A.  

I  \[ \text{F}_3\text{C-S-OH} \]  
II  \[ \text{F}_3\text{C-S-NH}_2 \]  
III  \[ \text{N=S-CF}_3 \]  
IV  \[ \text{HN=S-CF}_3 \]  

A.3  **Draw** the structures of 8–14 and clearly identify the stereochemistry where necessary. Also, **indicate** the introduced $^{18}$O atoms for 13 and 14 as shown in the example below.
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 ion-pair intermediate 21. Although the formation of 21 was observed by NMR, 21 gradually decomposes to give 18 and 22.

\[ \text{16} \xrightarrow{\text{Br}_2, \text{CH}_3\text{COOH}} \text{17} \quad \text{C}_{15}\text{H}_{12}\text{Br}_2\text{O} \]

\[ \text{Et}_3\text{N, CH}_2\text{Cl}_2} \xrightarrow{} \text{18} \quad \text{C}_{15}\text{H}_{10}\text{O} \]

\[ \text{Cl}_2\text{S} \xrightarrow{} \text{19} \quad \text{C}_{15}\text{H}_{10}\text{Cl}_2 \]

\[ \text{20} \xrightarrow{-\text{HCl}} \text{21} \]

\[ \text{18} + \text{19} \xrightarrow{} \text{22} \quad \text{C}_7\text{H}_8\text{Cl} \]

\[ \text{1H NMR (CD}_3\text{CN, ppm)} \]

\[ \text{20: } \delta 7.4-7.2 (5\text{H}), 3.7 (2\text{H}), 2.8 (2\text{H}), 2.2 (1\text{H}) \]

\[ \text{21: } \delta 8.5-7.3 (15\text{H}), 5.5 (2\text{H}), 3.4 (2\text{H}) \]

B.1 Draw the structures of 17–19 and 21. Identifying the stereochemistry is not necessary.
Prof. Nozoe (1902–1996) started the research field of non-benzenoid aromatic compounds, which are now commonly used in organic chemistry.

Photo courtesy: Tohoku Univ.

Part A

Linearifolianone is a natural product with a unique structure, which was originally isolated from *Inula linariifolia*. From valencene (1), a one-step conversion yields 2. Compound 2 is converted to ketone 4 in three steps via intermediate 3. Eremophilene (5) is converted into 6 by performing the same four-step conversion.
A.1 Draw the structures of 2 and 6 and clearly identify the stereochemistry where necessary.

Then, ketone 4 is converted into ester 15 as shown in the Scheme. Compound 8 (molecular weight: 188) retains all the stereocenters in 7. Compounds 9 and 10 have five stereocenters and no carbon-carbon
double bonds. $H_2^{18}O$ is used (instead of $H_2^{16}O$) to obtain $^{18}O$-labelled-lineariifolionones 13 and 14 from 11 and 12, respectively. Compounds 13 and 14 are $^{18}O$-labelled isotopomers. Ignoring isotopic labelling, both 13 and 14 provide the same product 15 with identical stereochemistry.
A.2 Choose the appropriate structure for A. 2pt

I $\text{F}_3\text{S-OH}$  
II $\text{F}_3\text{S-NH}_2$  
III $\text{O=S-CF}_3$  
IV $\text{O=S-CF}_3$

A.3 Draw the structures of 8–14 and clearly identify the stereochemistry where necessary. Also, indicate the introduced $^{18}\text{O}$ atoms for 13 and 14 as shown in the example below. 19pt
Part B

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

\[ \text{19} \quad \text{is synthesized as shown below.} \]

\[ \text{17} \quad \text{C}_{15} \text{H}_{12} \text{Br}_2 \text{O} \]

\[ \text{18} \quad \text{C}_{15} \text{H}_{10} \text{O} \]

\[ \text{19} \quad \text{C}_{15} \text{H}_{10} \text{Cl}_2 \]

\[ \text{20} \quad \text{OH} \quad \text{+ 19} \quad \text{HCl} \quad \text{21} \quad \text{22} \quad \text{+ 18} \]

\[ \text{1H NMR (CD}_3\text{CN, ppm)} \quad 20: \delta\ 7.4-7.2\ (5\ H),\ 3.7\ (2\ H),\ 2.8\ (2\ H),\ 2.2\ (1\ H) \]

\[ 21: \delta\ 8.5-7.3\ (15\ H),\ 5.5\ (2\ H),\ 3.4\ (2\ H) \]

B.1 **Draw** the structures of 17-19 and 21. Identifying the stereochemistry is not necessary.
# Playing with Non-benzenoid Aromaticity

## Part A

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| A.2 (2 pt) |
### Part B

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<td>19 (3 pt)</td>
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Dynamic Organic Molecules and Their Chirality

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Part A
Polycyclic aromatic hydrocarbons with successive ortho-connections are called [n]carbohelicenes (here, n represents the number of six-membered rings) (see below). [4]Carbohelicene ([4]C) is efficiently prepared by a route using a photoreaction as shown below, via an intermediate (Int.) that is readily oxidized by iodine.

The photoreaction 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 π systems.

<table>
<thead>
<tr>
<th>A.1</th>
<th>Draw the structures of A–C. Stereoisomers should be distinguished.</th>
<th>9pt</th>
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<tbody>
<tr>
<td>A.2</td>
<td>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 affording product D whose molecular weight was 2 Da lower than that of [5]carbohelicene. The $^1$H NMR chemical shifts of D are listed below. <strong>Draw</strong> the structure of D.</td>
<td></td>
</tr>
<tr>
<td></td>
<td>[D (δ, ppm in CS$_2$, r.t.), 8.85 (2H), 8.23 (2H), 8.07 (2H), 8.01 (2H), 7.97 (2H), 7.91 (2H)]</td>
<td></td>
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</tbody>
</table>

[5]- and larger [n]carbohelicenes have helical chirality and interconversion between enantiomers of these helicenes is significantly 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 a 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. If its helical chirality is considered, 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 \((P, P, P)\) as shown below.

\[
\begin{align*}
E & \quad (1, 2, 3) = (P, P, P)
\end{align*}
\]

**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. Given that interconversion between stereoisomers does not occur during the reaction, identify all the possible stereoisomers of \(G\) formed in this process, without duplication. As a reference, one isomer should be drawn completely with the chirality defined as in the example above, with numerical labels; the other stereoisomers should be listed with location numbers and \(M\) and \(P\) labels according to the same numbering. For instance, the other stereoisomers of \(E\) should be listed as \((1, 2, 3) = (P, M, P), (P, M, M), (P, P, M), (M, M, M), (M, M, P), (M, P, M), \) and \((M, P, M)\).
Part B

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

Representative metathesis reactions catalyzed by a ruthenium catalyst (Ru*) are shown below.

B.1 **Draw** the structure of intermediate I (its stereochemistry is not required). 3pt
B.2 Starting from the optically active precursor \( J \), the same reaction sequence gives the optically active sumanene derivative \( K \). The stereocenters in \( J \) suffer no inversion during the metathesis reaction. Draw the structure of \( K \) with the appropriate stereochemistry.
Dynamic Organic Molecules and Their Chirality

<table>
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Part A

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

![Diagram of helicene isomers](image)

[n]Carbohelicenes with $n$ larger than 4 can be enantiomerically separated by a 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. If its helical chirality is considered, 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 \((P, P, P)\) as shown below.

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**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 stereoisomers of helicene G \((C_{66}H_{36})\) are obtained. Identify all possible stereoisomers of G formed (without duplication) given that interconversion between stereoisomers does not occur during the reaction. As a reference, one stereoisomer should be drawn completely with the chirality defined using numeric and P/M labels (see example E). The other stereoisomers should be listed with location numbers and M/P labels according to the numbering in your reference structure. For example, the stereoisomers of E should 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 \((M, P, M)\).
Part B

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

Representative metathesis reactions catalyzed by a ruthenium catalyst (Ru*) are shown below.

B.1 **Draw** the structure of intermediate I (its stereochemistry is not required). 3pt
B.2 Starting from the optically active precursor \( J \), the same reaction sequence gives the optically active sumanene derivative \( K \). The stereocenters in \( J \) suffer no inversion during the metathesis reaction. **Draw** the structure of \( K \) with the appropriate stereochemistry.
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)
Part B

B.1 (3 pt)

B.2 (4 pt)
Please return this cover sheet together with all the related question sheets.
Likes and Dislikes of Capsule

<table>
<thead>
<tr>
<th>Question</th>
<th>A.1</th>
<th>A.2</th>
<th>A.3</th>
<th>A.4</th>
<th>A.5</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>Points</td>
<td>13</td>
<td>2</td>
<td>2</td>
<td>3</td>
<td>3</td>
<td>23</td>
</tr>
</tbody>
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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 as a comparison of 1 and the encapsulation behavior of these compounds was investigated.
The synthetic route to 2 is shown below. The elemental composition of compound 9: C; 40.49%, H; 1.70%, and O; 17.98% by mass.
A.1 **Draw** the structures of 4-9; the stereochemistry can be neglected. Use "PMB" as a substituent instead of drawing the whole structure of p-methoxybenzyl group shown in the scheme above.

In the mass spectrum of 1, the ion peak corresponding to its dimer (1₂) was clearly observed, whereas an ion peak for 3₂ was not observed in the spectrum of 3. In the ¹H NMR spectra of a solution of 1₂, all the NH protons derived from 1 were observed to be chemically equivalent, and their chemical shift was significantly different from that of the NH protons of 3. These data indicate that hydrogen bonds are formed between the NH moieties of 1 and atoms X of another molecule of 1 to form the dimeric capsule.

<table>
<thead>
<tr>
<th>A.2</th>
<th><strong>Circle</strong> all the appropriate atom(s) X in 1.</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>2pt</td>
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</tbody>
</table>

<table>
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<tr>
<th>A.3</th>
<th><strong>Give</strong> the number of the hydrogen bonds in the dimeric capsule (1₂).</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>2pt</td>
</tr>
</tbody>
</table>
The dimeric capsule of 1 (\(1_2\)) has an internal space wherein an appropriate small molecule Z can be encapsulated. This phenomenon is expressed by the following equation:

\[ Z + 1_2 \rightarrow Z@1_2 \] (1)

The equilibrium constant of the encapsulation of Z into \(1_2\) is given as below:

\[ K_a = \frac{[Z@1_2]}{[Z][1_2]} \] (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 \(^1\)H NMR spectra before and after addition of \(CH_4\).

Compound 2 also forms a rigid and larger dimeric capsule (\(2_2\)). The \(^1\)H 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 being kept constant. The chemical shifts for the H\(^a\) proton of 2 in the above solvents are summarized below, and no other signals from the H\(^a\) in 2, except for the listed, were observed. 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.

<table>
<thead>
<tr>
<th>solvent</th>
<th>(\delta) (ppm) of H(^a)</th>
</tr>
</thead>
<tbody>
<tr>
<td>(C_6D_6)</td>
<td>4.60</td>
</tr>
<tr>
<td>(C_6D_5F)</td>
<td>4.71</td>
</tr>
<tr>
<td>(C_6D_6/C_6D_5F)</td>
<td>4.60, 4.71, 4.82</td>
</tr>
</tbody>
</table>

A.4 **Determine** the number of \(C_6D_6\) and \(C_6D_5F\) molecules encapsulated in 2, giving 3pt each H\(^a\) signal.
$^1$H NMR measurements in C$_6$D$_6$ revealed that 2 can incorporate one molecule of 1-adamantane-carboxylic acid (AdA), and the association constants ($K_a$) which are expressed below were determined for various temperatures. [solvent@2] denotes a species containing one or more solvent molecules.

$$K_a = \frac{[Z@2_2]}{[Z][solvent@2_2]}$$

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

No C$_6$D$_6$ molecule is encapsulated in 1. 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).

<table>
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<tr>
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<th>A</th>
<th>B</th>
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<tr>
<td>(1)</td>
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<td>negative</td>
</tr>
<tr>
<td>(2)</td>
<td>positive</td>
<td>negative</td>
</tr>
<tr>
<td>(3)</td>
<td>$\Delta S$</td>
<td>$\Delta H$</td>
</tr>
<tr>
<td>(4)</td>
<td>1 and CH$_4$</td>
<td>2 and AdA</td>
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Likes and Dislikes of Capsule

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The synthetic route to 2 is shown below. The elemental composition of compound 9: C; 40.49%, H; 1.70%, and O; 17.98% by mass.
A.1 Draw the structures of 4-9; the stereochemistry can be neglected. Use "PMB" as a substituent instead of drawing the whole structure of \( p \)-methoxybenzyl group shown in the scheme above.

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 \( ^1H \) NMR spectra of a solution of \( 1_2 \), all the NH protons derived from 1 were observed to be chemically equivalent, and their chemical shift was significantly different from that of the NH protons of 3. These data indicate that hydrogen bonds are formed between the NH moieties 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 1.

A.3 Give the number of the hydrogen bonds in the dimeric capsule \( (1_2) \).
The dimeric capsule of \( \text{1} (\text{1}_2) \) has an internal space wherein an appropriate small molecule \( \text{Z} \) can be encapsulated. This phenomenon is expressed by the following equation:

\[
\text{Z} + \text{1}_2 \rightarrow \text{Z@1}_2
\]

The equilibrium constant of the encapsulation of \( \text{Z} \) into \( \text{1}_2 \) is given as below:

\[
K_a = \frac{[\text{Z@1}_2]}{[\text{Z}][\text{1}_2]}
\]

Encapsulation of a molecule into a capsule could be monitored by NMR spectroscopy. For example, \( \text{1}_2 \) in \( \text{C}_6\text{D}_6 \) gave different signals in the \( ^1\text{H} \) NMR spectra before and after addition of \( \text{CH}_4 \).

Compound \( \text{2} \) also forms a rigid and larger dimeric capsule (\( \text{2}_2 \)). The \( ^1\text{H} \) NMR spectrum of \( \text{2}_2 \) was measured in \( \text{C}_6\text{D}_6, \text{C}_6\text{D}_5\text{F} \), and a \( \text{C}_6\text{D}_6/\text{C}_6\text{D}_5\text{F} \) solvent mixture, with all other conditions being kept constant. The chemical shifts for the \( ^3\text{H} \) proton of \( \text{2}_2 \) in the above solvents are summarized below. These were the only signals observed for \( ^3\text{H} \) in \( \text{2} \). 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.

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</table>

**A.4** Determine the number of \( \text{C}_6\text{D}_6 \) and \( \text{C}_6\text{D}_5\text{F} \) molecules encapsulated in \( \text{2}_2 \), giving each \( ^3\text{H} \) signal. 3pt
$^1$H NMR measurements in C$_6$D$_6$ revealed that 2 can incorporate one molecule of 1-adamantanecarboxylic acid (AdA), and the association constants ($K_a$) which are expressed below were determined for various temperatures. [solvent@2] denotes a species containing one or more solvent molecules.

$$K_a = \frac{[Z@2]}{[Z][\text{solvent@2}]}$$

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

No C$_6$D$_6$ molecule is encapsulated in 1.

A.5 Choose the correct options (A or B) for each of the items (1)–(5) as defined in the following paragraph.
For 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).

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Likes and Dislikes of Capsule

**A.1** (13 pt)

<p>| | |</p>
<table>
<thead>
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<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>4</td>
<td>5</td>
</tr>
<tr>
<td>6</td>
<td>7</td>
</tr>
<tr>
<td>8</td>
<td>9</td>
</tr>
</tbody>
</table>
A.2 (2 pt)

\[
\begin{array}{c}
\text{HN} - \text{N} \\
\text{Ph} - \text{N} \\
\text{HN} - \text{N} \\
\text{Ph} - \text{N}
\end{array}
\]

A.3 (2 pt)

A.4 (3 pt)

<table>
<thead>
<tr>
<th>δ (ppm) of H³</th>
<th>numbers of C₆D₆</th>
<th>numbers of C₆D₅F</th>
</tr>
</thead>
<tbody>
<tr>
<td>4.60 ppm</td>
<td></td>
<td></td>
</tr>
<tr>
<td>4.71 ppm</td>
<td></td>
<td></td>
</tr>
<tr>
<td>4.82 ppm</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

A.5 (3 pt)

(1) :  (2) :  (3) :

(4) :  (5) :  