UNIVERSITY OF SWAZILAND
BACHELOR OF SCIENCE

EXAMINATION 2014

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|---|---|---|
| TITLE OF PAPER | : | INTRODUCTORY PHYSICAL CHEMISTRY |
| COURSE NUMBER | : | C202 |
| TIME | : | 3 HOURS |
| INSTRUCTIONS | : | THERE ARE SEVEN QUESTIONS |
| | : | ANSWER ANY FOUR QUESTIONS |
| | : | BEGIN THE ANSWER TO EACH QUESTION ON A SEPARATE SHEET OF PAPER |
| | : | DATA SHEETS ARE PROVIDED WITH THIS EXAMINATION PAPER |

DO NOT OPEN THIS PAPER UNTIL THE INVIGILATOR INSTRUCTS YOU TO DO SO.

## Question 1 [25 Marks]

a) Gases behave as ideal and non-ideal gases in defined P,V and T zones. With the aid of **any two** of the following: [15]
Lennard-Jones potential plot;
Compressibility plots and
Isotherm plots,

Compare and contrast real and ideal gases. Your account should make mention of interactions, equations and the kinetic theory of gases to help clarify your discussion.

b) A mixture of butane ($C_4H_{10}$) and propene ($C_3H_6$) occupied 35.5 L at 1.000 bar and 405 K. This mixture **reacted completely** with 220.6 g of $O_2$ to produce $CO_2$ and $H_2O$.
i) What was the composition of the original mixture? Assume ideal gas behaviour. MW ($O_2$)=32 g/mol [5]
ii) Calculate the partial pressure, mole fraction of each gas and the total pressure of the final mixture. [5]

## Question 2 [25 Marks]

A real gas equation of state for a gas is given by:

$$P = \frac{RT}{V_m - nb} - \frac{a}{V_m^2} \qquad P = \frac{RT}{V_m - 3b} - \frac{5a}{V_m^2} \qquad (1)$$

a) Based on van der Waals assumptions discuss the bases and significance of the main terms in equation (1) in terms of gas behaviour. [10]

b) Derive expressions for $V_{m,c}$, Tc and $P_c$. [6]

c) Find an expression for the Boyle's temperature, $T_B$. [5]

d) Estimate the temperature at which oxygen behaves as an ideal gas, $T_B$ given the constants:
a=6.493 $L^2 atm mol^{-2}$, b=$5.622 \times 10^{-2} L mol^{-1}$ [2]

e) Estimate the radii of real gas molecules using equation (1) for real gases given a critical molar volume of 250 $cm^3 mol^{-1}$ [2]

## Question 3 [25 Marks]

a) Using examples and/or diagrams compare and contrast **Any Three** of the following terms
i) reversible and irreversible expansion [5]
ii) path and state functions [5]
iii) change in internal energy and change in enthalpy [5]
iv) Work and heat [5]

b) the work done during the isothermal reversible expansion of a gas that satisfies the virial equation of state

Evaluate:

$$\frac{PV_m}{RT} = 1 + \frac{B}{V_m} + \frac{C}{V_m^2} + \ldots\ldots; B = -21.7cm^3mol^{-1} \ \& \ C = 1200cm^6mol^{-2}$$

(i). Derive an expression for work for a real gas that satisfies the virial equation in a reversible isothermal expansion [6]

(ii). Calculate work for 1.0 mol Ar at 273 K obeying the virial gas equation [4]

(iii). Calculate work for 1.0 mol Ar at 273 K obeying the perfect gas equation. [5]

Let expansion be from 500 $cm^3$ to 1000 $cm^3$ in each case.

## QUESTION 4 [25 marks]

Adiabatic expansion of an ideal gas is quite different from isothermal expansion.

a) Explain what is meant by adiabatic expansion, draw an adiabat and an isotherm on a P versus V graph and compare them. [8]

b) Derive the expression for the change in temperature of an adiabatic expansion of an ideal gas against constant external pressure from $V_i$ to $V_f$. [8]

c) A sample of argon at 1.0 atm pressure and 25$^oC$ expands reversibly and adiabatically from 0.50 L to 1.00 L. calculate: [9]
   i) final temperature
   ii) work done
   iii) change in internal energy.

## QUESTION 5 [25 MARKS]

a) Write short notes on **any two** of the following
   i) enthalpy change [5]
   ii) internal energy change [5]
   iii) Hess's Law [5]

b) To Calibrate a calorimeter a 0.120 g naphthalene, $C_{10}H_8(s)$, was burned at constant volume and it caused the temperature of the calorimeter to rise by 3.05 K. Then 0.10 g of an unknown compound was burned in the same calorimeter, causing a temperature rise of 2.05 K.

i) Calculate the heat capacity of the calorimeter [3]

ii) Is the unknown compound phenol, $C_6H_5OH(s)$ or ethanol, $CH_3CH_2OH(l)$ whose enthalpies of combustion are $\Delta_CH^{\theta}$=-3054 $kJmol^{-1}$ and -1368 $kJmol^{-1}$ respectively. [4]

c) Calculate the standard enthalpies of formation of:

i) $KClO_3(s)$ from the enthalpy of formation of KCl [4]

ii) $NOCl(g)$ from the enthalpy of formation of NO [4]

Given the attached table and the following information:

$2KClO_3(s) \rightarrow 2KCl(s) + 3O_2(g)$ $\Delta_f H^\theta = -89.4$ kJ/mol

$2NOCl(g) \rightarrow 2NO(g) + Cl_2(g)$ $\Delta_f H^\theta = +76.5$ kJ/mol

**Question 6 [25 Marks]**

a) Briefly discuss the statistical view of entropy [5]

b) 1.00 mol of perfect gas at 27°C is expanded isothermally from an initial pressure of 3.00 atm to a final pressure of 1.00 atm . Calculate $q$, $w$, $\Delta S_{sys}$, $\Delta S_{surr}$ and $\Delta S_{tot}$ if the expansion is done:

(1) reversibly. [5]

(2) against a constant external pressure of 1.00 atm. [5]

(3) adiabatically against a constant pressure of 1.00 atm. [5]

c) If 50g water at 80°C is poured into 100g water at 10°C in an insulated vessel given that $C_{p,m}$=75.5 $JK^{-1}mol^{-1}$: Calculate:

i) final temperature of the mixture [3]

ii) the entropy change [2]

**QUESTION 7[25 MARKS]**

a) Draw a sketch of the phase diagram of carbon dioxide and explain briefly the slopes and curvature of the liquid-solid and the liquid-gas boundaries, respectively. [15]

b) i) Derive the Clausius-Clapeyron equation for evaporation. [5]

ii) The triple point of benzene is at 5.5°C and 36 mm Hg. Predict the boiling point of benzene at 0.2 atm pressure. [5]

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**Useful Relations**

| | | | |
|---|---|---|---|
| $(RT)_{298.15K}$=2.4789 kJ/mol | | | |
| $(RT/F)_{298.15K}$=0.025 693 V | | | |
| T/K: 100.15 298.15 500.15 1000.15 | | | |
| T/Cm$^{-1}$: 69.61 207.22 347.62 695.13 | | | |
| 1mmHg=133.222 N m$^{-2}$ | | | |
| hc/k=1.438 78x10$^{-2}$ m K | | | |

| **1atm** | 1 cal | 1 eV | 1cm$^{-1}$ |
|---|---|---|---|
| **=1.01325x10$^{5}$ Nm$^{-2}$** | =4.184 J | =1.602 189x10$^{-19}$ J | =0.124x10$^{-3}$ eV |
| **=760torr**<br>**=1 bar** | | =96.485 kJ/mol<br>= 8065.5 cm$^{-1}$ | =1.9864x10$^{-23}$J |

**SI-units:**

***1 L = 1000 ml = 1000cm$^{3}$ = 1 dm$^{3}$***

1 dm = 0.1 m

1 cal (thermochemical) = 4.184 J

dipole moment: 1 Debye = 3.335 64x10$^{-30}$ C m

force: ***1N=1J m$^{-1}$= 1kgms$^{-2}$***=10$^{5}$ dyne    pressure: ***1Pa=1Nm$^{-2}$***=1Jm$^{-3}$

***1J = 1 Nm***

power: 1W = 1J s$^{-1}$    potential: 1V =1 J C$^{-1}$

magnetic flux: 1T=1Vsm$^{-2}$=1JCsm$^{-2}$    current: 1A=1Cs$^{-1}$

**Prefixes:**

| p | n | m | m | c | d | k | M | G |
|---|---|---|---|---|---|---|---|---|
| pico | nano | micro | milli | centi | deci | kilo | mega | giga |
| $10^{-12}$ | $10^{-9}$ | $10^{-6}$ | $10^{-3}$ | $10^{-2}$ | $10^{-1}$ | $10^{3}$ | $10^{6}$ | $10^{9}$ |

**General Data**

| | | |
|---|---|---|
| **speed of light** | **c** | **2.997 925x10$^{8}$ ms$^{-1}$** |
| charge of proton | *e* | 1.602 19x10$^{-19}$ C |
| Faraday constant | F=L*e* | 9.648 46x10$^{4}$ C mol$^{-1}$ |
| **Boltzmann constant** | **k** | **1.380 66x10$^{-23}$ J K$^{-1}$** |
| **Gas constant** | **R=Lk** | **8.314 41 J K$^{-1}$ mol$^{-1}$** |
| | | **8.205 75x10$^{-2}$ dm$^{3}$ atm K$^{-1}$ m**$\ell^{-1}$ |
| **Planck constant** | **h** | **6.626 18x10$^{-34}$ Js** |
| | $\hbar = \frac{h}{2\pi}$ | 1.054 59x10$^{-34}$ Js |
| **Avogadro constant** | **L or N$_{av}$** | **6.022 14x10$^{23}$ mol$^{-1}$** |
| Atomis mass unit | u | 1.660 54x10$^{-27}$ kg |
| **Electron mass** | **$m_e$** | **9.109 39x10$^{-31}$ kg** |
| Proton mass | $m_p$ | 1.672 62x10$^{-27}$ kg |
| Neutron mass | $m_n$ | 1.674 93x10$^{-27}$ kg |
| Vacuum permittivity | $\varepsilon_o = \mu_o^{-1}c^{-2}$ | 8.854 188x10$^{-12}$ J$^{-1}$ C$^{2}$ m$^{-1}$ |
| Vacuum permeability | $\mu_o$ | 4πx10$^{-7}$ Js$^{2}$C$^{-2}$ m$^{-1}$ |
| Bohr magneton | $\mu_B = e\hbar/2m_e$ | 9.274 02x10$^{-24}$ JT$^{-1}$ |
| Nuclear magneton | $\mu_N = e\hbar/2m_p$ | 5.05079x10$^{-27}$ JT$^{-1}$ |
| Gravitational constant | G | 6.67259x10$^{-11}$ Nm$^{2}$kg$^{-2}$ |
| **Gravitational acceleration** | **g** | **9.80665 ms$^{-2}$** |
| Bohr radius | $a_o$ | 5.291 77x10$^{-11}$ m |

# THE PERIODIC TABLE OF ELEMENTS

NON-METALS

METALLOIDS

METALS

| Group | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 | 13 | 14 | 15 | 16 | 17 | 18 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | IA | IIA | IIIB | IVB | VB | VIB | VIIB | VIIIB | | | IB | IIB | IIIA | IVA | VA | VIA | VIIA | VIIIA |
| Period 1 | 1 **H** 1.008 | | | | | | | | | | | | | | | | | 2 **He** 4.003 |
| 2 | 3 **Li** 6.94 | 4 **Be** 9.01 | | | | | | | | | | | 5 **B** 10.81 | 6 **C** 12.01 | 7 **N** 14.01 | 8 **O** 16.00 | 9 **F** 19.00 | 10 **Ne** 20.18 |
| 3 | 11 **Na** 22.99 | 12 **Mg** 24.31 | | | | | | | | | | | 13 **Al** 26.9 | 14 **Si** 28.09 | 15 **P** 30.97 | 16 **S** 32.06 | 17 **Cl** 35.45 | 18 **Ar** 39.95 |
| 4 | 19 **K** 39.10 | 20 **Ca** 40.08 | 21 **Sc** 44.96 | 22 **Ti** 47.90 | 23 **V** 50.94 | 24 **Cr** 52.01 | 25 **Mn** 54.9 | 26 **Fe** 55.85 | 27 **Co** 58.71 | 28 **Ni** 58.71 | 29 **Cu** 63.54 | 30 **Zn** 65.37 | 31 **Ga** 69.7 | 32 **Ge** 72.59 | 33 **As** 74.92 | 34 **Se** 78.96 | 35 **Br** 79.91 | 36 **Kr** 83.80 |
| 5 | 37 **Rb** 85.47 | 38 **Sr** 87.62 | 39 **Y** 88.91 | 40 **Zr** 91.22 | 41 **Nb** 91.22 | 42 **Mo** 95.94 | 43 **Tc** 98.9 | 44 **Ru** 101.1 | 45 **Rh** 102.9 | 46 **Pd** 106.4 | 47 **Ag** 107.9 | 48 **Cd** 112.4 | 49 **In** 114.8 | 50 **Sn** 118.7 | 51 **Sb** 121.8 | 52 **Te** 127.6 | 53 **I** 126.9 | 54 **Xe** 131.3 |
| 6 | 55 **Cs** 132.9 | 56 **Ba** 137.3 | 71 **Lu** 174.9 | 72 **Hf** 178.5 | 73 **Ta** 180.9 | 74 **W** 183.8 | 75 **Re** 186.2 | 76 **Os** 190.2 | 77 **Ir** 192.2 | 78 **Pt** 195.1 | 79 **Au** 196.9 | 80 **Hg** 200.6 | 81 **Tl** 204.4 | 82 **Pb** 207.2 | 83 **Bi** 208.9 | 84 **Po** 210 | 85 **At** 210 | 86 **Rn** 222 |
| 7 | 87 **Fr** 223 | 88 **Ra** 226.0 | 103 **Lr** 257 | 104 **Unq** | 105 **Unp** | 106 **Unh** | 107 **Uns** | 108 **Uno** | 109 **Une** | | | | | | | | | |

| | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **Lanthanides** | 57 **La** 138.9 | 58 **Ce** 140.1 | 59 **Pr** 140.9 | 60 **Nd** 144.2 | 61 **Pm** 146.9 | 62 **Sm** 150.9 | 63 **Eu** 151.3 | 64 **Gd** 157.3 | 65 **Tb** 158.9 | 66 **Dy** 162.5 | 67 **Ho** 164.9 | 68 **Er** 167.3 | 69 **Tm** 168.9 | 70 **Yb** 173.0 |
| **Actinides** | 89 **Ac** 227.0 | 90 **Th** 232.0 | 91 **Pa** 231.0 | 92 **U** 238.0 | 93 **Np** 237.1 | 94 **Pu** 239.1 | 95 **Am** 241.1 | 96 **Cm** 247.1 | 97 **Bk** 249.1 | 98 **Cf** 251.1 | 99 **Es** 254.1 | 100 **Fm** 257.1 | 101 **Md** 258.1 | 102 **No** 255 |

***Numbers below the symbol indicates the atomic masses; and the numbers above the symbol indicates the atomic numbers.***

## Standard molar Gibbs free energy and molar entropy of formation at 298.15 K

| | $M_r$ | $\Delta G_f^\theta$/KJ/mol | $S^\theta$/J $K^{-1}$ $mol^{-1}$ | | $M_r$ | $\Delta G_f^\theta$/KJ/mol | $S^\theta$/J $K^{-1}$ $mol^{-1}$ |
|---|---|---|---|---|---|---|---|
| $H_2O$(g) | 18.015 | -228.57 | 188.83 | $O_3$(g) | 47.998 | 163.2 | 238.93 |
| $H_2O$(l) | 18.015 | -120.35 | 109.6 | NO(g) | 30.006 | 86.55 | 210.76 |
| $H_2O_2$(l) | 34.015 | -120.35 | 109.6 | $NO_2$(g) | 46.006 | 51.31 | 240.06 |
| $NH_3$(g) | 17.031 | -16.45 | 192.45 | $N_2O_4$(g) | 92.012 | 97.89 | 304.29 |
| $N_2H_4$(l) | 32.045 | 149.43 | 121.21 | $SO_2$(g) | 64.063 | -300.19 | 248.22 |
| $N_3H$(l) | 43.028 | 327.3 | 140.6 | $H_2S$(g) | 34.080 | -33.56 | 205.79 |
| $N_3H$(g) | 43.028 | 328.1 | 238.97 | $SF_6$(g) | 146.054 | -1105.3 | 291.82 |
| $HNO_3$(l) | 63.013 | -80.71 | 155.60 | HF(g) | 20.006 | -273.2 | 173.78 |
| $NH_2OH$(s) | 33.030 | | | HCl(g) | 36.461 | -95.30 | 186.91 |
| $NH_4Cl$(s) | 53.492 | -202.87 | 94.6 | HCl(aq) | 36.461 | -131.23 | 56.5 |
| $HgCl_2$(s) | 271.50 | -178.6 | 146.0 | HBr(g) | 80.917 | -53.45 | 198.70 |
| $H_2SO_4$(l) ) | 98.078 | -690.00 | 156.90 | HI(g) | 127.912 | 1.70 | 206.59 |
| $H_2SO_4$(aq) | 98.078 | -744.53 | 20.1 | $CO_2$(g) | 44.010 | -394.36 | 213.74 |
| NaCl(s) | 58.443 | -384.14 | 72.13 | CO(g) | 28.011 | -137.17 | 197.67 |
| NaOH(s) | 39.997 | -379.49 | 64.46 | $AL_2O_3$(α,s) | 101.945 | -1582.3 | 50.92 |
| KCl(s) | 74.555 | -409.14 | 82.59 | SiO2 | 60.09 | -856.64 | 41.84 |
| KBr(s) | 119.011 | -380.66 | 95.90 | FeS(s) | 87.91 | -100.4 | 60.29 |
| KI(s) | 166.006 | -324.89 | 106.32 | $FeS_2$(s) | 119.975 | -166.9 | 52.93 |
| | | | | AgCl(s) | 143.323 | -109.79 | 96.2 |
| | | | | | | | |
| He(g) | 4.003 | 0 | 126.15 | Hg(g) | 200.59 | 31.82 | 174.96 |
| Ar(g) | 39.95 | 0 | 154.84 | Hg(l) | 200.59 | 0 | 76.02 |
| $H_2$(g) | 2.016 | 0 | 130.684 | Ag(g) | 107.87 | 245.65 | 173.00 |
| $N_2$(g) | 28.013 | 0 | 191.61 | Ag(s) | 107.87 | 0 | 42.55 |
| $O_2$(g) | 31.999 | 0 | 205.138 | Na(g) | 370.95 | 76.76 | 153.71 |
| $O_3$(g) | 47.998 | 163.2 | 238.93 | Na(s) | 22.99 | 0 | 51.21 |
| $Cl_2$(g) | 70.91 | 0 | 223.07 | | | | |
| $Br_2$(g) | 159.82 | 3.110 | 245.46 | | | | |
| $Br_2$(l) | 159.82 | 0 | 152.23 | | | | |
| $I_2$(g) | 253.81 | 19.33 | 260.69 | | | | |
| $I_2$(s) | 253.81 | 0 | 116.135 | | | | |
| | | | | | | | |

| | $M_r$ | $\Delta G_f^\theta$/KJ/mol | $S^\theta$/J $K^{-1}$ $mol^{-1}$ |
|---|---|---|---|
| organic compounds | | | |
| $CH_4$(g) methane | 16.043 | -50.72 | 186.26 |
| $C_2H_2$(g) ethyne | 26.038 | 209.20 | 200.94 |
| $C_2H_4$(g) ethene | 28.05 | 68.15 | 219.56 |
| $C_2H_6$(g) ethane | 30.070 | -32.82 | 229.60 |
| $C_3H_6$ cyclopropane(g) | 42.081 | 104.45 | 237.55 |
| $C_3H_6$ propene(g) | 42.081 | 62.78 | 267.05 |
| $C_4H_{10}$ n-butane (g) | 58.124 | -17.03 | 310.23 |
| $C_5H_{12}$ n-pentane(g) | 72.151 | -8.20 | 348.40 |
| $C_6H_{12}$ cyclohexane (l) | 84.163 | 26.8 | |
| $C_6H_{14}$ n-hexane (l) | 86.178 | | 204.3 |
| $C_6H_6$ benzene (l) | 78.115 | 124.3 | 173.3 |
| $C_6H_6$ benzene (g) | 78.115 | 129.72 | 269.31 |
| $C_8H_{18}$ n-octane (l) | 114.233 | 6.4 | 361.1 |
| $C_{10}H_8$ naphthalene (l) | 128.175 | | |
| $CH_3OH$ (g) | 32.042 | -161.96 | 239.81 |
| $CH_3OH$ (l) | 32.042 | -166.27 | 126.8 |
| $CH_3CHO$ (g) | 44.054 | -128.86 | 250.3 |
| $CH_3CH_2OH$ (l) | 46.07 | -174.78 | 160.7 |
| $CH_3COOH$ (l) | 60.053 | -389.9 | 159.8 |
| $CH_3COOC_2H_5$ (l) | 88.107 | -332.7 | 259.4 |
| $C_6H_5OH$ (s) | 94.114 | -50.9 | 146.0 |
| $C_6H_5NH_2$ (l) | 93.129 | | |
| $CH_2(NH_2)CO_2H$, glycine (s) | 75.068 | -373.4 | 103.5 |
| $C_6H_{12}O_6$, α-D-glucose (s) | 180.159 | | |
| $C_6H_{22}O_6$, β-D-glucose (s) | 180.159 | -910 | 212 |
| $C_{12}H_{22}O_{11}$, sucrose (s) | 342.303 | -1543 | 360.2 |
| $CH_3CH(OH)COOH$ | 90.079 | | |
| lactic acid (s) | | | |
| | | | |
| | | | |
| | | | |

Source: American Institute of Physics handbook, McGraw-Hill.

Standard molar enthalpies of formation at 298.15 K

| | $M_r$ | $\Delta H_f^{\theta}$/KJ/mol | | $M_r$ | $\Delta H_f^{\theta}$/KJ/mol |
|---|---|---|---|---|---|
| $H_2O(g)$ | 18.015 | -241.8 | $O_3(g)$ | 47.998 | +142.7 |
| $H_2O(l)$ | 18.015 | -285.8 | $NO(g)$ | 30.006 | +90.2 |
| $H_2O_2(l)$ | 34.015 | -187.8 | $NO_2(g)$ | 46.006 | +33.2 |
| $NH_3(g)$ | 17.031 | -46.1 | $N_2O_4(g)$ | 92.012 | +9.2 |
| $N_2H_4(l)$ | 32.045 | +50.6 | $SO_2(g)$ | 64.063 | -296.8 |
| $N_3H(l)$ | 43.028 | +264.1 | $H_2S(g)$ | 34.080 | -20.6 |
| $N_3H(g)$ | 43.028 | +294.1 | $SF_6(g)$ | 146.054 | -1209 |
| $HNO_3(l)$ | 63.013 | -174.1 | $HF(g)$ | 20.006 | -271.1 |
| $NH_2OH(s)$ | 33.030 | -114.2 | $HCl(g)$ | 36.461 | -92.3 |
| $NH_4Cl(s)$ | 53.492 | -314.4 | $HCl(aq)$ | 36.461 | -167.2 |
| $HgCl_2(s)$ | 271.50 | -224.3 | $HBr(g)$ | 80.917 | +36.4 |
| $H_2SO_4(l)$ ) | 98.078 | -814.0 | $HI(g)$ | 127.912 | +26.5 |
| $H_2SO_4(aq)$ | 98.078 | -909.3 | $CO_2(g)$ | 44.010 | -393.5 |
| $NaCl(s)$ | 58.443 | -411.0 | $CO(g)$ | 28.011 | -110.5 |
| $NaOH(s)$ | 39.997 | -426.7 | $AL_2O_3(\alpha,s)$ | 101.945 | -1675.7 |
| $KCl(s)$ | 74.555 | -435.9 | $SiO2(s)$ | 60.085 | -910.9 |
| $KBr(s)$ | 119.011 | -392.2 | $FeS(s)$ | 87.91 | -100.0 |
| $KI(s)$ | 166.006 | -327.6 | $FeS_2(s)$ | 119.975 | -178.2 |
| **Diatomics(g)** | — | 0 | $AgCl(s)$ | 143.323 | -127.1 |

Enthalpies of fusion and evaporation $\Delta H_m$/KJ/mol at the transition temperature

| | $T_f$/K | Fusion[a] | $T_b$/K | Evaporation[b] | |
|---|---|---|---|---|---|
| He | 3.5 | 0.021 | 4.22 | 0 084 | |
| Ar | 83.81 | 1.188 | 87.29 | 6.506 | |
| $H_2$ | 13.96 | 0.117 | 20.38 | 0.9163 | |
| $N_2$ | 63.15 | 0.719 | 77.35 | 5.586 | |
| $O_2$ | 54.36 | 0.444 | 90.18 | 6.820 | |
| $Cl_2$ | 172.12 | 6.406 | 239.05 | 20.410 | |
| $Br_2$ | 265.90 | 10.573 | 332.35 | 29.45 | |
| $I_2$ | 386.75 | 15.52 | 458.39 | 41.80 | |
| Hg | 234.29 | 2.292 | 629.73 | 59.296 | |
| Ag | 1234 | 11.30 | 2436 | 250.63 | |
| Na | 370.95 | 2.601 | 1156 | 98.01 | |
| $CO_2$ | 217.0 | 8.33 | 194.64 | 25.23⊥ | |
| $H_2O$ | 273.15 | 6.008 | 373.15 | 40.656 | (44.016 at 298.15 K) |
| $NH_3$ | 195.40 | 5.652 | 239.73 | 23.351 | |
| $H_2S$ | 187.61 | 2.377 | 212.80 | 18.673 | |
| $CH_4$ | 90.68 | 0.941 | 111.66 | 8.18 | |
| $C_2H_6$ | 89.85 | 2.86 | 184.55 | 14.7 | |
| $C_6H_6$ | 278.65 | 10.59 | 353.25 | 30.8 | |
| $CH_3OH$ | 175.25 | 3.159 | 337.22 | 35.27 | (37.99 at 298.15K) |

⊥ Sublimation: [a]various pressures: [b]at 1atm

Temperature dependence of heat capacities, $C_{p,m} = a+bT+cT^{-2}$

| | a/J $K^{-1}mol^{-1}$ | b/$10^{-3}$J $K^{-2}mol^{-1}$ | c/$10^5$J $Kmol^{-1}$ |
|---|---|---|---|
| Gases (298-2000K) | | | |
| He, Ne, Ar, Kr, Xe | 20.78 | 0 | 0 |
| $H_2$ | 27.28 | 3.26 | 0.50 |
| $O_2$ | 29.96 | 4.18 | -1.67 |
| $N_2$ | 28.58 | 3.77 | -0.50 |
| $Cl_2$ | 37.03 | 0.67 | -2.85 |
| $CO_2$ | 44.23 | 8.79 | -8.62 |
| $H_2O$ | 30.54 | 10.29 | 0 |
| $NH_3$ | 29.75 | 25.10 | -1.55 |
| $CH_4$ | 23.64 | 47.86 | -1.92 |

Standard molar enthalpies of formation and combustion at 298.15 K.

| | $M_r$ | $\Delta H_f^{\theta}$/KJ/mol | $\Delta H_c^{\theta}$/KJ/mol |
|---|---|---|---|
| $CH_4(g)$ | 16.043 | -74.81 | |
| $C_2H_2(g)$ | 26.038 | +226.8 | 1300 |
| $C_2H_4(g)$ | 28.054 | +52.30 | 1411 |
| $C_2H_6(g)$ | 30.070 | -84.64 | 1560 |
| $C_3H_6$ cyclopropane(g) | 42.081 | 53.35 | 2091 |
| $C_3H_6$ (propene(g) | 42.081 | 20.5 | 2058 |
| $C_4H_{10}$ n-butane (g) | 58.124 | -126.11 | 2877 |
| $C_5H_{12}$ n-pentane(g) | 72.151 | -146.4 | 3536 |
| $C_6H_{12}$ cyclohexane (l) | 84.163 | -156.2 | 3920 |
| $C_6H_{14}$ n-hexane (l) | 86.178 | -198.7 | 4163 |
| $C_6H_6$ benzene (l) | 78.115 | +48.99 | 3268 |
| $C_8H_{18}$ n-octane (l) | 114.233 | -249.8 | 5471 |
| $C_{10}H_8$ naphthalene (l) | 128.175 | +78.53 | 5157 |
| $CH_3OH$ (l) | 32.042 | -239.0 | 726.1 |
| $CH_3CHO$ (g) | 44.054 | -166.0 | 1193 |
| $CH_3CH_2OH$ (l) | 46.070 | -277.0 | 1368 |
| $CH_3COOH$ (l) | 60.053 | -484.2 | 874.5 |
| $CH_3COOC_2H_5$ (l) | 88.107 | -486.6 | 2231 |
| $C_6H_5OH$ (s) | 94.114 | -165.0 | 3054 |
| $C_6H_5NH_2$ (l) | 93.129 | -31.1 | 3393 |
| $NH_2CO.NH$, urea(s) | 60.056 | -333.0 | 632.2 |
| $CH_2(NH_2)CO_2H$, glycine (s) | 75.068 | -537.2 | 964.4 |
| $C_6H_{12}O_6$, $\alpha$-D-glucose (s) | 180.159 | -1274 | 2802 |
| $C_6H_{22}O_6$, $\beta$-D-glucose (s) | 180.159 | -1268 | 2808 |
| $C_{12}H_{22}O_{11}$, sucrose (s) | 342.303 | -2222 | 5645 |
| $CH_3CH(OH)COOH$ lactic acid (s) | 90.079 | -694.0 | 1344 |

Source: American Institute of Physics handbook, McGraw-Hill.

# Standard molar Gibbs free energy and molar entropy of formation at 298.15 K

| | $M_r$ | $\Delta G_f^0$/KJ/mol | $S^0$/J $K^{-1}$ $mol^{-1}$ | | $M_r$ | $\Delta G_f^0$/KJ/mol | $S^0$/J $K^{-1}$ $mol^{-1}$ |
|---|---|---|---|---|---|---|---|
| $H_2O$(g) | 18.015 | -228.57 | 188.83 | $O_3$(g) | 47.998 | 163.2 | 238.93 |
| $H_2O$(l) | 18.015 | -120.35 | 109.6 | NO(g) | 30.006 | 86.55 | 210.76 |
| $H_2O_2$(l) | 34.015 | -120.35 | 109.6 | $NO_2$(g) | 46.006 | 51.31 | 240.06 |
| $NH_3$(g) | 17.031 | -16.45 | 192.45 | $N_2O_4$(g) | 92.012 | 97.89 | 304.29 |
| $N_2H_4$(l) | 32.045 | 149.43 | 121.21 | $SO_2$(g) | 64.063 | -300.19 | 248.22 |
| $N_3H$(l) | 43.028 | 327.3 | 140.6 | $H_2S$(g) | 34.080 | -33.56 | 205.79 |
| $N_3H$(g) | 43.028 | 328.1 | 238.97 | $SF_6$(g) | 146.054 | -1105.3 | 291.82 |
| $HNO_3$(l) | 63.013 | -80.71 | 155.60 | HF(g) | 20.006 | -273.2 | 173.78 |
| $NH_2OH$(s) | 33.030 | | | HCl(g) | 36.461 | -95.30 | 186.91 |
| $NH_4Cl$(s) | 53.492 | -202.87 | 94.6 | HCl(aq) | 36.461 | -131.23 | 56.5 |
| $HgCl_2$(s) | 271.50 | -178.6 | 146.0 | HBr(g) | 80.917 | -53.45 | 198.70 |
| $H_2SO_4$(l) ) | 98.078 | -690.00 | 156.90 | HI(g) | 127.912 | 1.70 | 206.59 |
| $H_2SO_4$(aq) | 98.078 | -744.53 | 20.1 | $CO_2$(g) | 44.010 | -394.36 | 213.74 |
| NaCl(s) | 58.443 | -384.14 | 72.13 | CO(g) | 28.011 | -137.17 | 197.67 |
| NaOH(s) | 39.997 | -379.49 | 64.46 | $AL_2O_3$(α,s) | 101.945 | -1582.3 | 50.92 |
| KCl(s) | 74.555 | -409.14 | 82.59 | $SiO_2$ | 60.09 | -856.64 | 41.84 |
| KBr(s) | 119.011 | -380.66 | 95.90 | FeS(s) | 87.91 | -100.4 | 60.29 |
| KI(s) | 166.006 | -324.89 | 106.32 | $FeS_2$(s) | 119.975 | -166.9 | 52.93 |
| | | | | AgCl(s) | 143.323 | -109.79 | 96.2 |
| | | | | | | | |
| He(g) | 4.003 | 0 | 126.15 | Hg(g) | 200.59 | 31.82 | 174.96 |
| Ar(g) | 39.95 | 0 | 154.84 | Hg(l) | 200.59 | 0 | 76.02 |
| $H_2$(g) | 2.016 | 0 | 130.684 | Ag(g) | 107.87 | 245.65 | 173.00 |
| $N_2$(g) | 28.013 | 0 | 191.61 | Ag(s) | 107.87 | 0 | 42.55 |
| $O_2$(g) | 31.999 | 0 | 205.138 | Na(g) | 370.95 | 76.76 | 153.71 |
| $O_3$(g) | 47.998 | 163.2 | 238.93 | Na(s) | 22.99 | 0 | 51.21 |
| $Cl_2$(g) | 70.91 | 0 | 223.07 | | | | |
| $Br_2$(g) | 159.82 | 3.110 | 245.46 | | | | |
| $Br_2$(l) | 159.82 | 0 | 152.23 | | | | |
| $I_2$(g) | 253.81 | 19.33 | 260.69 | | | | |
| $I_2$(s) | 253.81 | 0 | 116.135 | | | | |
| | | | | | | | |

| | $M_r$ | $\Delta G_f^0$/KJ/mol | $S^0$/J $K^{-1}$ $mol^{-1}$ |
|---|---|---|---|
| organic compounds | | | |
| $CH_4$(g) methane | 16.043 | -50.72 | 186.26 |
| $C_2H_2$(g) ethyne | 26.038 | 209.20 | 200.94 |
| $C_2H_4$(g) ethene | 28.05 | 68.15 | 219.56 |
| $C_2H_6$(g) ethane | 30.070 | -32.82 | 229.60 |
| $C_3H_6$ cyclopropane(g) | 42.081 | 104.45 | 237.55 |
| $C_3H_6$ propene(g) | 42.081 | 62.78 | 267.05 |
| $C_4H_{10}$ n-butane (g) | 58.124 | -17.03 | 310.23 |
| $C_5H_{12}$ n-pentane(g) | 72.151 | -8.20 | 348.40 |
| $C_6H_{12}$ cyclohexane (l) | 84.163 | 26.8 | |
| $C_6H_{14}$ n-hexane (l) | 86.178 | | 204.3 |
| $C_6H_6$ benzene (l) | 78.115 | 124.3 | 173.3 |
| $C_6H_6$ benzene (g) | 78.115 | 129.72 | 269.31 |
| $C_8H_{18}$ n-octane (l) | 114.233 | 6.4 | 361.1 |
| $C_{10}H_8$ naphthalene (l) | 128.175 | | |
| $CH_3OH$ (g) | 32.042 | -161.96 | 239.81 |
| $CH_3OH$ (l) | 32.042 | -166.27 | 126.8 |
| $CH_3CHO$ (g) | 44.054 | -128.86 | 250.3 |
| $CH_3CH_2OH$ (l) | 46.07 | -174.78 | 160.7 |
| $CH_3COOH$ (l) | 60.053 | -389.9 | 159.8 |
| $CH_3COOC_2H_5$ (l) | 88.107 | -332.7 | 259.4 |
| $C_6H_5OH$ (s) | 94.114 | -50.9 | 146.0 |
| $C_6H_5NH_2$ (l) | 93.129 | | |
| $CH_2(NH_2)CO_2H$, glycine (s) | 75.068 | -373.4 | 103.5 |
| $C_6H_{12}O_6$, α-D-glucose (s) | 180.159 | | |
| $C_6H_{22}O_6$, β-D-glucose (s) | 180.159 | -910 | 212 |
| $C_{12}H_{22}O_{11}$, sucrose (s) | 342.303 | -1543 | 360.2 |
| $CH_3CH(OH)COOH$ | 90.079 | | |
| lactic acid (s) | | | |
| | | | |
| | | | |
| | | | |

Source: American Institute of Physics handbook, McGraw-Hill.